THE PRODUCTION OF ACTIVATED CARBON FROM WASTE BARK FOR EFFLUENT TREATMENT IN THE PULP AND PAPER INDUSTRY

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ABSTRACT

In this study, it is shown that activated carbon can be produced from the bark of Spruce and Jack Pine for use in wastewater treatment.

The bark was pyrolyzed in a tube furnace at 1200 ^{o}F for 2 hrs, and then activated by steam. The activation conditions were varied from 1200 to 1700 ^{o}F with residence times of 15 to 60 min. The yield of activated carbon ranged from 6 to 29 per cent based on original air-dried bark. The activity of the carbon was determined by measuring the Chemical Oxygen Demand (COD) and color removal from the bleaching effluent of a kraft pulp mill which was treated with various dosages of activated carbon.

The adsorptive capacity of the carbon could be increased by increasing the activation temperature and time, with a corresponding reduction in the yield of carbon.

At a carbon concentration of 10 g/l, the powdered carbon could remove up to 70 per cent of the COD and 95 per cent of the coloring materials from the effluent leaving the first caustic extraction stage of a bleach plant which contained 1200 ppm of COD and color transmittance of 50 per cent at a wavelength of 580 mμ. At 20 g/l, the reductions were 80 and 98 per cent, respectively, for COD and color.

Regeneration of spent carbon by steam treatment was feasible with little loss in either activity or weight.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The pulp and paper industry has been increasingly concerned about water pollution abatement. Much effort has been made on finding an effective and economic method for treating the effluent from a pulp mill while meeting the increasing environmental quality standards.

Two major types of pollutants found in pulp mill wastewaters are materials that exert oxygen demand (wood sugars, fat, etc.) and that cause color (products of lignin degradation) in the receiving stream.

At present, a number of treatment processes are in operation at many pulp mills. They include primary treatment (settling), aerated lagoon, activated sludge, and chemical coagulation. However, no single method was found to satisfactorily remove major types of pollutants. This is due to the fact that the color causing materials which are mostly lignin-related compounds are largely nonbiodegradable (1), but they contribute to the COD of the effluent. Although these compounds have not been found to be obnoxious to aquatic life, they may hinder light penetration into the stream and retard algal growth. The main source of these color materials comes from the bleach plant and in particular, from the first caustic extraction stage.

Another area of concern at a pulp mill is the disposal of waste bark from the wood room. The bark removed in the debarking process is equivalent to one-half of the volume of dried pulp produced a day. A

fraction of the bark can be burned in the boiler to generate steam, but the remaining bark must be disposed of by other means such as the method of land-filling or use in tannin extraction.

One method of color removal that is widely used is activated carbon adsorption. It is conceived that if a method of producing activated carbon from bark for use in waste treatment is found, it would solve the problem of bark disposal and of color discharge.

Hence, the purpose of this study was to investigate the feasibility of producing activated carbon from waste bark and its use in the treatment of pulp mill effluent. Bark was carbonized and then activated by steam in a tube furnace, and the effects of temperature and activation time were noted. The activity of resulting carbon was determined in terms of per cent COD and color removal from the bleach plant effluent. An investigation was also conducted to study the steam regeneration of spent carbon.

2. LITERATURE REVIEW

2.1 Methods of manufacturing activated carbon

Activated carbon is an amorphous form of carbon (2) which has been specially treated to produce a very large surface area ranging from 300 to 2000 m^2/g. This large surface area provides the activated carbon with the ability to adsorb gases and vapors from gases, and dissolved materials from liquids.

There are two distinct types of activated carbon; liquid phase and gas phase carbons. Liquid phase or decolorizing carbons are light, fluffy, and generally in powdered form. They are made from low density starting materials such as: saw dust, bone, wood, and paper mill waste liquors. Gas phase carbons are hard dense granules, derived from coal, coke, coconut shell, and petroleum residues.

Virtually, any carbonaceous material can be used for the manufacture of activated carbon. In general, the preparation of activated carbon consists of two stages, namely, carbonization (pyrolysis) and activation.

The carbonization involves heating of the raw material in the absence of air at temperature in the range of 500 to 800 ^{o}C. This process drives off most of the volatile matters and produces a rather unreactive charcoal.

An activation method that is widely used involves controlled oxidation of the carbon with steam, CO_2, or air. The oxidizing gas

removes residual hydrocarbons and also develops an intricate network of pores in the carbon mass, thus rendering the carbon reactive. The oxidation is usually carried on from 15 min to several hours depending upon the activity desired; and the temperature of activation is much higher than that of carbonization.

2.2 Mechanism of activation process

The activation process, including the carbonization stage, is a series of complex chemical reactions the mechanisms of which are not well understood yet. Studies have been done to determine the molecular structure of activated carbon that might contribute to the understanding of activation processes.

Wolff (3) studied X-ray diffraction of activated carbon and found that activated carbon in its simplest form is composed of randomly oriented microcrystallites consisting of many layers of aromatic or fused hexagonal rings, with a plane width of 20 to 50 Angstroms (A^{o}). Garten and Weiss (4) proposed that carbonization is a polymerization process resulting from thermal dehydration with formation of double bonds. Further heating results in the aromatization of some of the double bonds, causing small aromatic nuclei to form amid large heterocyclic structures. It is also believed that the size of the layer planes is influenced by the maximum temperature attained during carbonization.

It has been postulated (3, 5) that activation occurs in two ways. First, large pores ($> 100\ A^{o}$) are formed by the removal of the

most reactive material consisting of hydrocarbon radicals attached to the edge carbons of the microcrystallite. Second, micropores (5 to 20 A^{o}) are formed by the burn out of large segments of individual microcrystallite layer planes. Baker (6) also proposed a similar mechanism of activation which consists partly of increasing the surface area by producing numerous small capillaries.

Snow et al. (7) found an interesting fact that inorganic matters present in the starting material causes dislocations during microcrystallite formation and speeds up pore development during activation.

Recent studies at Colorado University (8) indicated that the porous structure of the starting material has a strong influence on the activation by carbon dioxide, and that in order to develop a large surface area, a substantial micropore structure must be present in the starting material.

When steam is used to activate the carbon there are several possible reactions (9):

$$C + H_2O\ (g) \longrightarrow CO + H_2$$

$$C + 2H_2O\ (g) \longrightarrow CO_2 + 2H_2$$

$$C + CO_2 \longrightarrow 2CO$$

$$CO + H_2O\ (g) \longrightarrow CO_2 + H_2$$

Since the activating reaction is endothermic, external heat is required. If, however, the product gases are burnt to provide heat, the activation becomes self-sustained after the initial heating (10).

2.3 Adsorption phenomenon

Adsorption in liquid phase is a process for separating small quantities of organic impurities from dilute solution. It may be explained in terms of interfacial action. Molecules at the solid surface (adsorbent) are subject to unbalanced forces which tend to attract other molescules in the liquid phase. This adsorption is known as physical adsorption.

Upon contact with a liquid containing organic materials, activated carbon selectively adsorbs these materials until an equilibrium is reached. In water carbon has a great attraction for large organic molecules and nonpolar compounds (11), and the force of attraction is much greater when the adsorbed molecules are similar in size to the pores.

There are three main factors that affect the efficiency of the adsorption process, namely, (i) contact time, (ii) temperature, and (iii) pH.

(i) Contact time. At ambient conditions, adsorption is a relatively slow process and adsorption equilibrium is reached only after a sufficiently long contact time. Agitation or mixing of the solution tends to speed up the adsorption rate and, hence, reduces the length of contact time.

(ii) Temperature. Generally, the rate and adsorptive capacity increase slightly with decreasing temperature of the solution.

(iii) pH of the liquid phase. The pH effect on the adsorptive power of activated carbon is due to the fact that pH influences the degree of dissociation of color materials in solution. Undissociated

molecules are found to be more strongly adsorbed than the ions resulting from these molecules. It has been found that (12) electropositive materials are adsorbed by the carbon more effectively in alkali solution, while electronegative matters are removed better in acidic solution. Amphoteric compounds, such as colloids and some natural colors, are adsorbed best near their isoelectric point, where they show neither acid or basic properties. However, pH has no effect on the adsorption of nonelectrolytes such as sugar.

Quantitatively, adsorption is usually formulated from the empirical Freundlich or Langmuir isotherm.

Langmuir isotherm is expressed by the following equation (13):

$$\frac{X}{M} = \frac{abC}{1 + aC}$$

where

X = weight of solute adsorbed,

M = weight of adsorbent (carbon),

C = equilibrium concentration of solute, and

a, b = constants.

Freundlich isotherm is based on the following expression (13):

$$\frac{X}{M} = kC^n$$

where

X, M, C = same as above, and

k, n = constants depending on temperature, nature of adsorbate, and adsorbent.

Both adsorption isotherms describe graphically the relation between the weight of material adsorbed at equilibrium per unit weight of carbon and the concentration of adsorbate (see Figure 1).

2.4 Application of activated carbon in wastewater treatment

The ability of charcoal to remove color from solution was first known in the fifteenth century (14). Later, with the development of the activation process in Germany, activated carbon found application in the cane sugar refineries. Powdered carbon was used as a decolorizer to remove colored impurities from the sugar syrup. Its use in water purification on a plant scale did not come about until the late 1920's (15). The carbon was mainly employed to eliminate taste and odor from drinking waters.

Although application of activated carbon for wastewater treatment is quite new, its potential value as a practical and economical treatment process has stimulated much research in this area.

Carbon adsorption as a tertiary treatment process to remove refractory organic matters from domestic sewage and industrial wastes has been reported in several studies (16, 17, 18, 19, 20). Cooper and Hagen (21) recommended activated carbon for advanced waste treatment where reclamation is of importance. Treatment of secondary industrial effluent with carbon was found to remove up to 85 per cent of Total Organic Carbon (TOC) (22). Activated carbon combined with coagulation-filtration can be a potential replacement for the traditional biological treatment (23, 24). Fox et al. (25) at Dow Chemical reported good

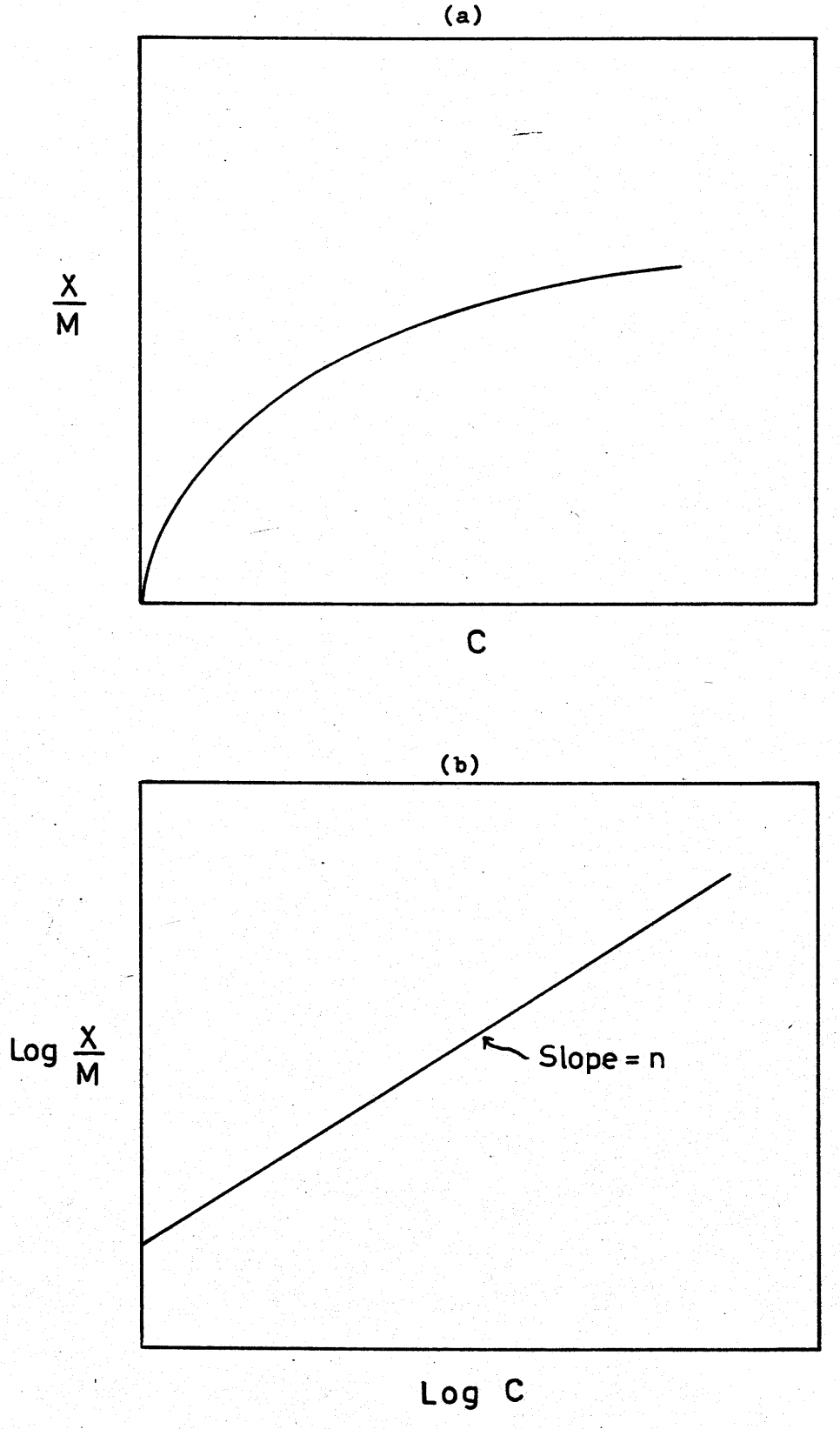

Figure 1. Graphical presentation of Langmuir isotherm (a) and Freundlich isotherm (b).

results of purification of a waste brine by activated carbon.

Within the pulp and paper industry, carbon adsorption appears to be of particular interest in removing colored matters from the effluent (26, 27). Recently, a three-year study was conducted at St. Regis Paper Company (28) to develop a novel method of recycling the mill effluent after treatment with activated carbon. The technique was claimed to achieve 90 per cent reduction in present water requirements at pulp mills.

2.5 Regeneration of spent carbon

In the use of activated carbon for treatment of wastewater, it is usually economical to regenerate and reuse the spent carbon. There are several methods for reactivating carbon (29): solvent wash, acid or caustic wash, thermal reactivation, and steam regeneration. When solvent is used to reactivate the carbon, the adsorbate is allowed to come into contact with the solvent which dissolves the adsorbed materials in a carbon bed. The bed is then drained of the solvent and the regenerated carbon is ready for use. If an acid or caustic is more effective than a solvent, it may be used in place of solvent. Thermal regeneration involves three successive steps: drying, baking, and activating by air in a multiple hearth furnace. With the method of steam regeneration, the steam is passed through the spent carbon and is either vented to the atmosphere or condensed and recovered.

3. APPARATUS

A schematic diagram of the apparatus used to produce activated carbon is shown in Figure 2.

The tubular reactor was constructed from a 2.0 in. schedule 5S steel pipe, approximately 28.0 in. long. Both ends of the pipe were fitted with steel caps which could be removed for loading and unloading materials. Attached to each cap was a retaining disc and a stainless steel screen to keep the bark within the heating region of the furnace.

External heat for the process was supplied by a Lindburg Heviduty tube furnace equipped with a temperature controller having a temperature range from 390 to 2192 ^{o}F.

A metering pump delivered distilled water to the reactor at the rate of 5 mls/min. During the experiment, helium gas was bubbled through the water to remove traces of dissolved oxygen (nitrogen could be used in place of helium). Upon entering the hot reactor, the distilled water vaporized to steam which in turn activated the charcoal.

A cooling coil and condenser connected to the pipe outlet enabled tar and condensate to be collected. Noncondensable gases escaped through a vent.

Color determination of the effluent was conducted using a Welch Chem-Anal System Spectrophotometer. This system consisted of the following units: power supply, light source, monochromator, sample compartment, detector, and meter. The sample compartment contained four 1 cm square

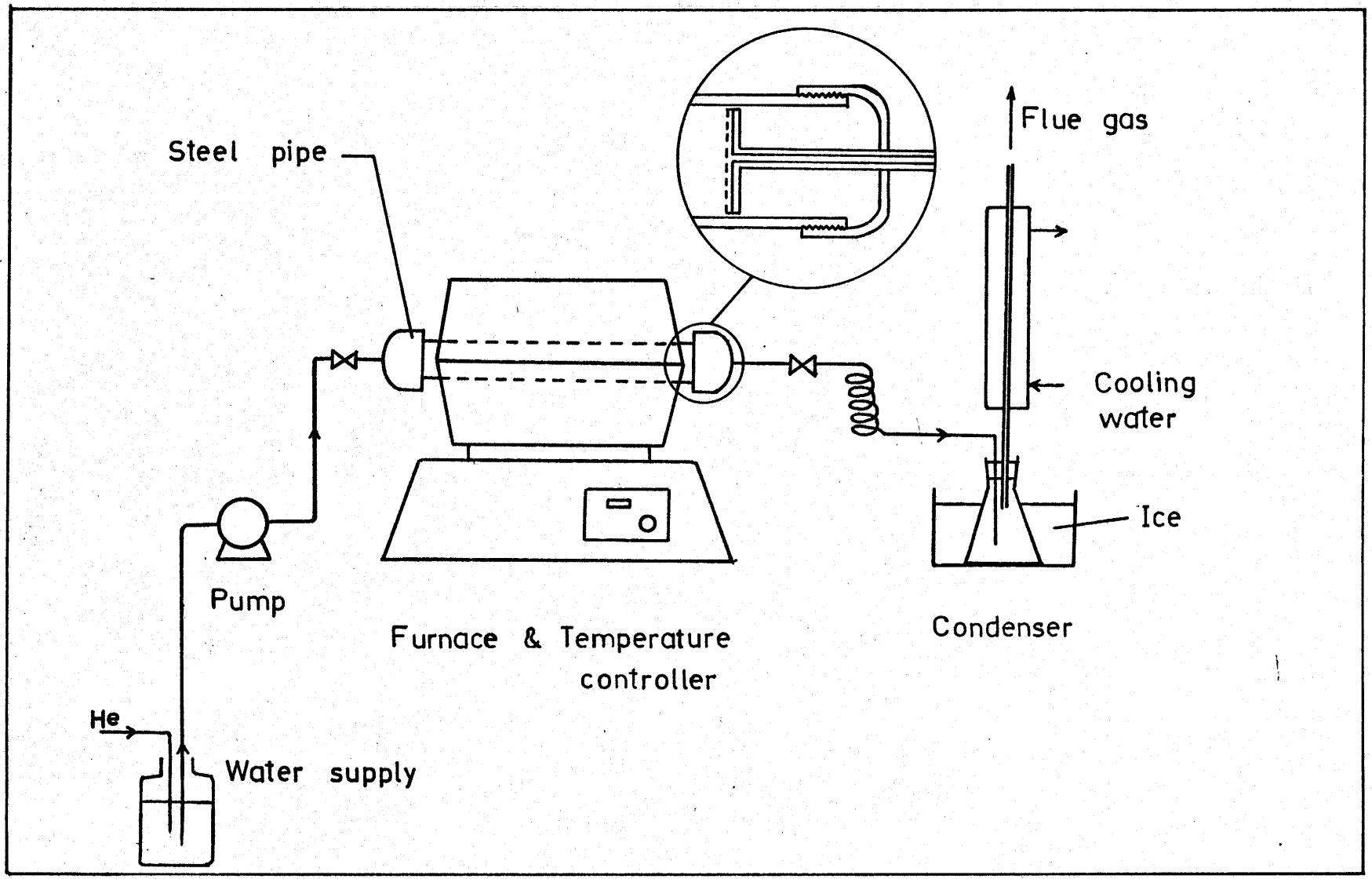

Figure 2. Schematic diagram of the apparatus.

cuvettes (cells). To ensure precise absorbance measurements, the same cuvette was continually used as the sample holder.

A mechanical shaker of rotary type was employed in mixing the effluent sample and activated carbon. The shaker had switches for setting the speed and time of mixing.

A revolving ball mill was used to pulverize the carbon. The ball mill was made of a porcelain cylindrical shell, 6.0 in. long and 5.0 in. diameter, and filled with eight to ten 0.5 in. steel balls. It was driven by a motor (Model JK2, Zero-Max) at a speed of about 25 rpm.

All apparatus for analytical tests are given in the APPENDICES.

4. PROCEDURE

4.1 Analytical procedure

4.1.1 COD analysis. The COD is a measure of the oxygen equivalent of the organic fraction in a sample of wastewater which can be oxidized by permanganate or dichromate in an acid solution. There are three methods which have been commonly used for COD analysis. These are:

(i) Dichromate oxidation,

(ii) Permanganate oxidation, and

(iii) Rapid COD test.

Fould and Lunsford (30) reported in a comparative analysis that the dichromate method has the highest oxidation yield. However, this method is rather costly in terms of chemical reagents and lengthy reflux time. On the other hand, the Rapid COD test as proposed by Jeris (31) reduces considerably the testing time, but it has disadvantages due to the sensitivity to digestion temperature and the requirement of a mercury salt. It was decided to use a modified permanganate method for COD analysis in this work because of the following reasons:

First, a modified permanganate method which was commonly used to determine the "hardness" of wood pulp was found to be also suitable for determining COD of bleach plant effluent. This method requires very little chemicals and a short reaction time (5 min), and can be carried out at room temperature.

Second, there is a direct relationship between the Permanganate Number (K Number) by this method and the COD obtained from Rapid COD test (see APPENDIX A.1).

4.1.2 K Number[a]. The permanganate method is based on the K Number which is defined as the number of mls of 0.1 N $KMnO_4$ solution consumed by 1.0 g of moisture-free pulp under acidic condition (32). The complete procedure for determining K Number is given in APPENDIX A.2.

In correlating K Number with Rapid COD, samples of effluent were treated with various dosages of activated carbon and filtered through 0.45 μ millipore filter disc. The filtrates were then analyzed for Rapid COD and K Number.

4.1.3 Color analysis. Color determinations were conducted using a Welch Anal System Colorimeter. A wavelength of 580 mμ which gave maximum sensitivity as stated by Foushee (33) was used in all tests. The raw effluent (pH 8.2) had an initial light absorbance of about 0.350 at this wavelength.

A method used for determining the per cent color removal was developed as follows. The effluent was diluted with distilled water in a series of dilutions from 0 to 100 per cent, and for each dilution the absorbance (optical density) was measured. A calibration curve of absorbance versus per cent dilution was plotted and used for expressing

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[a]This is not the same K Number which is used in the determination of the relative "hardness" of pulp.

color removal efficiency after carbon treatment.

4.2 Carbonization and activation

Shredded bark obtained from the Prince Albert Pulp Mill Company was air-dried and further crushed in a hammermill to a final mesh size range from 10 to 50 (by Endecotts standard sieve).

About 140.0 g of bark was placed in the reactor and carbonized at 1200 ^{o}F for 2 hrs. At the end of the carbonization period, the temperature was raised to the desired activation temperature and water was pumped through the reactor at the rate of 5 mls/min. Upon entering the hot reactor, the water vaporized to steam which activated the charcoal. When activation was completed, the hot carbon was allowed to cool off and reweighed. The product carbon was crushed in a ball mill for 15 min, and then separated into two different mesh sizes: granular (50 to 100 mesh) and powder (230 to 400 mesh).

By varying the furnace temperature and residence time for the activation period it was possible to obtain carbons of different degrees of activity. Figure 3 is the flow sheet of the manufacture of activated carbon in this study.

4.3 Activity determination

The test for adsorptive activity consisted of mixing 0.2, 0.4, 1.0, and 2.0 g of activated carbon with 100 mls of bleaching effluent in 250 ml Erlenmeyer flasks and agitating the slurry mixtures on a mechanical shaker at 150 rpm for at least 2 hrs. The mixtures were then separated by filtering through 0.45 μ millipore filter discs. A sample of

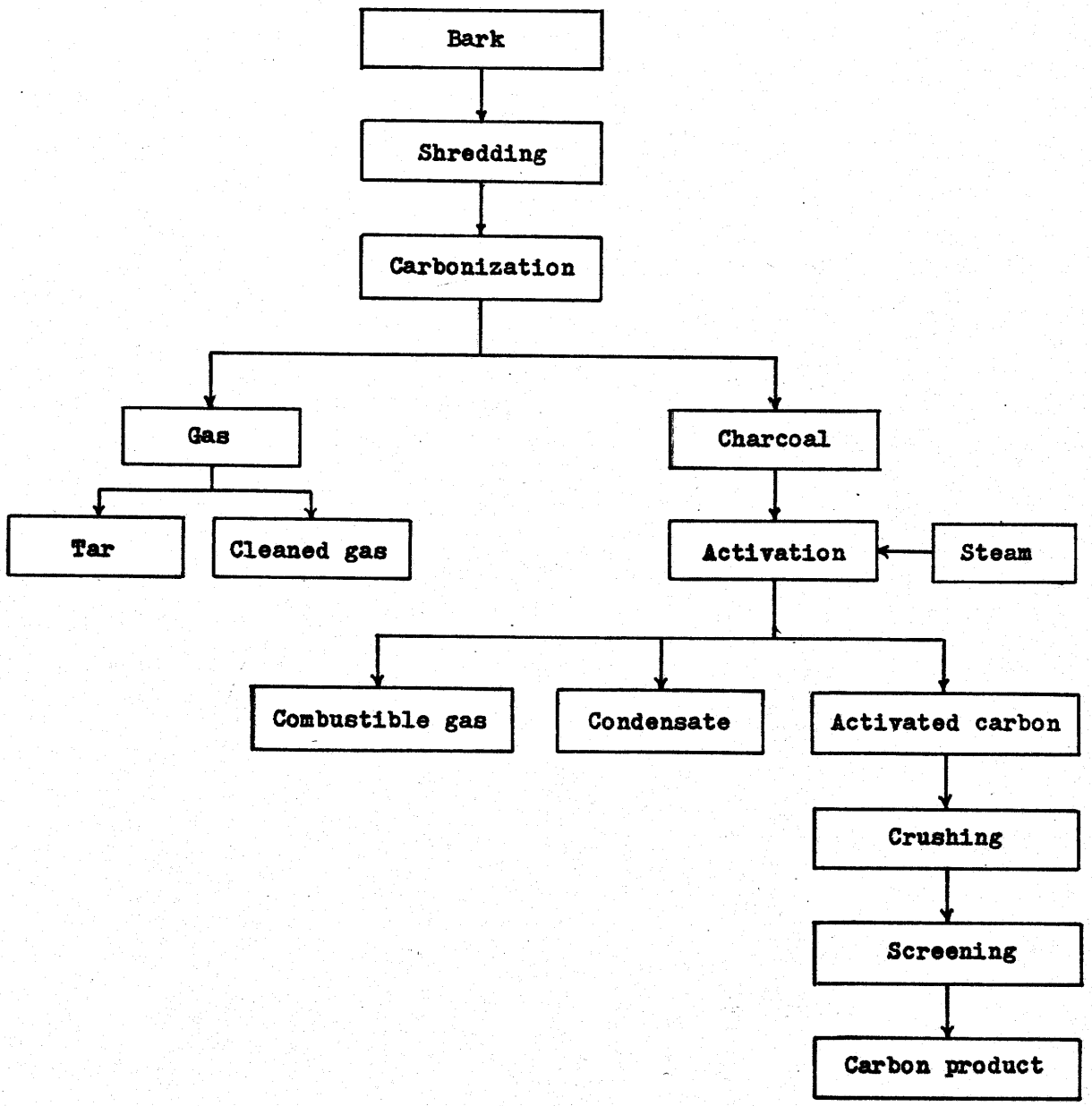


Figure 3. Flow sheet of activated carbon manufacture.

raw effluent without carbon was used as a control. The filtrates were then analyzed for K Number and light absorbance.

The activity of activated carbon was expressed in terms of COD and color removal from the effluent.

4.4 Test for the effect of contact time

A preliminary test was conducted to determine the contact time necessary for adsorption to reach equilibrium.

One gram of an arbitrary activated carbon was weighed and added to each of five 100 mls aliquots of filtered effluent. These five treated samples were agitated on a shaker for 1, 2, 3, 4, and 10 hrs, respectively, while a sixth sample was stirred as a control. At the end of its contact time, each sample was filtered through a 0.45 μ filtered disc and the K Number was measured.

4.5 Test for temperature effect

The effect of the temperature of effluent on adsorption was determined by measuring the activity of an arbitrary carbon at various temperatures of 5, 24, and 47 °C. To maintain a constant temperature environment the adsorption procedure was carried out in an incubator set at the desired temperature.

4.6 Test for pH effect

The extent to which pH of the effluent might affect the adsorption was studied by measuring the activity of carbon in effluent of pH varying from 4 to 12. Concentrated H_2SO_4 or NaOH was used to adjust the

pH to a desired value.

4.7 Regeneration procedure

The procedure for regeneration consisted of placing a known amount of spent activated carbon in a copper tube, 7.0 in. long and 1.0 in. Inside Diameter (ID), and covering two ends of the tube with glass wool. The copper tube was subsequently inserted in the reactor (previously used in producing activated carbon). The reactor was then heated rapidly to 1200 ^{o}F in the tube furnace, and distilled water was pumped into the reactor at the rate of 5 mls/min for about 30 min. At the end of regeneration, the reactivated carbon was removed and tested for activity.

5. RESULTS AND DISCUSSION

5.1 Correlation of K Number with Rapid COD

As can be seen from Figure 4, there is a linear relationship between Rapid COD and K Number. The solid line is the least squares curve fit of the data points, and it may be represented by the following relation:

$$COD = (212.8)(K\ Number) - 137$$

This relation applies well for K Number range of 2.5 to 6.0 which corresponds to COD range of 400 to 1130 ppm. The broken line is the extrapolation by eyeball through the origin.

5.2 Calibration curve of color removal

A plot of light absorbance versus per cent dilution is shown in Figure 5. In accordance with Beer's law, a linear relationship is obtained and can be expressed by the following equation:

$$y = mx + y_o$$

where

x = per cent dilution,

y = light absorbance,

y_o = initial light absorbance, and

m = slope of the straight line.

Since $$m = -\frac{y_o}{100}$$

the above equation becomes:

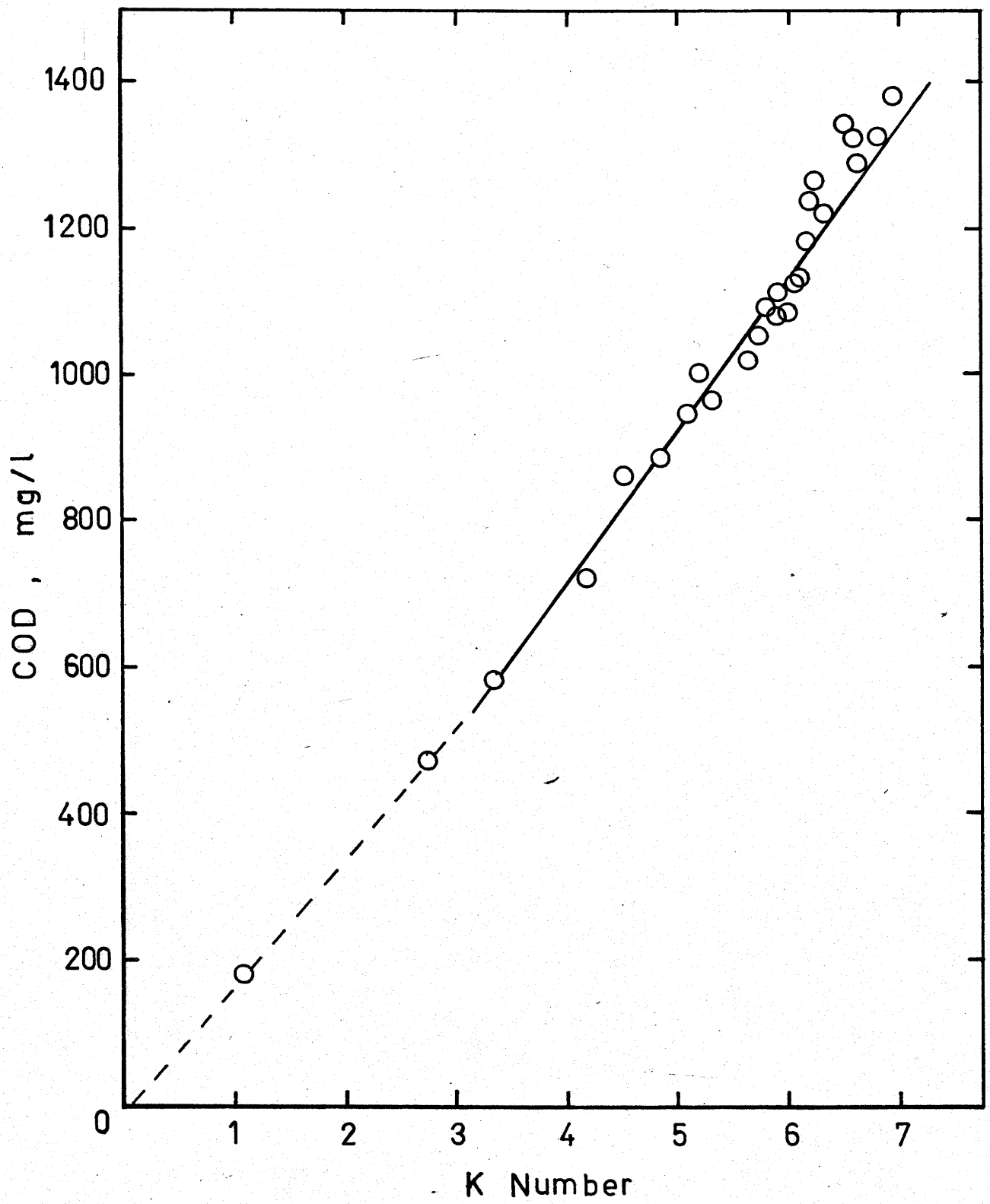


Figure 4. Correlation between K Number and COD.

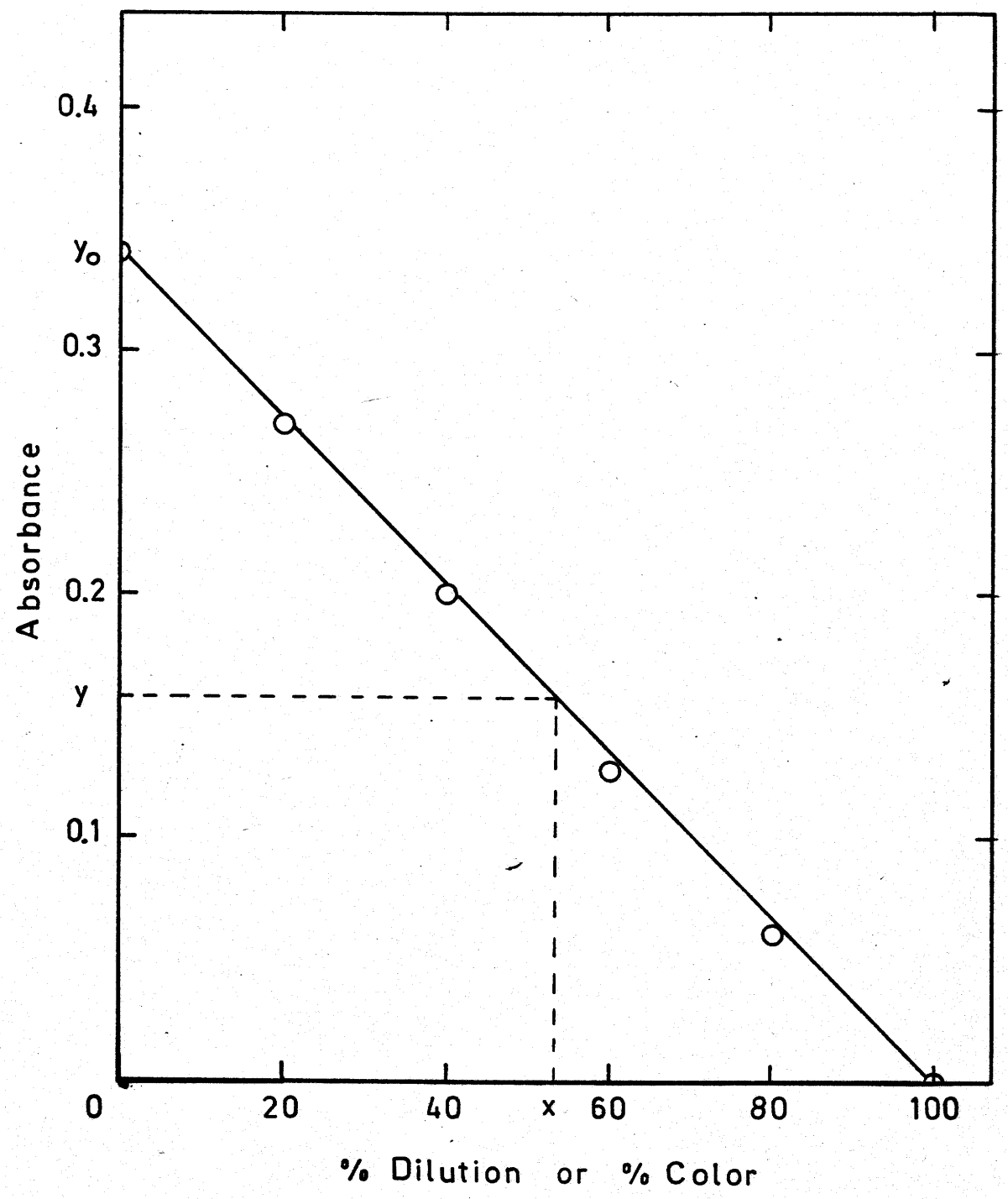


Figure 5. Plot of light absorbance versus per cent dilution.

$$y = -\frac{y_o}{100} x + y_o$$

Hence, the per cent of color removal (dilution) is given by the following expression:

$$x = \frac{(y_o - y)}{y_o} \times 100.$$

5.3 Effect of contact time on adsorption

From the plot of per cent COD remaining against contact time (see Figure 6), it is observed that adsorption equilibrium was essentially reached in 2 hrs of mixing. The rate of COD reduction was initially high in the first hour, then diminished to zero. As a result, a contact time of 2 hrs was used to ensure that equilibrium was reached.

5.4 Effect of temperature on adsorption

As is evident from Figure 7, the temperature in a normal range (5 to 47 ^{o}C) has little effect on the adsorption process. It is, therefore, convenient to carry out the carbon adsorption at ambient temperature.

5.5 Effect of pH on adsorption

The pH effect on adsorption efficiency of carbon is shown graphically in Figure 8. As pH of the effluent was lowered from 12 to 4, the COD removal increased from 40 to 66 per cent while color removal increased by about 10 per cent. This indicates that activated carbon gives greater adsorption with increase in acidity of the solution, and that the organic impurities in the effluent are of electronegative nature.

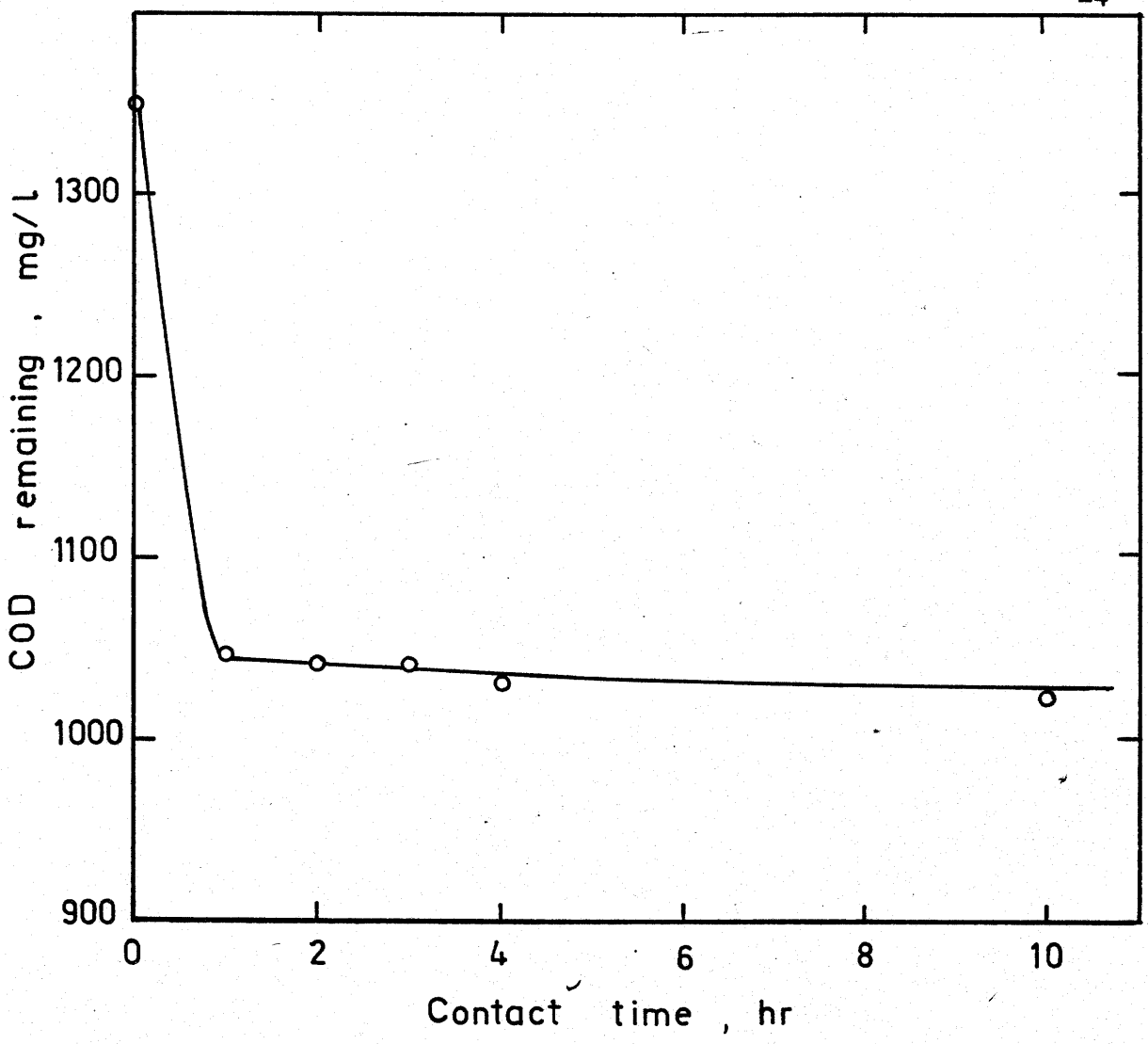


Figure 6. Plot of COD remaining versus contact time.

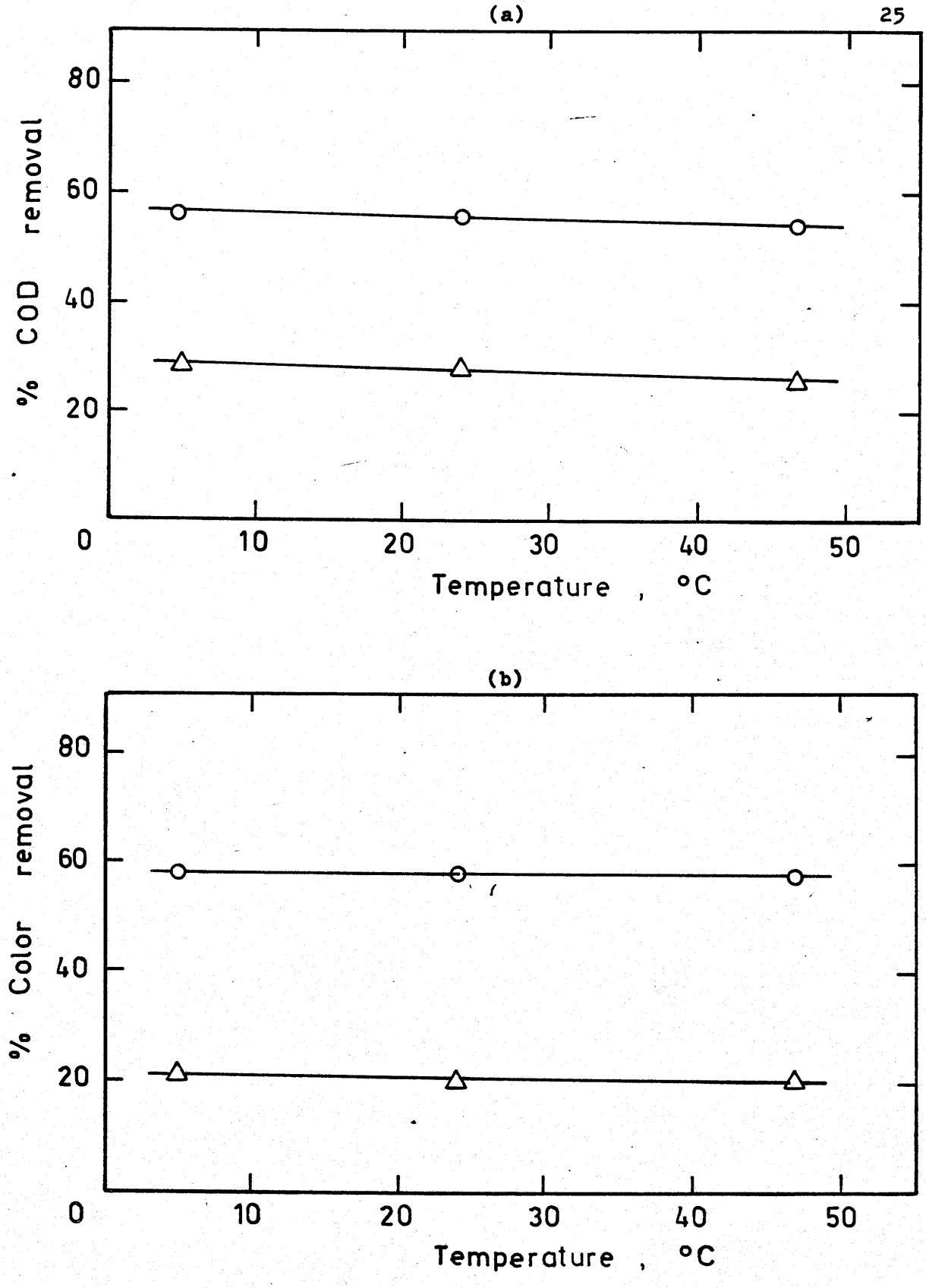


Figure 7. Effect of temperature on COD removal (a) and color removal (b). carbon concentration (conc.): o = 10 g/l, Δ = 4 g/l.

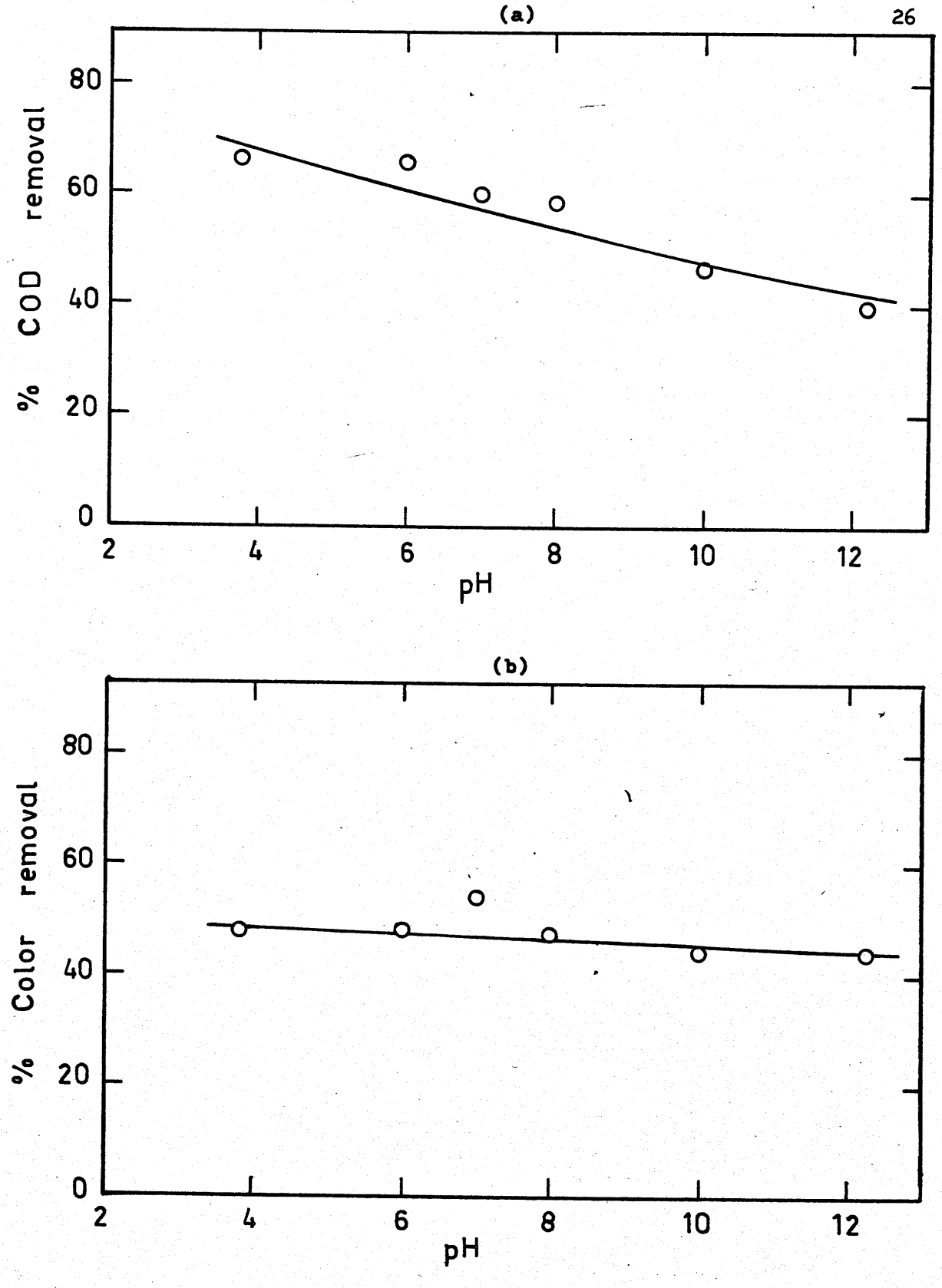


Figure 8. Effect of pH on COD removal (a) and color removal (b). carbon conc. = 10 g/l.

5.6 Physical properties of activated carbon

Physically, the activated carbon produced from bark is characterized by its fineness, low density, and large surface area per unit weight. Some representative samples of activated carbon were analyzed for specific surface area and carbon content.

The surface area was determined from nitrogen-adsorption by the Brunauer, Emmett, and Teller (BET) method (34). The carbon content was determined by Proximate analysis (35).

Table 1 shows the results of surface area and carbon content for two samples.

Table 1. Physical properties of activated carbon.

Sample	Surface area (m^2/g)	% by weight			
		Moisture	Volatile	Ash	Fixed carbon
1[a]	785	1.32	5.66	6.95	86.50
2[b]	870	1.10	7.65	13.20	78.10

[a]Carbon produced at 1500 °F and 30 min activation.

[b]Carbon produced at 1600 °F and 30 min activation.

5.7 Per cent yield of activated carbon

From the plot of yield versus activation temperature (see Figure 9), it is evident that activation time has little effect on the yield during activation at 1200 °F. The 70 per cent loss at 1200 °F, therefore, occurs during the carbonization stage. At higher temperature the yield is a function of both temperature and duration of activation. For a given activation time, the yield decreases linearly with increasing temperature. The straight lines through the data were obtained by the method of least squares curve fit for each activation time.

5.8 Particle size distribution

Table 2 gives the size distribution of activated carbon prior to grinding. Temperature and duration of the activation period appear to have little effect on this distribution. Figure 10 shows the size distribution of the pulverized bark and the nonactivated and activated carbon. The bark has a mesh size of 10 to 35, while the nonactivated and activated carbon have a size range of 14 to 100 and 30 to 100 mesh, respectively. It is evident, therefore, that a substantial size reduction occurs during the carbonization stage.

5.9 Color removal activity

Figures 11 and 12 show the color removal activity of powdered and granular activated carbon as a function of carbon concentration while temperature and duration of activation are two parameters. As the concentration of carbon increases, the per cent color removal appears to increase with a decreasing rate and levels off at 20 g/l. At 1600 °F

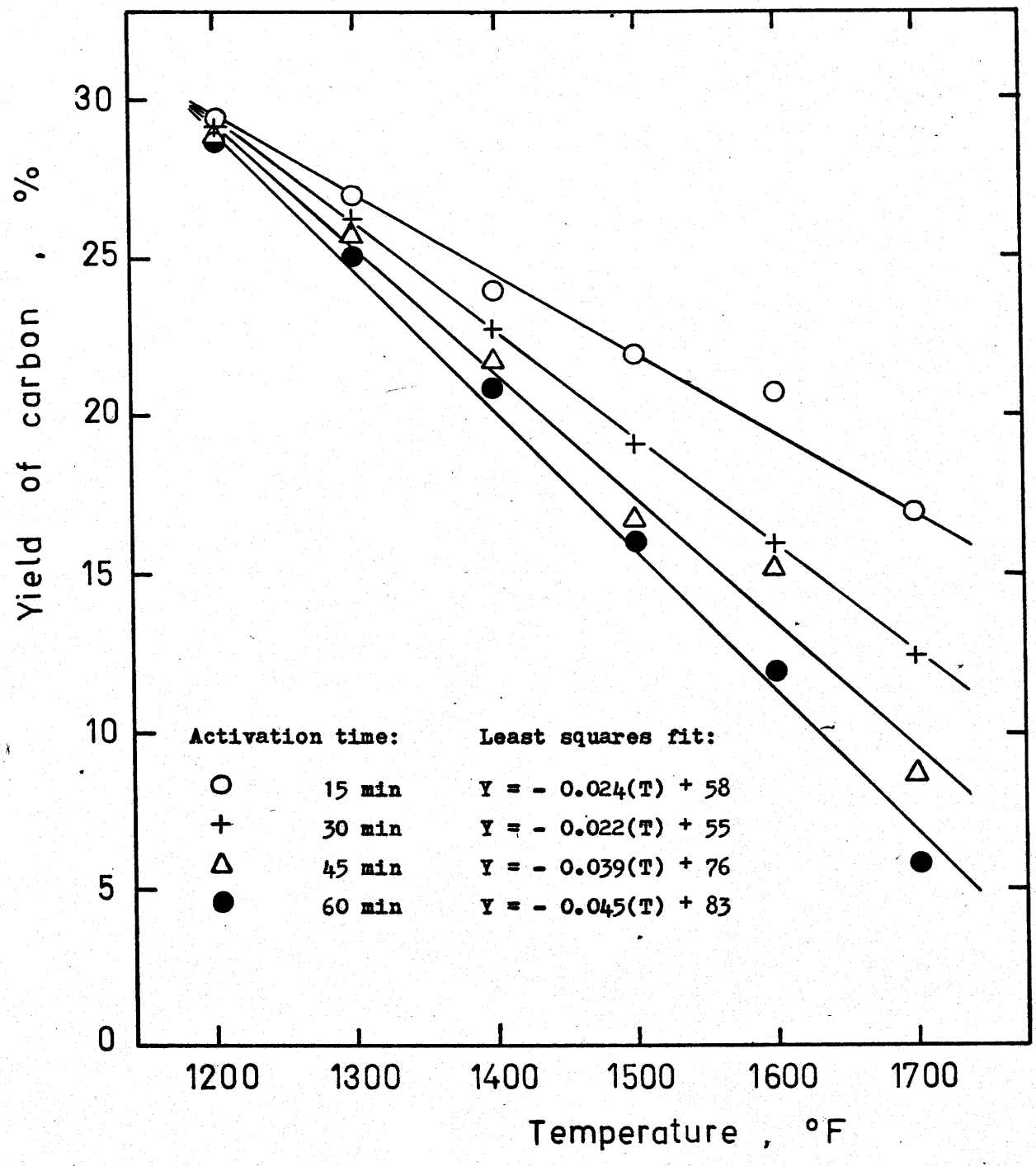


Figure 9. Plot of yield of carbon versus activation temperature.

Table 2. Size distribution (% weight) of activated carbon prior to grinding.

Activation temperature (°F)	Activation time (min)	Endecotts mesh size			
		25 to 50	50 to 100	100 to 230	230 to 400
1300 (704 °C)	15	73.5	14.5	7.0	4.8
	30	77.5	12.6	6.3	3.6
	45	69.4	12.8	11.1	6.7
	60	69.1	13.2	10.4	7.3
1400 (760 °C)	15	68.1	16.5	9.3	6.1
	30	60.8	22.3	13.8	3.0
	45	70.2	17.4	8.2	4.0
	60	71.5	18.9	5.7	3.9
1500 (816 °C)	15	70.0	15.9	7.1	4.0
	30	71.5	13.4	8.6	4.9
	45	72.5	12.0	9.6	6.0
	60	70.9	15.7	7.2	6.0
1600 (871 °C)	15	68.0	19.3	8.2	4.2
	30	70.8	17.8	7.0	4.3
	45	62.0	21.6	10.9	5.4
	60	58.5	22.2	11.0	8.2
1700 (927 °C)	15	60.2	18.4	12.5	8.9
	30	58.2	19.2	13.6	9.0
	45	58.0	18.2	14.8	8.9
	60	56.2	19.5	14.0	10.2

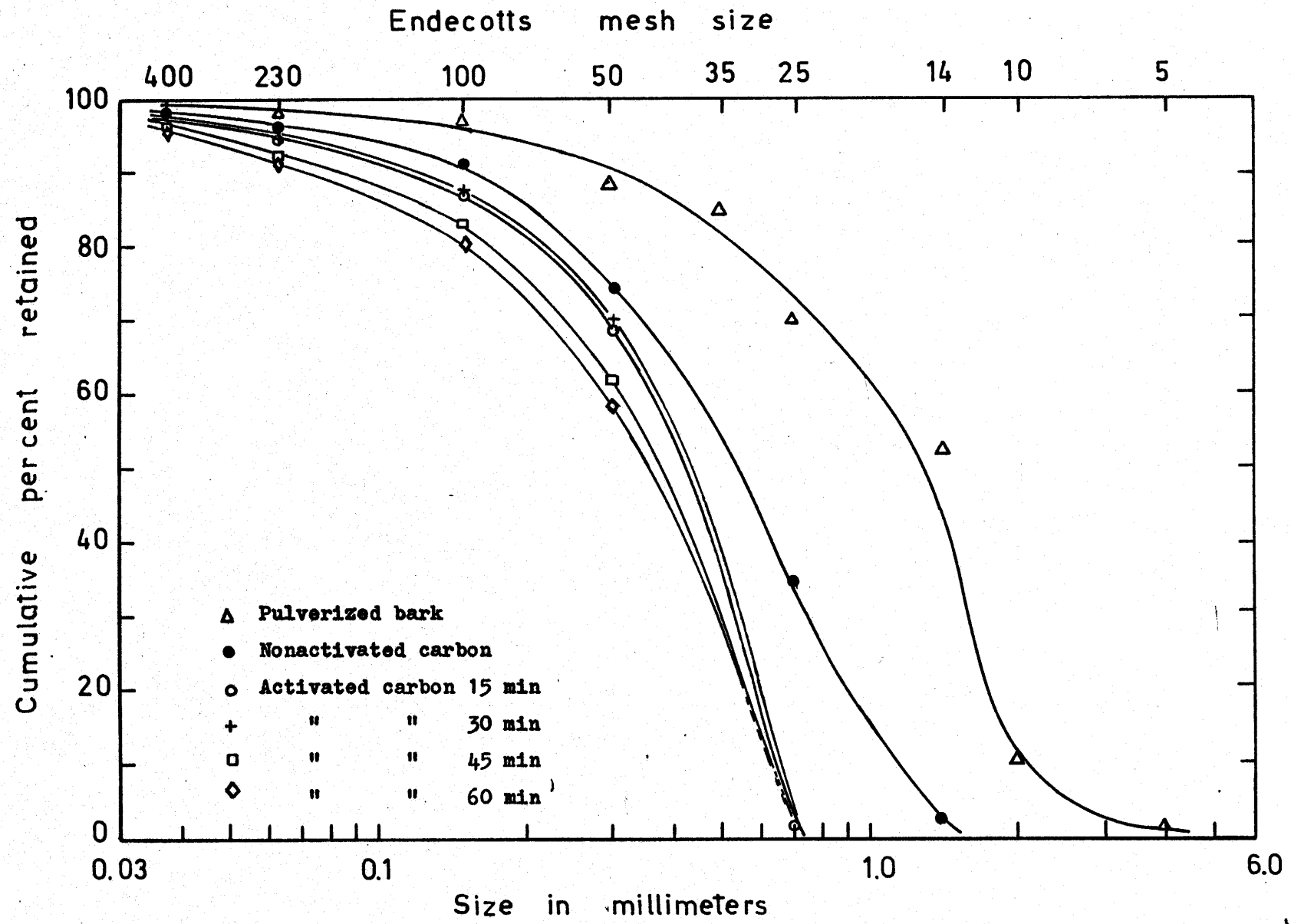


Figure 10. Size distribution of bark and nonactivated and activated carbon.

(At activation temperature 1600 °F)

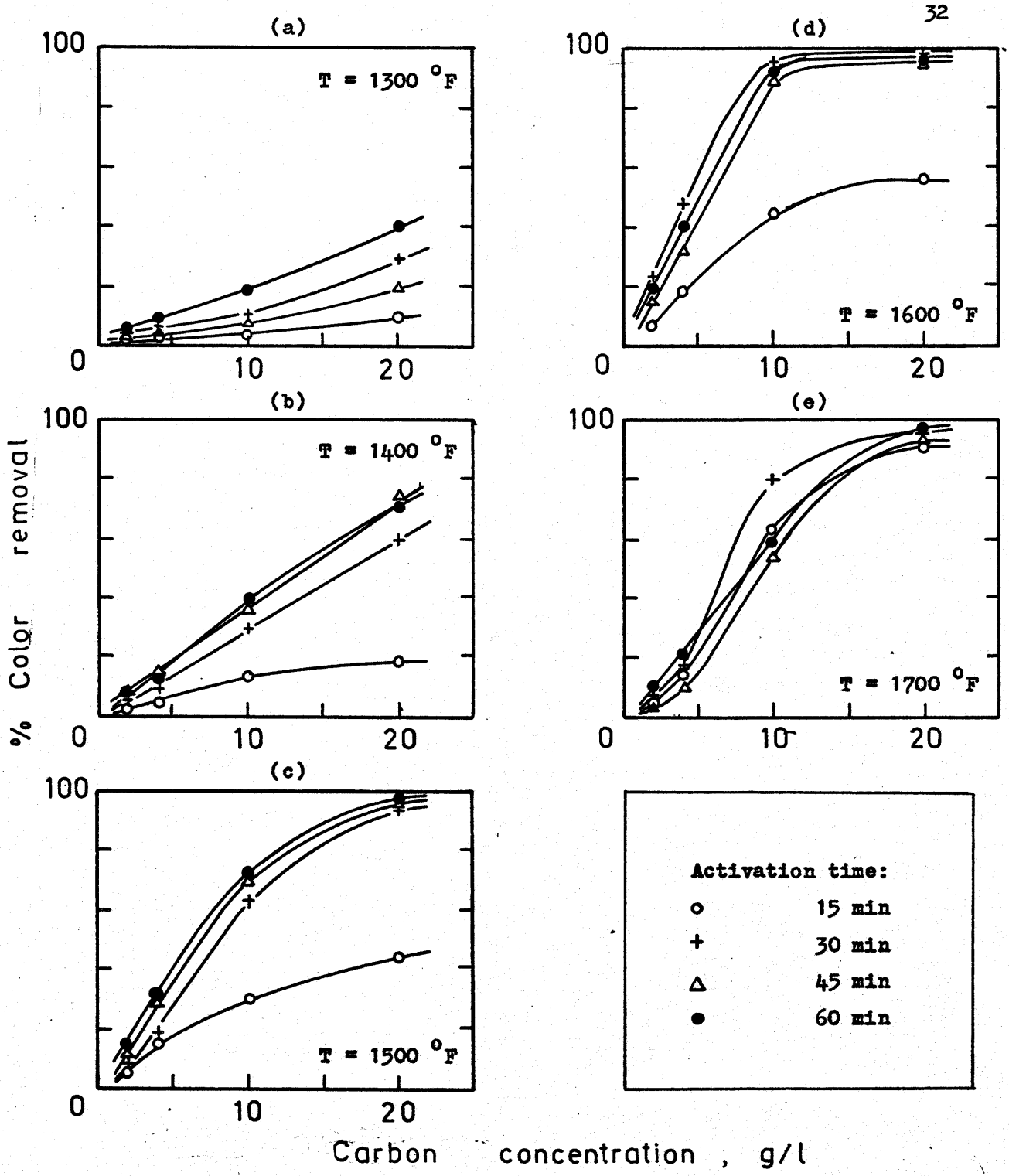


Figure 11. Color removal activity of powdered carbon.

(particle size = 230 to 400 mesh)

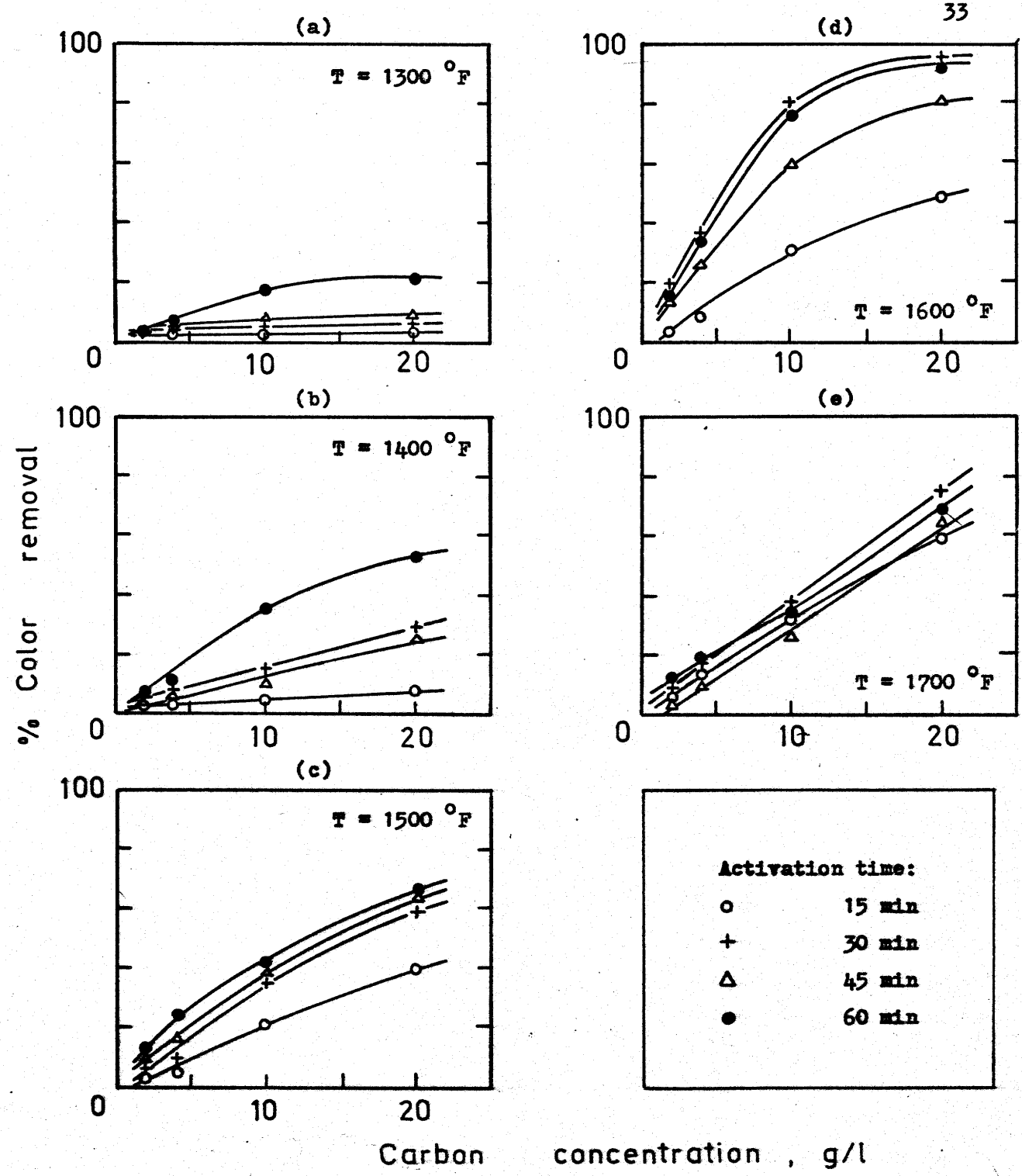


Figure 12. Color removal activity of granular carbon.

(particle size = 50 to 100 mesh)

activation temperature (see Figure 11d), for instance, treatment of the effluent with 4 g/l of carbon removes 40 per cent of the colored matters and about 90 to 95 per cent at 10 g/l, but an additional 10 g/l will only remove another 4 per cent of the color. Therefore, it is evident that an increase in carbon concentration does not produce a proportional increase in the percent of color removal because adsorption is more difficult as the concentration of color in solution approaches zero.

It is noted that the color activity is rather low for 1300 ^{o}F activation temperature. But, in general, the activity of the carbon increases rapidly with increased activation temperature and, apart from the 15 min run, it does not significantly change as activation time varies from 30 to 60 min.

Figures 13 and 14 show the plots of color activity versus activation temperature for carbon concentration of 10 and 20 g/l. The color activity appears to increase almost proportionally with temperature and reaches a maximum value in the neighborhood of 1600 ^{o}F and 30 min activation. At 1700 ^{o}F there is a drop off in the color activity as seen in Figure 13. This may be partly due to the experimental error and to the fact that extremely high temperature tends to destroy the active sites of the carbon as evidenced from the presence of white ash in the carbon. However, this fall in the activity is not noticeable when the applied carbon concentration is higher, that is, 20 g/l, (see Figure 14) because it is overcome by the excess amount of carbon.

In comparison of the results in Figures 11 and 12, it is found that under the same conditions of contact time, temperature, and pH,

Figures 13 and 14. Plots of per cent color removal versus activation temperature for powdered carbon.

(particle size = 230 to 400 mesh)

Activation time:

○ 15 min

□ 30 min

△ 45 min

● 60 min

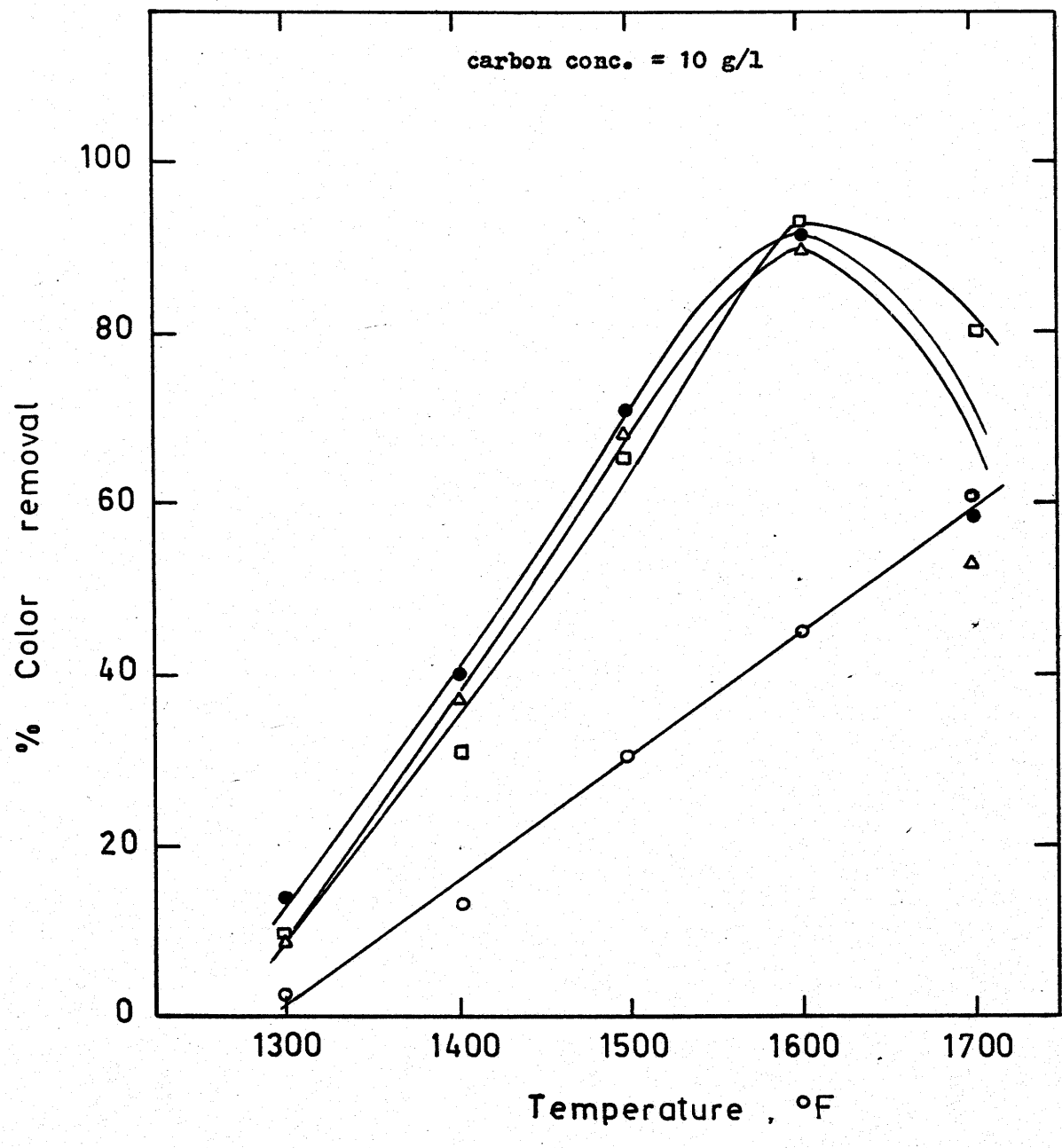

carbon conc. = 10 g/l
100
80
60
40
20
0
% Color removal
1300
1400
1500
1600
1700
Temperature , °F

Figure 13.

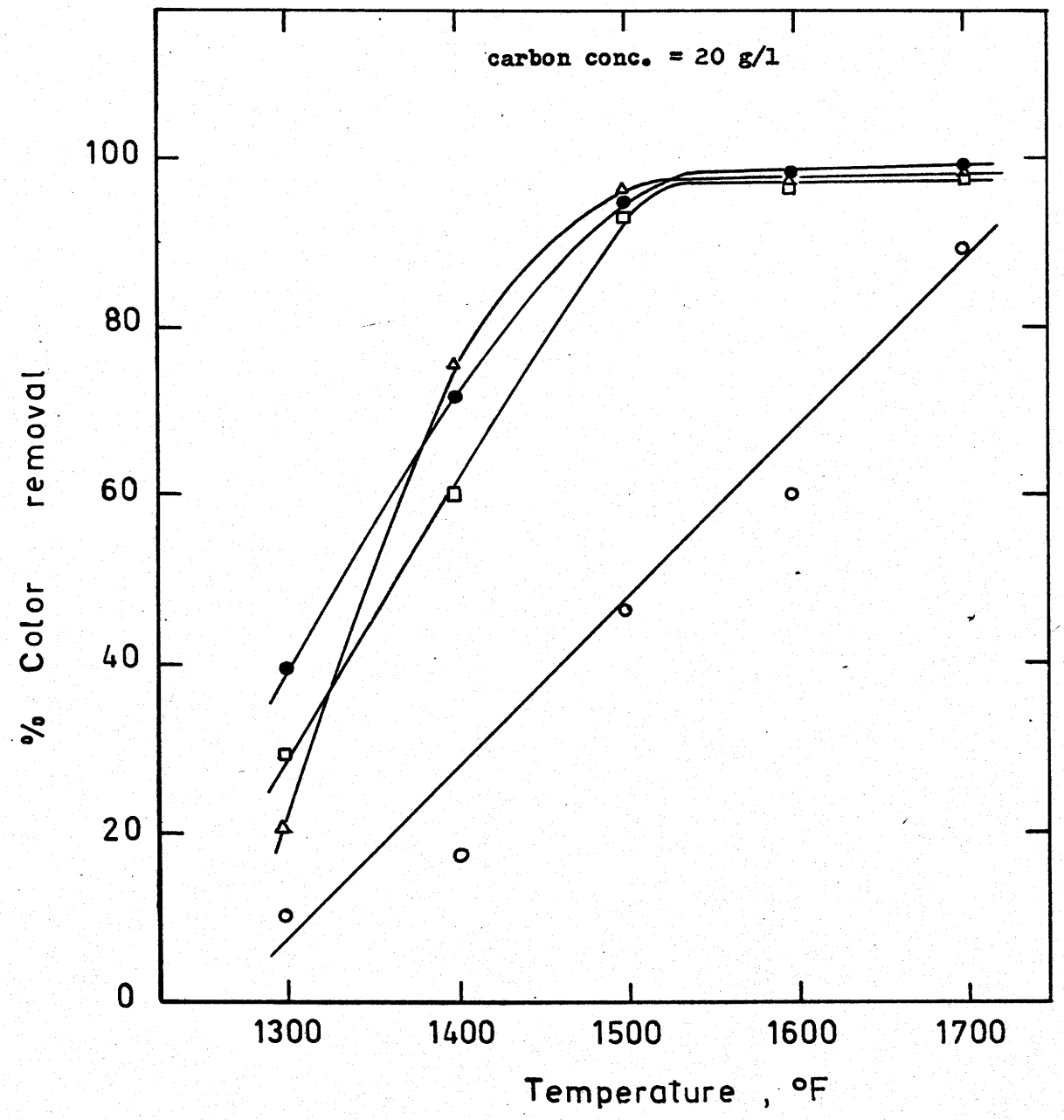

carbon conc. = 20 g/l
% Color removal
100
80
60
40
20
0
1300
1400
1500
1600
1700
Temperature , °F

Figure 14.

the powdered carbon (230 to 400 mesh) is slightly more efficient than the granular carbon (50 to 100 mesh) by a difference of 5 to 10 per cent.

5.10 COD removal activity

Like the color removal activity, the COD removal activity of activated carbon increases with increasing temperature and duration of the activation period as shown in Figures 15 to 18. The per cent COD removal for a given carbon concentration is generally less than that for color removal. This may be accounted for by the fact that activated carbon has a greater attraction for large organic molecules, such as the colored substances, than for small degradable organic compounds which make up the bulk of COD in the pulp mill effluent.

It is also observed that the maximum COD reduction is approximately 80 per cent (as compared to the color removal of 98 per cent) at 1600 to 1700 ^{o}F activation temperature. Consequently, some 20 per cent of the organic material which does not contribute to the color of the effluent cannot be removed by activated carbon. With the initial COD concentration of 1200 to 1300 ppm, the bleach plant effluent will still retain an average COD level of 250 ppm after treatment with carbon.

5.11 Regeneration of spent carbon

It is observed from Figures 19 and 20 that the regeneration of spent carbon by steam at 1200 ^{o}F is feasible. The activity of once-spent carbon can be readily recovered to near original activity with very little weight loss (estimated at 3 to 5 per cent). The requirement of fresh carbon, therefore, can be reduced greatly if a regeneration

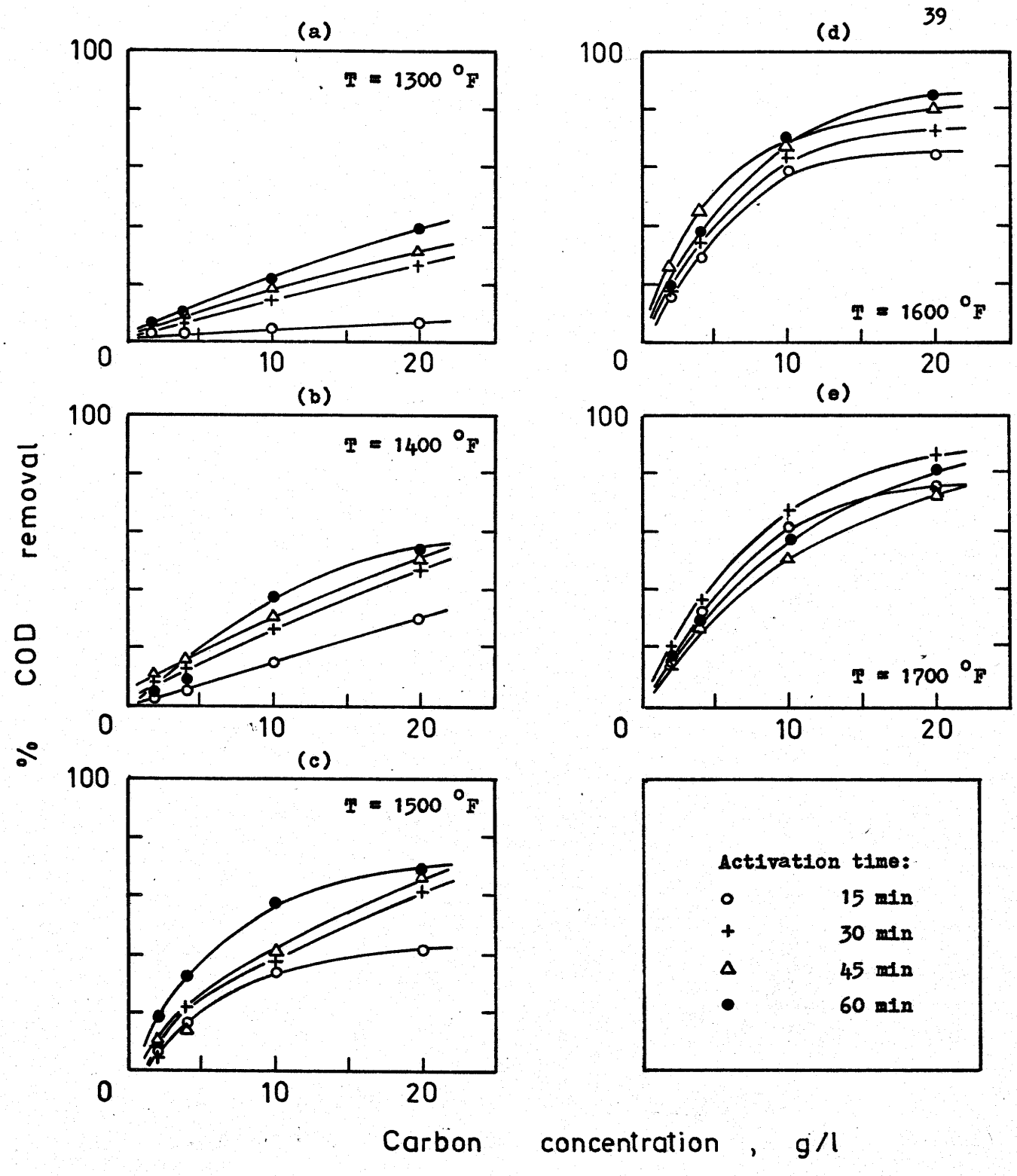


Figure 15. COD removal activity of powdered carbon.

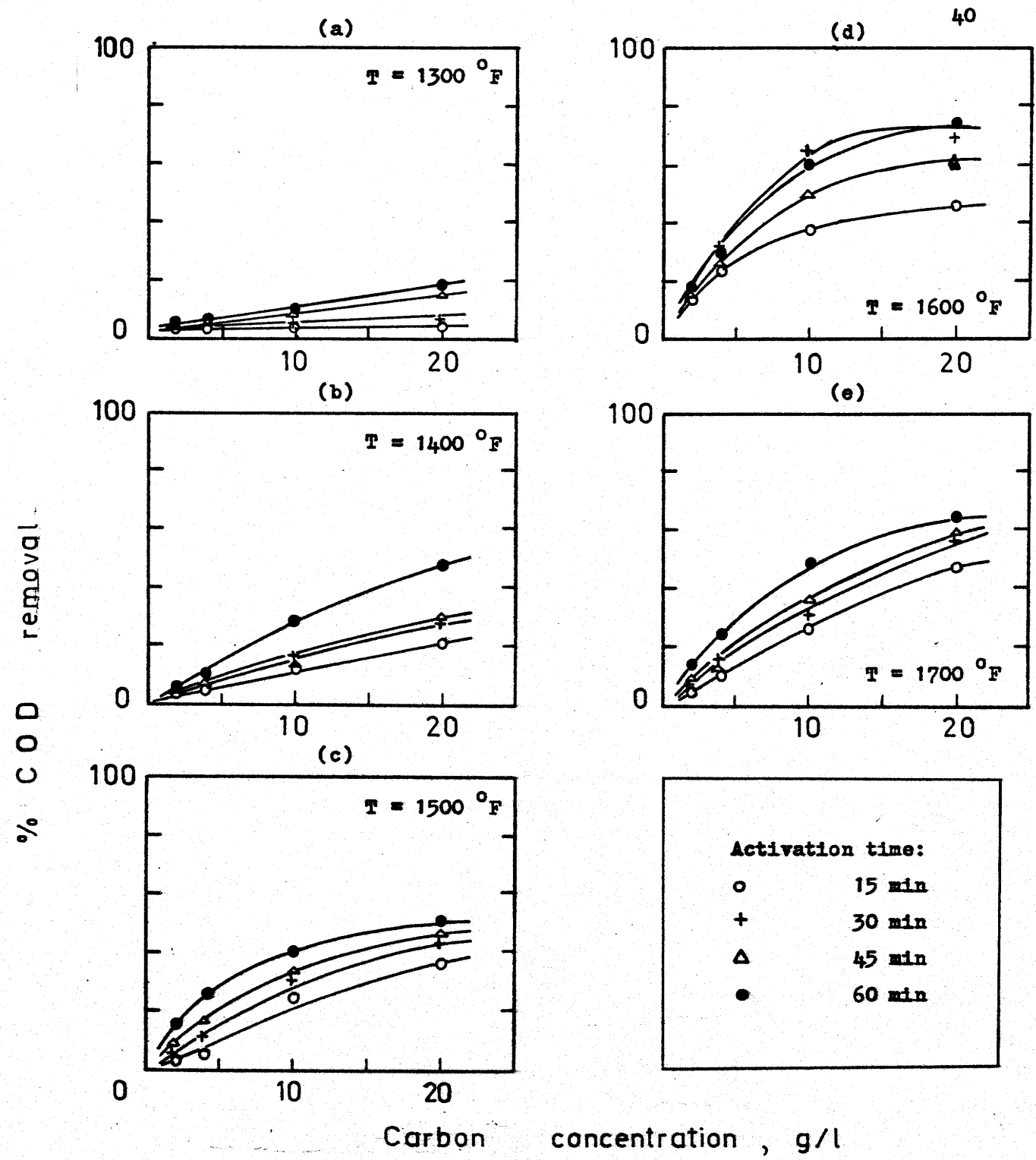


Figure 16. COD removal activity of granular carbon.

Figures 17 and 18. Plots of per cent COD removal versus activation temperature for powdered carbon.

Activation time:

o	15 min
□	30 min
△	45 min
●	60 min

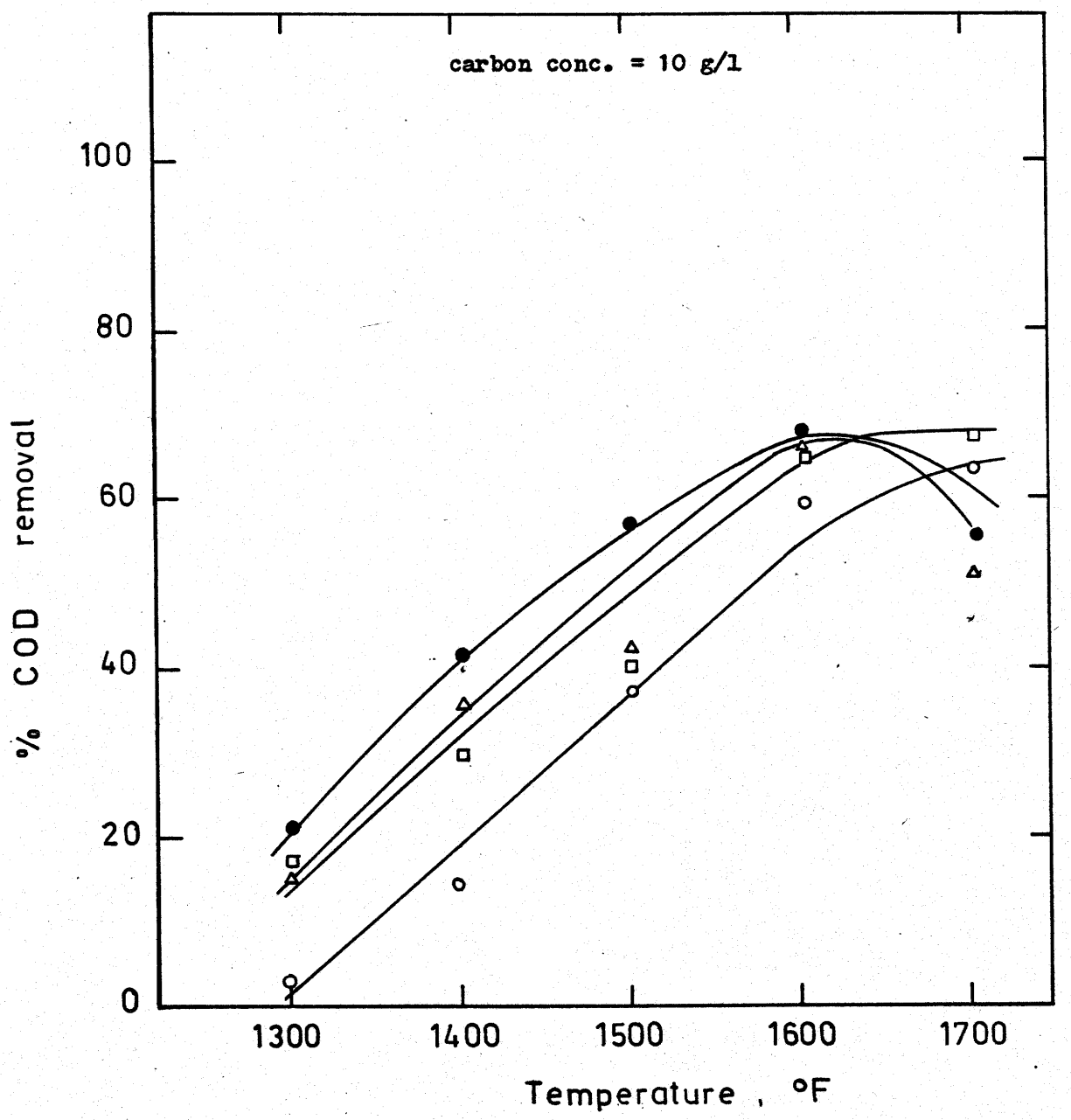

carbon conc. = 10 g/l
100
80
60
40
20
0
% COD removal
1300
1400
1500
1600
1700
Temperature , °F

Figure 17.

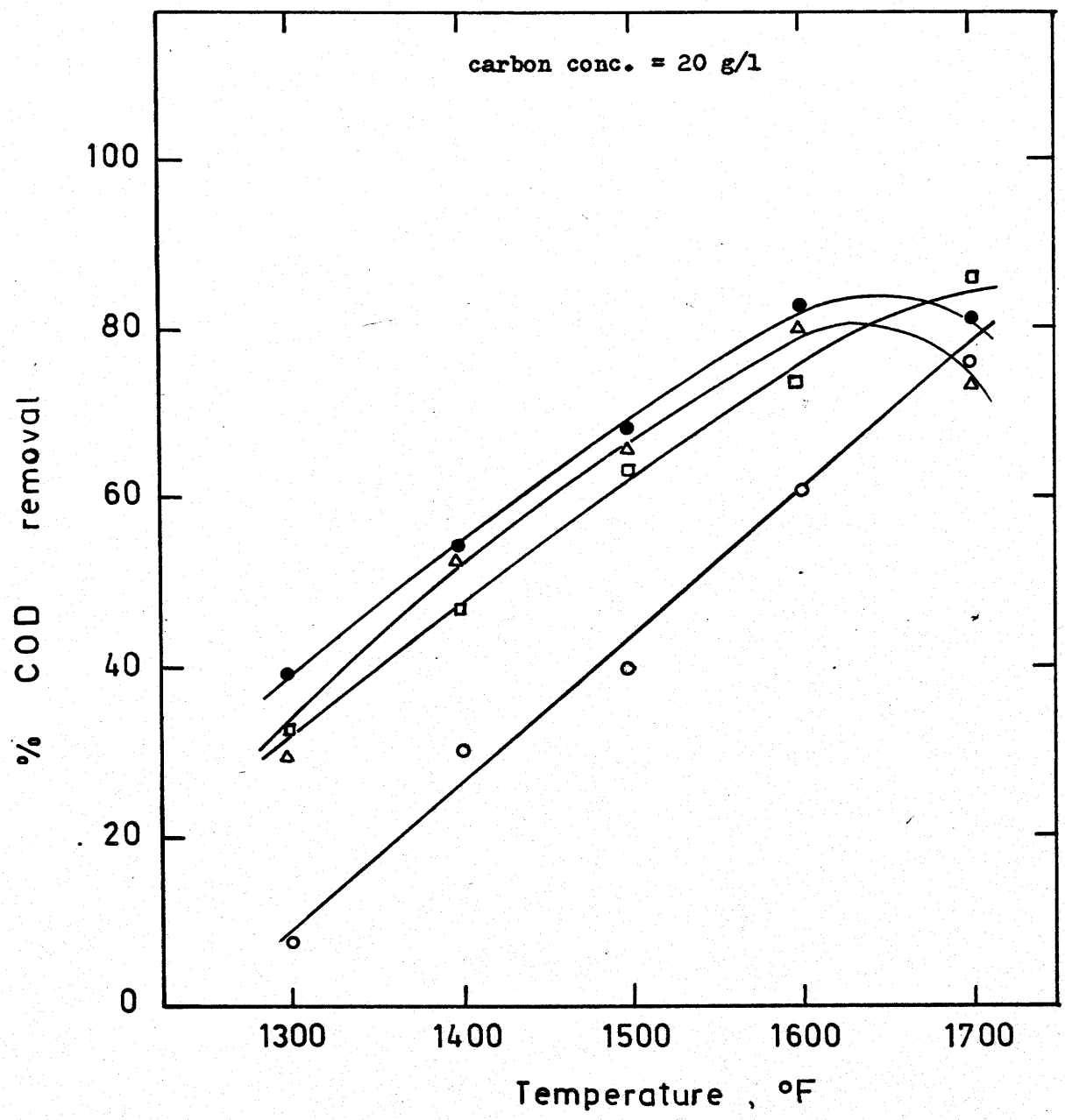

carbon conc. = 20 g/l
% COD removal
100
80
60
40
20
0
1300
1400
1500
1600
1700
Temperature , °F

Figure 18.

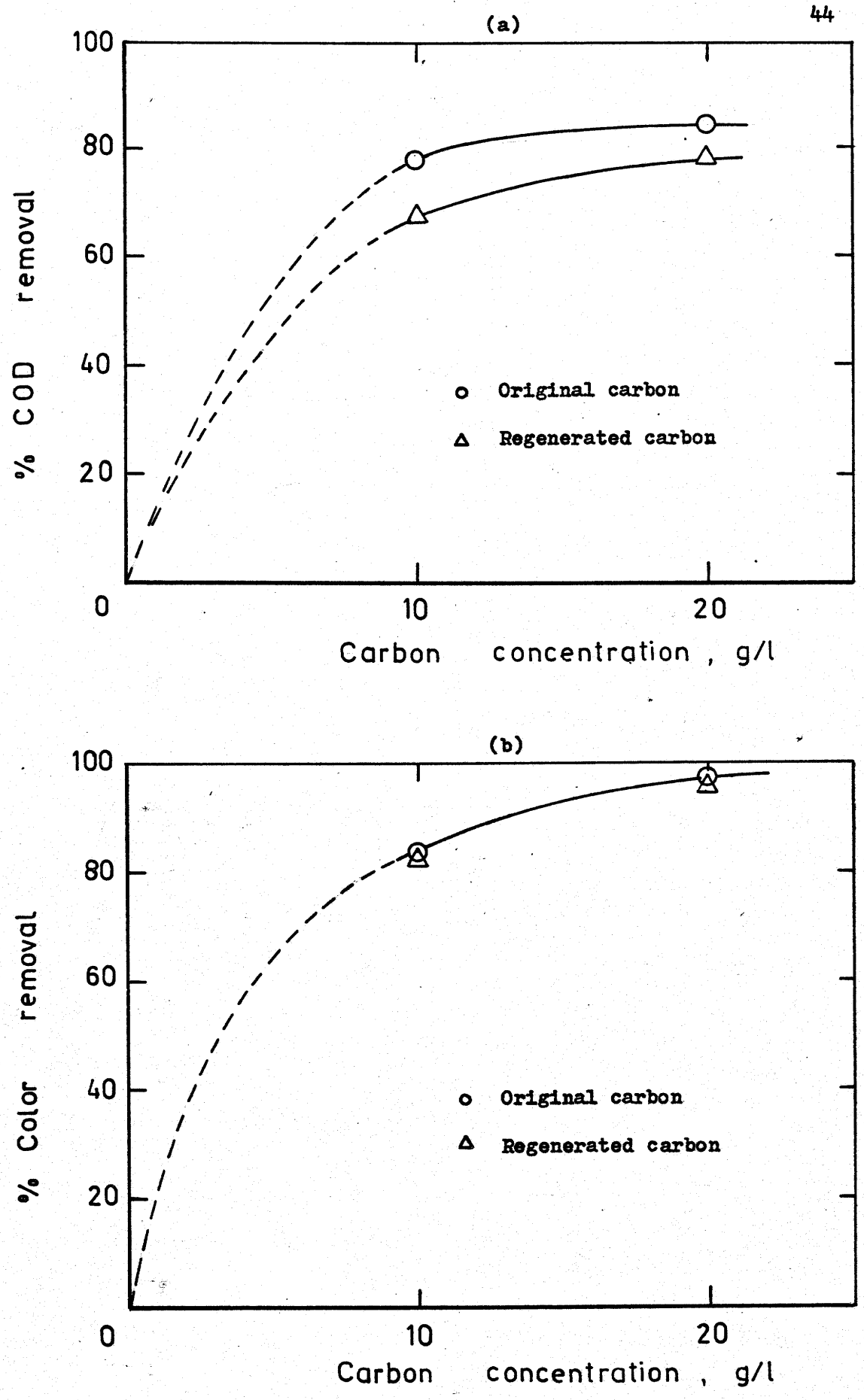
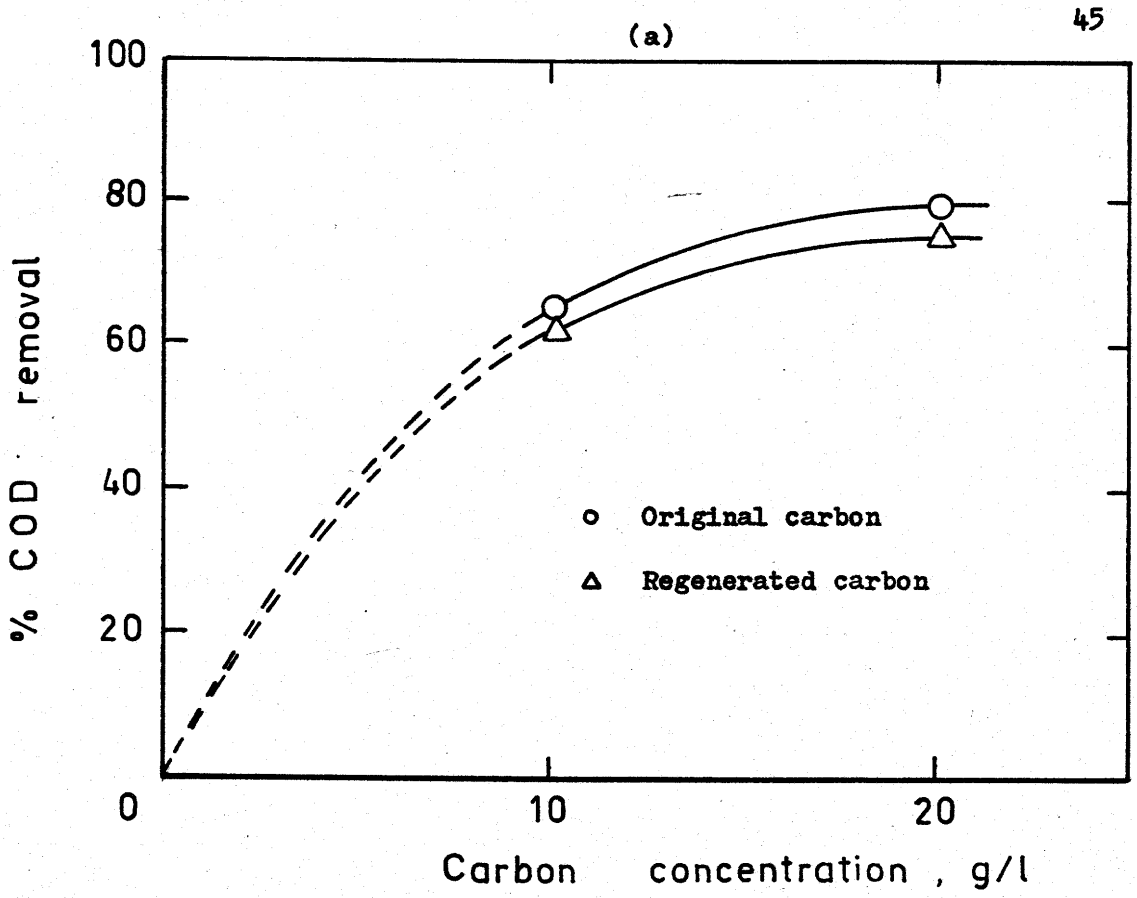


Figure 19. COD activity (a) and color activity (b) of the powdered carbon.



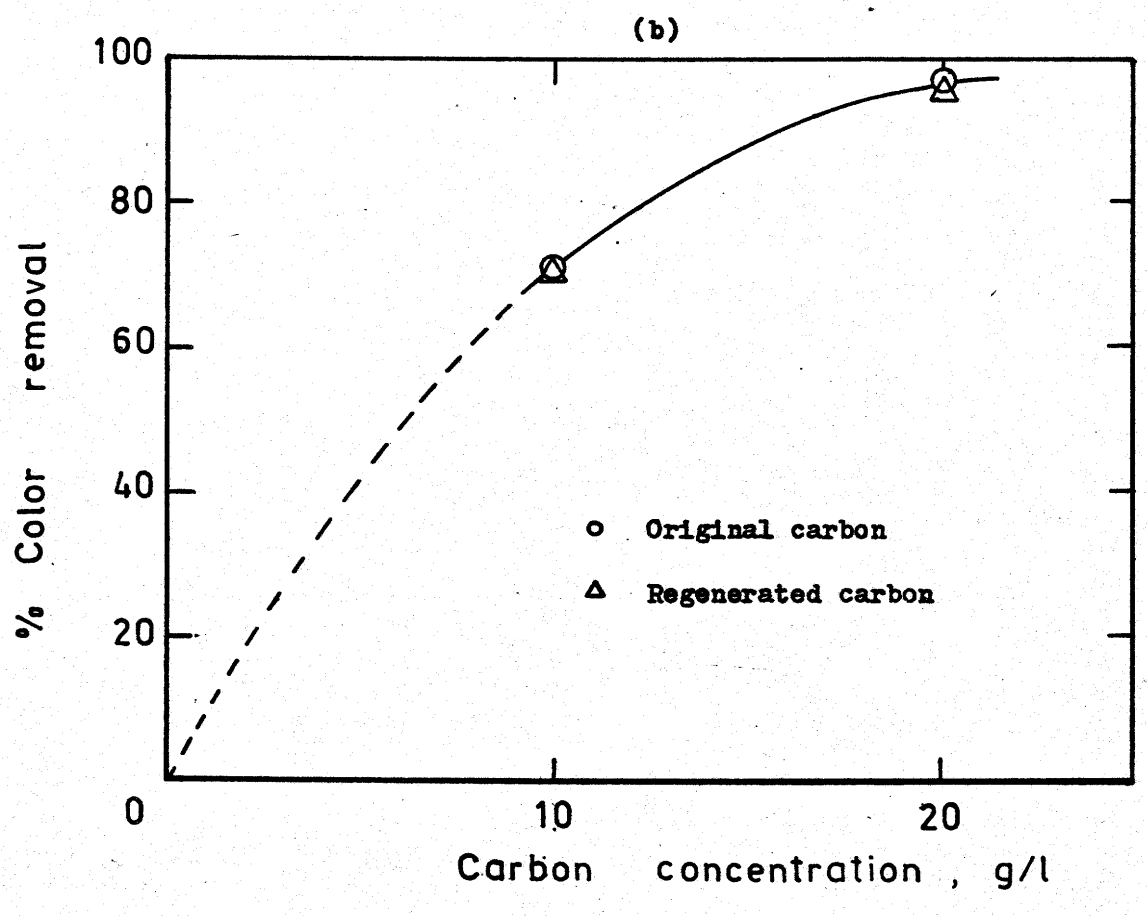


Figure 20. COD activity (a) and color activity (b) of the granular carbon.

cycle is incorporated with a carbon bed adsorber, and this is quite significant in terms of cost reduction.

5.12 General discussion

Because of the variable nature of the experimental conditions (that is, temperature, activation time, carbon concentration, etc.), it is not possible to pinpoint the optimum conditions under which the activated carbon is to be produced and utilized. The selection of a suitable carbon will largely depend upon the degree of treatment and economic considerations. Nevertheless, the experiemental results obtained from this study represent some important application criteria. Since the activated carbon produced at 1600 ^{o}F and 30 to 45 min of activation appears to have adsorptive capacity near the maximum attainable, and that the yield of carbon drops off rapidly with increased temperature and duration, it will not be economical to produce activated carbon at beyond these conditions.

The activated carbon produced from bark has large surface area and relatively high carbon content which account for its great adsorptive ability in liquid phase. It can remove nearly all the colored matters from the bleach plant effluent, but take up only some 80 per cent of the COD. However, if the color of the bleaching effluent is the main concern and that the remaining COD may be eliminated in a further treatment process along with wastewaters from other sources, then the use of activated carbon is very beneficial.

The quantity of activated carbon required to treat all bleach

plant effluent may be estimated by using the data available from the Prince Albert Pulp Mill Company. It is a typical kraft mill with a capacity of 750 tons (short)/day and produces about 4 million Imperial gal/day bleaching effluent. This effluent has an initial COD concentration of about 1250 ppm and light absorbance of 0.350 at a wavelength of 580 mμ (at pH = 8.2). On the assumption that the carbon is activated at the condition of 1600 ^{o}F and 30 min duration and that a treatment concentration of 10 g carbon /l of effluent is applied to affect COD and color removal of 70 and 95 per cent, respectively (see Figures 13 and 17) then the quantity of carbon required will be roughly 400,000 lb/day on a once-through basis. The waste bark currently available for manufacturing carbon (20 per cent of the total bark from the wood room) is 76 tons/day. If the average value of 15 per cent (from Figure 9) is taken for the yield, the quantity of carbon produced will be 23,000 lb/day. It is evident, therefore, that on a once-through basis the amount of carbon which can be produced will not meet the requirement. To make the treatment process feasible, one must reuse the spent carbon by means of regeneration. The fresh carbon will compensate for the carbon loss incurred by regeneration process and by handling. Still, it will be a challenging task to design an incorporated system consisting of three units: activated carbon reactor, carbon bed adsorber, and carbon regenerator.

5.13 Discussion of errors

From the experimental results obtained in this study, it is ob-

served that some inconsistency was encountered in the calculated activity of carbon. The main sources of experimental errors might arise from the following:

- A prolonged cooling period following the activation might affect the extent of activation, and if the reactor was hot and still contained sufficient water vapor, it could cause the activating reaction to proceed beyond the set limit.

- The surface of carbonized bark was not uniformly exposed to the oxidizing steam in the reactor. This caused a nonuniformity in the activity of carbon and accounted for a few unusual crossing-over of the curves in Figures 11, 12, and 15.

- Possible errors in the light absorbance reading were due to fluctuations in pH and temperature of the effluent.

- Also, some errors could be introduced in the determination of COD and K Number.

The magnitude of the overall error in COD and color removal activity is estimated to be $\pm$ 10 per cent.

6. CONCLUSIONS

Due to many interrelated variables and limitations, the optimum conditions under which activated carbon can be produced will be influenced by the economic factors and the extent to which the effluent is treated. However, some conclusions may be drawn from the results of this study:

1). Bark of Spruce and Jack Pine can be carbonized and activated to produce highly active carbon.

2). The temperature of activating reaction should not exceed 1700 ^{o}F. The activity of carbon increases with increased temperature and length of activation time and with reduction in the yield of carbon. It is a maximum when the activation temperature and time is 1600 ^{o}F and 30 min, respectively.

3). At carbon concentration of 20 g/l, the maximum COD removal attainable is about 80 per cent (the initial COD level is 1250 ppm) while the maximum color removal is 98 per cent (the initial light absorbance is 0.350 at the wavelength of 580 mμ).

4). Under the same conditions of adsorption, the powdered carbon has a greater adsorptive capacity than the granular carbon, but it has a disadvantage of difficulty in handling. The activated carbon is more effective in acidic than in alkali solutions. Temperature of the effluent has no effect on the adsorption of carbon (5- 50°C).

5). Regeneration of spent carbon by treatment with steam at

1200 ^{o}F for about 30 min can restore the original activity to the carbon with little weight loss.

7. RECOMMENDATIONS

Further works are suggested to cover the following aspects:

1). Perhaps the carbonization can be carried out at a lower temperature ($< 1200\ ^{o}F$) in order to increase the yield of activated carbon.

2). The possibility of using black liquor or effluent from caustic wash as the activating fluid instead of distilled water should be considered.

3). A flow reactor in which bark is continuously converted into activated carbon may be designed.

4). More studies on reactivation of spent carbon should be done with regard to temperature and time variables.

5). Combined wastewater treatments consisting of activated carbon and other methods should be studied.

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APPENDIX A.1

RAPID COD TEST

(i) Apparatus

1). Three 500 ml Erlenmeyer flasks.

2). One hot plate.

3). Three thermometers, 0 to 210 $^{o}C \pm {}^{o}C$.

4). One 5 ml volumetric pipet.

(ii) Reagents

1). 0.05 N dichromate-acid solution. Dissolve 5.0 g $K_2Cr_2O_7$ and 20.0 g $AgSO_4$ in a solution consisting of 1.0 l each of concentrated H_2SO_4 and H_3PO_4.

2). 0.05 N ferrous ammonium sulfate. Dissolve 20.0 g of $Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$ in distilled water, add 20 mls concentrated H_2SO_4, and dilute to 1.0 l. This solution is standardized against 0.050 N $K_2Cr_2O_7$ prior to use.

3). Ferroin indicator solution. Dissolve 1.485 g of 1, 10 phenanthroline (monohydrate), together with 0.695 g of $FeSO_4 \cdot 7H_2O$ in water and dilute to 100 mls.

4). Mercuric sulfate ($HgSO_4$).

5). Dichromate standard (0.050 N). Dissolve 2.4518 g $K_2Cr_2O_7$ dried, primary standard grade, in distilled water and dilute to 1.0 l.

(iii) Procedure

1). Add approximately 0.3 g of $HgSO_4$ to a 500 ml Erlenmeyer flask.

2). Pipet 5 mls or a suitable aliquot of the effluent sample diluted to 5 mls into the flask. Mix well.

3). Two blanks are run by substituting 5 mls distilled water for the sample and continuing with steps 4 through 8. The average of these two titrations is used in the calculations.

4). Carefully add 25 mls of dichromate-acid solution to the flask and swirl the contents.

5). Place the flask on a preheated hot plate and heat to 165 $\pm$ 1 ^{o}C. A thermometer should be immersed in the solution and frequent swirling should be employed. Tilt the flask so that the bulb of the thermometer is immersed when reading the temperature. Remove from heat when 165 $\pm$ 1 ^{o}C is reached.

6). Carefully add approximately 300 mls of distilled water.

7). Cool the solution in a water bath to ambient temperature.

8). Add five drops of ferroin indicator and titrate to an orange end point with ferrous ammonium sulfate.

9). Two standards are run by adding 25 mls of 0.050 dichromate, acidifying with 20 mls concentrated H_2SO_4, and continuing with steps 6, 7, and 8.

(iv) Calculations

The COD is calculated as follows:

$$N = \frac{(25)(0.05)}{\text{mls from step 9}}$$

where

N = normality of $Fe(NH_4)_2 (SO_4)_2$ and

$$COD(mg/l) = \frac{N \times 8000}{\text{mls sample}} \text{ (mls from step 3 - mls from step 8).}$$

Table A.1 Correlation between K Number and COD.

K Number	COD (ppm)	K Number	COD (ppm)
1.10	180	5.97	1063
2.73	480	6.00	1086
3.35	583	6.05	1084
4.15	722	6.05	1128
4.55	864	6.07	1131
4.70	887	6.17	1189
4.85	889	6.20	1243
5.10	946	6.25	1262
5.20	1005	6.27	1128
5.35	960	6.30	1220
5.65	1022	6.55	1344
5.67	1054	6.60	1327
5.73	1084	6.62	1289
5.80	1092	6.85	1321
5.92	1112	6.95	1383
5.92	1082		

APPENDIX A.2

K NUMBER TEST

(i) Apparatus

1). Mechanical stirrer.

2). Reaction beakers (1000 ml glass beakers).

3). Automatic burettes.

4). Stop watch.

(ii) Reagents

1). 0.1 N $KMnO_4$ solution (accurate to $\pm$ 0.005 N). This permanganate solution is standardized against pure sodium oxalate ($Na_2C_2O_4$).

2). 0.1 N sodium thiosulfate ($Na_2S_2O_3 \cdot 5H_2O$). Dissolve 24.8 g of CP sodium thiosulfate and dilute with distilled water to 1.0 l. Add 1 ml of chloroform to preserve the solution. This solution is standardized against $KMnO_4$ as follows: add to a definite volume of 0.1 N $KMnO_4$ solution, some potassium iodide (1.0 N) and H_2SO_4 (0.1 N), then titrate the liberated iodine with sodium thiosulfate using starch indicator solution.

3). 1.0 N KI. Dissolve 166.0 g of KI and dilute to 1.0 l. The solution should not contain free iodine or iodate.

4). 4.0 N H_2SO_4. Add 112 mls of concentrated H_2SO_4 to about 500 mls of cold distilled water and dilute to 1.0 l at 20 ^{o}C.

5). Starch indicator solution. Stir 3.0 g of soluble starch in

100 mls of 1 per cent salicylic acid solution. Boil the mixture till the starch is dissolved then dilute to 1.0 l.

(iii) Procedure

1). Measure 25 mls 0.1 N $KMnO_4$ into a 200 ml beaker.

2). Measure 25 mls 4.0 N H_2SO_4 into a graduate cylinder.

3). Put about 700 mls of distilled water into a large beaker; then add the measured H_2SO_4 and mix thoroughly. Reserve 100 mls of this acid solution in a beaker for rinsing out $KMnO_4$.

4). Start magnetic stirrer, add 50 mls of effluent sample to the large beaker.

5). Pour $KMnO_4$ into the large beaker and start stop watch, then rinse out $KMnO_4$.

6). At 5 min $\pm$ 10 sec, add 5 mls KI solution.

7). Titrate with 0.1 N $Na_2S_2O_3$, adding 5 mls of starch indicator when the color is yellowish. Continue to titrate till the blue-green color disappears.

8). For blank determination, repeat the same procedure without adding effluent sample.

Iiv) Calculation

$$\text{K Number} = \tfrac{1}{2}(\text{mls of } Na_2S_2O_3 \text{ for blank} - \text{mls of } Na_2S_2O_3 \text{ for sample}).$$

APPENDIX B

EXPERIMENTAL DATA

Table B.1 Effect of contact time on adsorption.
(carbon conc.[a] = 10 g/l)

Contact time (hr)	0	1	2	3	4	10
Residual COD (ppm)	1353	1049	1049	1048	1030	1029

[a]concentration.

Table B.2 Effect of temperature on adsorption.

Temperature	Initial COD (ppm)	Residual COD	% COD removal	Initial abs.[a]	Final abs.	% Color removal
Carbon conc. = 4 g/l						
5 °C	1230	885	28.0	0.365	0.284	22.0
24 °C	1230	879	28.5	0.365	0.285	21.8
47 °C	1257	943	24.9	0.360	0.280	22.2
Carbon conc. = 10 g/l						
5 °C	1230	530	57.0	0.365	0.140	59.0
24 °C	1230	533	56.6	0.365	0.150	59.0
47 °C	1257	570	54.6	0.360	0.150	58.4

[a]absorbance.

Table B.3 Effect of pH on adsorption.
(carbon conc. = 10 g/l)

pH	Initial COD (mg/l)	Residual COD	% COD removal	Initial abs.	Final abs.	% Color removal
3.8	1043	342	67	0.300	0.160	47
6.0	1047	346	67	0.330	0.170	48
7.0	1047	415	61	0.365	0.165	55
8.0	1053	437	59	0.400	0.210	47
10.0	1053	565	47	0.400	0.220	45
12.2	1053	638	40	0.410	0.225	45

Table B.4 Per cent yield of activated carbon.

Temperature (^{o}F) \ Time (min)	15	30	45	60
1200	29.4	29.0	28.7	28.5
1300	27.0	26.0	25.5	25.0
1400	23.7	22.6	21.6	20.8
1500	21.8	19.0	16.5	15.9
1600	20.6	15.7	15.0	11.8
1700	16.8	12.2	8.5	5.8

Table B.5 Size distribution of bark.

Mesh size[a]	% by weight	Cumulative % retained
5	0.70	0.70
10	9.20	9.90
14	43.20	53.10
25	17.70	70.80
35	14.20	85.00
50	3.74	88.74
100	7.60	96.34
230	3.38	99.72
400	0.27	99.99

Table B.6 Size distribution of carbonized bark.

Mesh size[a]	% by weight	Cumulative % retained
14	3.98	3.98
25	30.12	34.10
35	19.62	53.72
50	20.00	73.72
100	16.87	90.59
230	6.00	96.59
400	1.98	98.57
+ 400	1.30	99.87

[a]Standard Endecotts mesh size.

Table B.7 - Activity of activated carbons at 1300 °F.

Activation time (min)	Mesh size	Carbon conc. (g/l)	Initial COD (mg/l)	Residual COD (mg/l)	% COD removal	Initial abs.	Final abs.	% Color removal
15	50 to 100	2	1283	1273	1	0.360	0.359	0
	"	4	"	1246	3	"	0.356	1
	"	10	"	1241	3	"	0.349	3
	"	20	"	1240	3	"	0.345	4
	230 to 400	2	1217	1210	1	"	0.358	1
	"	4	"	1206	1	"	0.357	1
	"	10	"	1206	1	"	0.350	3
	"	20	"	1129	7	"	0.324	10
30	50 to 100	2	1273	1262	1	0.360	0.349	3
	"	4	"	1242	2	"	0.348	3
	"	10	"	1241	3	"	0.345	4
	"	20	"	1236	3	"	0.344	4
	230 to 400	2	1217	1209	1	"	0.358	1
	"	4	"	1102	9	"	0.348	3
	"	10	"	985	19	"	0.320	11
	"	20	"	820	33	"	0.245	31

Continued . . . . . .

Table B.7 (continued)

Activation time (min)	Mesh size	Carbon conc. (g/l)	Initial COD (mg/l)	Residual COD (mg/l)	% COD removal	Initial abs.	Final abs.	% Color removal
45	50 to 100	2	1273	1246	2	0.360	0.358	1
	"	4	"	1230	3	"	0.349	3
	"	10	"	1153	9	"	0.349	3
	"	20	"	1060	17	"	0.338	6
	230 to 400	2	1220	1193	2	"	0.358	1
	"	4	"	1129	7	"	0.356	2
	"	10	"	1023	16	"	0.331	8
	"	20	"	884	27	"	0.290	19
60	50 to 100	2	1273	1246	2	0.360	0.349	3
	"	4	"	1230	3	"	0.336	7
	"	10	"	1156	9	"	0.291	19
	"	20	"	1039	18	"	0.280	22
	230 to 400	2	1220	1158	5	"	0.349	3
	"	4	"	1081	11	"	0.330	8
	"	10	"	948	22	"	0.302	16
	"	20	"	730	40	"	0.210	41

Table B.8 Activity of activated carbons at 1400 °F.

Activation time (min)	Mesh size	Carbon conc. (g/l)	Initial COD (mg/l)	Residual COD (mg/l)	% COD removal	Initial abs.	Final abs.	% Color removal
15	50 to 100	2	1217	1169	4	0.354	0.340	4
	"	4	"	1145	6	"	0.340	4
	"	10	"	1063	13	"	0.335	5
	"	20	"	947	22	"	0.326	8
	230 to 400	2	"	1174	4	"	0.340	4
	"	4	"	1150	6	"	0.340	4
	"	10	"	1043	14	"	0.310	12
	"	20	"	845	31	"	0.310	15
30	50 to 100	2	1251	1193	5	0.350	0.338	3
	"	4	"	1160	7	"	0.328	6
	"	10	"	1025	18	"	0.290	17
	"	20	"	900	28	"	0.239	31
	230 to 400	2	"	1106	12	"	0.330	6
	"	4	"	1092	13	"	0.320	8
	"	10	"	884	29	"	0.237	32
	"	20	"	657	47	"	0.131	61

Continued . . . . . .

Table B.8 (continued)

Activation time (min)	Mesh size	Carbon conc. (g/l)	Initial COD (mg/l)	Residual COD (mg/l)	% COD removal	Initial abs.	Final abs.	% Color removal
45	50 to 100	2	1124	1118	1	0.354	0.347	2
	"	4	"	1092	3	"	0.340	4
	"	10	"	975	13	"	0.326	8
	"	20	"	801	29	"	0.265	25
	230 to 400	2	1204	1071	11	0.360	0.316	12
	"	4	"	1001	17	"	0.302	16
	"	10	"	772	36	"	0.220	39
	"	20	"	554	54	"	0.075	75
60	50 to 100	2	1049	1012	4	0.350	0.325	7
	"	4	"	943	10	"	0.315	10
	"	10	"	756	28	"	0.220	37
	"	20	"	544	48	"	0.160	54
	230 to 400	2	1065	1020	5	"	0.315	10
	"	4	"	959	10	"	0.297	15
	"	10	"	650	39	"	0.210	40
	"	20	"	480	54	"	0.105	70

Table B.9 Activity of activated carbons at 1500 °F.

Activation time (min)	Mesh size	Carbon conc. (g/l)	Initial COD (mg/l)	Residual COD (mg/l)	% COD removal	Initial abs.	Final abs.	% Color removal
15	50 to 100	2	1256	1218	3	0.360	0.349	3
	"	4	"	1189	5	"	0.338	6
	"	10	"	940	25	"	0.280	22
	"	20	"	804	36	"	0.216	40
	230 to 400	2	"	1126	9	"	0.335	7
	"	4	"	1010	20	"	0.305	15
	"	10	"	779	38	"	0.252	30
	"	20	"	754	40	"	0.198	45
30	50 to 100	2	1241	1179	5	0.358	0.340	5
	"	4	"	1130	9	"	0.322	10
	"	10	"	852	31	"	0.230	36
	"	20	"	719	42	"	0.143	60
	230 to 400	2	"	1190	4	"	0.326	9
	"	4	"	918	26	"	0.297	17
	"	10	"	745	40	"	0.122	66
	"	20	"	447	64	"	0.018	95

Continued . . . . . .

Table B. 9 (continued)

Activation time (min)	Mesh size	Carbon conc. (g/l)	Initial COD (mg/l)	Residual COD (mg/l)	% COD removal	Initial abs.	Final abs.	% Color removal
45	50 to 100	2	1241	1130	9	0.358	0.330	8
	"	4	"	1042	16	"	0.300	16
	"	10	"	819	34	"	0.220	38
	"	20	"	670	46	"	0.136	62
	230 to 400	2	"	1124	9	"	0.322	10
	"	4	"	1012	18	"	0.254	29
	"	10	"	735	41	"	0.100	72
	"	20	"	416	66	"	0.020	94
60	50 to 100	2	1327	1128	15	0.360	0.313	13
	"	4	"	995	25	"	0.274	24
	"	10	"	762	41	"	0.216	40
	"	20	"	650	49	"	0.125	65
	230 to 400	2	"	1080	18	"	0.312	13
	"	4	"	887	33	"	0.248	31
	"	10	"	548	58	"	0.100	72
	"	20	"	415	69	"	0.018	95

Table B.10 Activity of activated carbons at 1600 °F.

Activation time (min)	Mesh size	Carbon conc. (g/l)	Initial COD (mg/l)	Residual COD (mg/l)	% COD removal	Initial abs.	Final abs.	% Color removal
15	50 to 100	2	1344	1131	15	0.355	0.340	4
	"	4	"	1022	24	"	0.323	9
	"	10	"	825	38	"	0.245	31
	"	20	"	583	48	"	0.180	49
	230 to 400	2	1023	985	12	0.345	0.320	7
	"	4	"	948	27		0.283	18
	"	10	"	410	60	"	0.190	45
	"	20	"	390	62	"	0.145	58
30	50 to 100	2	1289	1082	16	0.360	0.288	20
	"	4	"	864	33	"	0.234	35
	"	10	"	430	67	"	0.072	80
	"	20	"	386	70	"	0.018	95
	230 to 400	2	1023	858	16	0.345	0.262	24
	"	4	"	672	34	"	0.183	47
	"	10	"	379	63	"	0.021	94
	"	20	"	288	72	"	0.007	98

Continued . . . . . .

Table B.10 (continued)

Activation time (min)	Mesh size	Carbon conc. (g/l)	Initial COD (mg/l)	Residual COD (mg/l)	% COD removal	Initial abs.	Final abs.	% Color removal
45	50 to 100	2	1227	1053	14	0.360	0.310	14
	"	4	"	928	24	"	0.274	24
	"	10	"	628	49	"	0.144	60
	"	20	"	417	66	"	0.068	81
	230 to 400	2	1208	894	26	0.350	0.300	14
	"	4	"	648	46	"	0.241	31
	"	10	"	363	70	"	0.025	93
	"	20	"	228	81	"	0.007	98
60	50 to 100	2	1271	1034	19	0.360	0.302	16
	"	4	"	870	32	"	0.235	35
	"	10	"	483	62	"	0.075	79
	"	20	"	317	75	"	0.018	95
	230 to 400	2	1246	1020	18	0.355	0.287	19
	"	4	"	793	36	"	0.213	40
	"	10	"	392	68	"	0.035	90
	"	20	"	184	84	"	0.007	98

Table B.11 Activity of activated carbon at 1700 °F.

Activation time (min)	Mesh size	Carbon conc. (g/l)	Initial COD (mg/l)	Residual COD (mg/l)	% COD removal	Initial abs.	Final abs.	% Color removal
15	50 to 100	2	1230	1166	5	0.360	0.335	7
	"	4	"	1092	11	"	0.306	15
	"	10	"	860	30	"	0.237	34
	"	20	"	634	48	"	0.140	61
	230 to 400	2	1204	970	19	0.350	0.332	5
	"	4	"	799	33	"	0.300	14
	"	10	"	432	64	"	0.126	64
	"	20	"	198	73	"	0.035	90
30	50 to 100	2	1230	1161	6	0.360	0.330	8
	"	4	"	1060	14	"	0.302	16
	"	10	"	847	31	"	0.223	38
	"	20	"	533	56	"	0.086	76
	230 to 400	2	1204	948	21	0.350	0.332	5
	"	4	"	751	38	"	0.290	17
	"	10	"	384	68	"	0.066	81
	"	20	"	150	87	"	0.014	96

Continued . . . . . .

Table B.11 (continued)

Activation time (min)	Mesh size	Carbon conc. (g/l)	Initial COD (mg/l)	Residual COD (mg/l)	% COD removal	Initial abs.	Final abs.	% Color removal
45	50 to 100	2	1283	1198	7	0.360	0.345	4
	"	4	"	1140	11	"	0.324	10
	"	10	"	836	35	"	0.206	26
	"	20	"	543	57	"	0.126	65
	230 to 400	2	1257	1092	13	0.355	0.344	3
	"	4	"	935	25	"	0.323	9
	"	10	"	629	50	"	0.167	53
	"	20	"	320	74	"	0.011	97
60	50 to 100	2	1257	1080	14	0.355	0.314	10
	"	4	"	955	24	"	0.302	15
	"	10	"	653	48	"	0.230	35
	"	20	"	427	66	"	0.113	68
	230 to 400	2	"	1060	16	"	0.316	11
	"	4	"	916	27	"	0.284	20
	"	10	"	560	55	"	0.142	60
	"	20	"	251	80	"	0.011	97

Table B.12 Activity of original and regenerated carbons.

	Mesh size	Carbon conc. (g/l)	Initial COD (mg/l)	Residual COD (mg/l)	% COD removal	Initial abs.	Final abs.	% Color removal
Original carbon	50 to 100	10	1151	394	65	0.420	0.126	70
	"	20	"	230	80	"	0.008	98
	230 to 400	10	1180	260	78	0.410	0.068	83
	"	20	"	212	82	"	0.006	98
Regenerated carbon	50 to 100	10	1168	427	63	0.410	0.120	70
	"	20	"	292	75	"	0.018	95
	230 to 400	10	1152	377	67	0.385	0.065	83
	"	20	"	254	78	"	0.013	96