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Solvent Regeneration of Phenol**

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**Effect of Adsorbent Surface Properties on the
Uptake and Solvent Regeneration of Phenol**

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Abstract

The effects of carbon surface properties on the uptake of phenol by carbonaceous adsorbents and subsequent regeneration by acetone leaching was investigated. As-received carbons derived from different source materials were evaluated at pH 2 and pH 9, and the surface properties of selected adsorbents were varied by surface oxidation in concentrated HNO₃ and/or heat treatment under nitrogen. Carbons derived from different source materials exhibited similar total uptake and reversible (acetone extractable) uptake at pH 2, but exhibited a wide range of reversibility at pH 9, under conditions which promote oxidative coupling reactions. Surface acidity was investigated as a factor contributing to the reversibility of as-received carbons and surface oxidation was evaluated as a means of improving regenerability. Oxidation of a coal- and wood-based adsorbents in concentrated HNO₃ increased their surface acidity, as measured by Boehm titration technique and reduced the uptake of phenol, but increased the reversible uptake. Reversibility was found to correlate with total acidity, reaching a plateau at a surface acidity of about 1 $\mu\text{eq}/\text{m}^2$. Water vapor uptake on surface treated carbons correlated with surface acidity, suggesting that selectivity for water may contribute to the suppression of oxidative coupling reactions.

Introduction

Aqueous waste streams from petroleum refining, coal processing and steel industries often contain phenolic compounds at concentrations on the order of 5000 ppm. These compounds must be degraded or separated from process wastewaters prior to discharge to receiving waters or municipal wastewater treatment plants. Furthermore, recovery of phenolic compounds may be economically desirable. The use of adsorbents for such purposes is an attractive option. One adsorbent, activated carbon, exhibits a high adsorption capacity for phenolic compounds and is cost-effective. Phenolic compounds are adsorbed strongly by activated carbon and may interact with carbon surfaces in several ways, depending on the adsorption conditions. A distinction must be made between i) adsorption mechanisms which dominate at short equilibration times, low temperatures, low pH, and in the absence of molecular oxygen, and ii) the mechanism of oxidative coupling, a surface reaction, which becomes important under opposite conditions in each of the above respects. This distinction is of considerable practical importance, because the reversibility of phenol adsorption has been shown to decrease as a result of oxidative coupling (Grant and King, 1990).

Adsorption Mechanisms for Phenolic Compounds. Considerable research has been done to identify mechanisms of adsorption of phenolic compounds. Based upon FTIR spectroscopy of p-nitrophenol after adsorption, Mattson et al. (1969) concluded that the reactivity of phenolic compounds was due to the π -electron system of the aromatic ring, which can act as an electron acceptor in a donor-acceptor complex. Substituent groups on the phenol molecule that withdraw electrons and thus decrease electron density of the ring would act to increase adsorption, which explains experimental observations. Mattson et al. further suggest that surface carbonyl groups are likely adsorption sites due to their high dipole moments and strong electron-donating capacities. Carboxylic oxygens, having smaller dipole moments, would be less likely adsorption sites.

Coughlin and Ezra (1968) suggest that at low concentrations, phenol molecules adsorb in a planar orientation and are held by dispersion forces acting between the π -electrons of the graphitic basal planes and the phenol molecule. Mahajan et al. (1980) argue that phenol molecules may form hydrogen bonds with polar oxygen centers on the carbon surface, but may have to compete with water for those sites.

Insight into adsorption mechanisms has been gained through experiments designed to evaluate the effect of surface modifications on the uptake of phenolic compounds. Coughlin and Ezra (1968) showed that oxidation of carbon surfaces with $(\text{NH}_4)_2\text{S}_2\text{O}_8$ increased the base-adsorption capacity and reduced the adsorption capacity for phenol. They hypothesized that chemisorbed oxygen removed electrons from the graphitic basal plane, reducing dispersion forces between the phenol molecules and the surface. Mahajan et al. (1980) found that acid treatment reduced the capacity for phenols (on a surface area basis) in the order $\text{HNO}_3 > (\text{NH}_4)_2\text{S}_2\text{O}_8 > \text{H}_2\text{O}_2$. Graphite doped with boron, which is known to remove π -electrons from the graphite surface, also displayed a reduced sorption capacity. Mattson et al. (1969) suggested that oxidation of carbonyl groups to carboxylic groups would decrease the electron donating capacity of the surface, and reduce the subsequent capacity for phenolic compounds. However, data reported by Mahajan et al. (1980) show that oxidation with H_2O_2 , HNO_3 , and $\text{K}_2\text{S}_2\text{O}_8$ increase both CO and CO_2 -evolving surface groups, suggesting that both carboxylic and carbonyl surface groups increased. They attribute decreases in phenol adsorption on oxidized carbon to either i) an increased selectivity for water; or ii) a decreased number of available adsorption sites or decreased interaction energy. They further postulate that adsorbed water clusters may block adsorbent pore entrances.

Coughlin and Ezra (1968) showed that reduction of a previously acidified carbon surface with zinc amalgam restored phenol capacity. Capacity restoration was also achieved by Mahajan et al. (1980) using heat treatment in N_2 . They hypothesized that this effect was due to i) removal of surface oxygen groups; and ii) an increase in the alkalinity of the surface.

Oxidative Coupling of Phenolic Compounds. In addition to acting strictly as an adsorbent, activated carbon may participate in surface reactions, and has been shown to be an oxidation catalyst. Solutions of amino

acids, dibasic organic acids, and ferrous iron which are otherwise stable can be oxidized in the presence of carbon (Garten and Weiss, 1957). Grant and King (1990) identified oxidative coupling as a mechanism responsible for the irreversible adsorption of phenolic compounds. They found that uptake increased with increasing time and temperature, and observed significant hysteresis. They attributed these findings to a surface reaction, which was further supported by GC/MS analysis of phenolic compounds extracted from carbon with acetone, which demonstrated the presence of phenolic polymers not found in control samples containing no carbon. Polymers with the composition $C_{6n}H_{4n+2}O_n$ were identified; polymer abundance decreased with increasing molecular weight. Phenolic polymers were also identified by GC/MS analysis of methylene chloride extracts of carbon loaded with *o*-cresol in the presence of oxygen (Vidic and Suidan, 1991; Abuzaid and Nakhla, 1994).

In further support of an oxidative coupling mechanism, Grant and King (1990) demonstrated that the irreversible adsorption of several phenolic compounds correlated with the Critical Oxidation Potential (COP) of Fieser, which relates to the relative ease of oxidation. Therefore, molecules with electron-withdrawing functional groups ($NO_2 > COOH > CHO$) have greater COP values and exhibit largely reversible adsorption, while electron repelling groups ($OCH_3 > CH_3 > Cl > H$) are more highly reactive. A similar analysis was performed by Vidic et al. (1993a,b) with several substituted phenols, and was extended to consider the effect of substituent position. They found that the substituent effect on the adsorption isotherm and on adsorption irreversibility was in the order ortho > para > meta.

Grant and King (1990) showed that the reversible adsorption of phenol decreased, and irreversible adsorption increased, with increasing oxygen content in the adsorption reactor. The effect of molecular oxygen on the adsorption of phenolic compounds was further investigated by Vidic, Suidan and co-workers in a series of papers (Vidic et al., 1990; Vidic and Suidan, 1991; Vidic et al. 1993b). Isotherms were measured in the presence and absence of molecular oxygen (using methodologies designated as oxic and anoxic). Uptake of phenol, 3-ethylphenol, *o*-cresol, and natural organic matter extracted from lake water was significantly greater in the presence of molecular oxygen over a two-week equilibration. About 90% of the adsorbed *o*-cresol was recovered when loaded in the absence of oxygen; however, recovery ranged from 12 to 32% when *o*-cresol was loaded in the presence of oxygen. Furthermore, extraction efficiency increased with increased *o*-cresol surface loading, exhibiting a nearly linear dependence.

Vidic and Suidan (1992), found that both the rate and extent of *o*-cresol uptake showed a dependence on the amount of oxygen present in the adsorption reactor. Cooney and Xi (1994) established that in the absence of oxidative coupling, adsorption of substituted phenols by powdered (<45 micron) F400 carbon reached equilibrium in about 30 minutes. When oxidative coupling occurred, on the other hand, aqueous phenolic compound concentrations decreased continually over a 40-day observation period. Further, the rate of surface

reaction increased with increasing adsorbent concentration, illustrating the catalytic role of the activated carbon. The rate of surface reaction was shown to decrease with increasing electron-withdrawing capability (i.e., higher COP) of a substituted group on the adsorbate molecule, and the substituent effect on reactivity was in the order ortho > para > meta.

Adsorbent characteristics which may influence the adsorption of phenolic compounds include surface area, pore structure, surface functional groups, and ash (metal) content. Grant and King (1990) investigated the impacts of surface functionality on the irreversible adsorption of phenolic compounds. Surface characterization included i) elemental analysis, ii) reaction with LiAlH_4 to quantify active hydrogen, and iii) FTIR analysis. Irreversible adsorption did not correlate well with oxygen content, total heteroatom content, or active hydrogen for five carbon samples. Experiments with polymeric resins showed that surfaces containing ester groups (Amberlite XAD-7) or carboxylic acid groups (Amberlite IRC-50) reversibly adsorbed phenol, while Duolite S-761, which contains phenolic groups, showed about 30-35% irreversibility. It was concluded that surface functional groups, with the exception of perhaps phenolic groups, were not primary sources of irreversibility. The effects on the irreversibility of phenol adsorption due to surface components related to adsorbent ash content were investigated by treating carbon surfaces with KMnO_4 solutions. Such treatment increased the ash content, primarily as Mn, and decreased phenol recovery.

Sorial et al. (1993) studied the adsorption of p-chlorophenol on several different adsorbents; however, no surface chemical properties were characterized. A lignin-based adsorbent was the most reactive (on a surface area basis), exhibiting the largest capacity for p-chlorophenol under oxic and anoxic conditions, and the greatest increase in capacity in the presence of O_2 . This carbon also had the highest manganese content, 38 ppm, compared to values ranging from 1.1 to 11.0 ppm for the other carbons. The amount of sorbate recovered from the lignin carbon by regenerating with methanol and methylene chloride was similar to that for three bituminous carbons, ranging from 30% to 50%. The least reactive carbon, in terms of both adsorption capacity and impact of O_2 was a wood-based carbon. This adsorbent exhibited no reactivity toward oxygen, and was nearly 100% regenerable. This carbon had the lowest manganese content, the highest pore volume, the lowest apparent density, and the greatest capacity for large-molecular-weight color producing compounds (based on a molasses adsorption test).

Objective and Approach

While significant progress has been made toward understanding of oxidative coupling phenomena by carbonaceous adsorbents, the role of the carbon surface and other factors contributing to the oxidative coupling of phenolic compounds are not well understood. Our goal is to identify the primary factors that control this

catalytic behavior, and to investigate further how the catalytic properties of carbon surfaces can be altered through surface modification. This information will help identify criteria for the selection of activated carbons, and conditions for using these adsorbents which minimize irreversibilities due to oxidative coupling, thereby facilitating the recovery of phenolic compounds from relatively dilute solutions characteristic of industrial waste streams.

Through preliminary screening experiments, we identified four representative carbons derived from different starting materials (coal, wood, peat and coconut shell) and created by different methods of activation. Phenol uptake and regeneration were measured at several values of pH to provide a comparison among adsorbents under conditions which either suppress (low pH) or promote (high pH) oxidative coupling (Grant and King, 1990; Cooney and Xi, 1994). Isotherms were measured at high pH (ca. 9) to simulate conditions typical of industrial wastewater streams (Greminger and King 1979). In addition to the activated carbon materials, two synthetic adsorbents manufactured from pyrolyzed sulfonated styrene-divinylbenzene were examined.

The effects of acid washing, to remove alkaline impurities and ash components, were evaluated under high pH conditions. Surface oxidation and heat treatment were employed as techniques to alter surface functional group type and density. Heat treatment of carbon samples was employed to remove oxygen-containing functionality selectively. Depending upon temperature, oxygen is evolved upon heating as CO₂, H₂O, and CO, representing different classes of surface structures. The oxygen evolved as CO₂ is released at temperatures ranging from 300 to 700 °C, while higher temperatures ranging from 500 to 1000 °C are required to release chemisorbed CO. Water is evolved from 200 to 600°C.

Several carbons heat treated at 1000 °C were subsequently oxidized in aqueous solutions of HNO₃. Aqueous-phase oxidation in HNO₃ solutions has been shown to create new carboxyl, lactonic and phenolic functionality (Bandosz et al. 1992), and as noted previously, Mahajan et al. (1980) found an increase both CO and CO₂ -evolving surface groups, suggesting that both carboxylic and carbonyl surface groups increased. Oxidation may reduce the catalytic activity of the surface by reducing oxygen adsorption capacity and rate, increasing selectivity for water, modifying the charge distribution on graphitic basal planes, and/or changing the adsorbed configuration of phenolic molecules. Under extreme conditions, oxidation may change adsorbent pore structure, enlarging micropores and reducing total surface area. Heat treatment of oxidized carbons at 650 °C was carried out to remove strong acid and other CO₂-evolving surface functional groups (Puri, 1981).

Methods and Materials

Adsorbents. The activated carbon adsorbents and pyrolyzed synthetic resins selected for study are shown in Table 1. The carbons exhibit a range of starting materials and activation conditions, while the pyrolyzed

styrene-divinylbenzene resins are characterized by a range of surface hydrophobicity. As-received and surface treated adsorbents were characterized by: i) elemental analysis; ii) surface area and pore size distribution; iii) wettability and water uptake; iv) water vapor adsorption; and v) acid-base adsorption characteristics, measured by the Boehm technique.

Adsorbent Pretreatment. All carbons used in this research were pretreated to remove fines using the following washing procedure. Approximately 25 grams of adsorbent were sonicated in a bath-type ultrasonic cleaner (Bransonic 220, Branson Cleaning Equipment) for 30 seconds and rinsed with distilled water processed through a Milli-Q water purification system (Millipore Corp) consisting of a prefilter, an activated carbon bed, two beds containing a mixture of strong acid and strong base ion-exchange resins, and two cellulose acetate membranes to remove microscopic particles. Some washed carbons were pretreated further to remove ash components and alkaline impurities using the following acid-washing procedure. Approximately 25 grams of adsorbent was extracted with 2-N HCl in a soxhlet extractor for 42 hours. After the extraction step, the sample was boiled for four hours, then exhaustively rinsed until the pH of the suspension was in the range 5 to 6. The carbon sample was then dried at 100 °C under vacuum, and stored in a vacuum desiccator until use.

Adsorbent Heat Treatment. Adsorbents were heat treated in a tube furnace (Model LSTF341C, Lindberg) capable of temperatures up to 1100 °C. An oxygen-free atmosphere was maintained by flowing purified nitrogen gas at a rate of 30 ml/min with a back pressure of 4 to 5 psi. Adsorbents were de-gassed at 100°C for 24 hours prior to heat treatment. Target temperatures were attained at a ramping rate of 10 °C per minute and maintained for a "soak" time of 24 hours, after which the furnace was allowed to cool to ambient conditions. Heat treated samples are coded as either H1 (1000 °C) or H6 (650 °C).

Surface Oxidation. Activated carbons were oxidized in 70% HNO₃ using a solution to solid ratio of about 17:1 w/w. Solutions were kept stirred for the duration of the contact, and temperature was maintained constant within 3°C. After oxidation, the carbon was rinsed exhaustively until the pH of the suspension was in the range 5 to 6. Oxidized samples are coded by the symbol "OX" followed by the duration of the treatment in hours and the temperature in degrees Celsius (e.g. OX 2/50).

Elemental Analysis Elemental analysis (Table 2) was performed in the College of Chemistry Microanalytical Laboratory at the University of California, Berkeley. Weight fractions of carbon, hydrogen and nitrogen were determined with a Perkin-Elmer Model 240 Elemental Analyzer. Combustion products from samples burned in excess oxygen were determined with a thermal conductivity detector. Care was taken to avoid confounding influences of adsorbed water. Samples were dried at 160 °C under vacuum, and stored in a desiccator until analysis. Samples were weighed in an anaerobic glove box, and analyzed using an air-sensitive technique. The weight percentage of oxygen + sulfur was estimated by difference. The sulfur content of these

samples is expected to be less than 1% based on measurements reported in the literature (Munson 1985, Karanfil 1995).

Adsorbent Surface Area. Surface area (Table 3) and pore size distribution were measured with a PMI model 201 BET Analyzer (Porous Materials, Inc.) using gaseous nitrogen at 77 K. Surface area was determined by fitting low-pressure data ($p/p_0 < 0.25$) to the BET adsorption equation (Gregg and Sing 1982) using a non-linear regression algorithm (Sigma Plot, Jandel Scientific). Precision of replicate samples averaged 5%.

Adsorbent Wetting and Water Uptake. Two different procedures were evaluated for the purpose of wetting adsorbent surfaces. The first technique involved boiling in water for 30 min followed by centrifugation to remove interstitial water. The second technique involved equilibrating washed samples with water in a thermostatted bath at 25 °C for either 48 or 114 hours, followed by centrifugation. The two techniques gave similar water uptake values, and both had reproducibilities better than 2%. With the second technique, there was no significant difference between equilibration for 48 and 114 hours. Water uptake values measured using the second technique are reported in Table 3.

Water Vapor Adsorption. Water vapor uptake was measured in a batch system. Approximately one gram of carbon was arranged in a shallow layer in a glass weighing vial, outgassed in a vacuum oven (25 in Hg) at 160 °C, cooled in a desiccator, and weighed. Carbon samples were equilibrated over a saturated salt solution prepared from reagent-grade CH_3COONa , yielding a relative humidity (RH) of 22.5% (Greenspan 1977). The salt solution was stirred continuously and the carbon was equilibrated for a period of six days at 25 °C. A potassium acetate solution was chosen to control humidity because i) the relative humidity was low enough to be within the linear portion of the water vapor isotherm (Lin and Nazaroff 1996); and, ii) the relative humidity was high enough to result in significant uptake values and therefore minimize experimental error. Water vapor uptake values, reported in Table 3, were taken as a measure of the affinity of the surface for water.

Adsorbent Acid/Base Characterization. The acid/base characteristics of adsorbents were characterized using the Boehm technique (Bandosz et al. 1992) and are reported in Table 3. A 0.4-gram aliquot of carbon was equilibrated with 20 g of either 0.05-N HCl, NaOH, Na_2CO_3 or NaHCO₃ for at least 48 hours. After equilibration, the solution was filtered and titrated with either standard base (NaOH) or acid (HCl); endpoints were determined from the first derivative of the titration curve. NaOH titrant was standardized against 0.05-N potassium hydrogen phthalate, the endpoint was determined from the first derivative of the titration curve. All solutions were prepared using reagent-grade chemicals, in Milli-Q water that was boiled for 30 minutes to remove dissolved CO_2 . Reproducibility of the technique was generally within a few percent.

It is often assumed that NaHCO_3 uptake corresponds to strong carboxyl acidity, while Na_2CO_3 further reacts with weak carboxyl and α -lactonic functionality, and NaOH further reacts with phenolic acidity (Noh and Schwarz 1990).

Mass Spectrometry Analysis. Mass spectrometry analysis was performed in the College of Chemistry Mass spectrometry Laboratory at the University of California, Berkeley. Acetone extracts of loaded carbons were analyzed by a triple sector (EBE) mass spectrometer (Micromass Inc.) using 70 eV electron impact ionization and direct probe sample introduction.

Phenol Analysis. Phenol was analyzed by gas chromatography (GC) using a Varian Star 3600 CX gas chromatograph with FID detection. The analytical column (Supelco) was a 6' long, 0.125" OD (1.8-mm ID) glass column packed with 80/100 mesh Carbopak C, a non-porous, inert, graphitized carbon black coated with 0.1% SP-1000. A nitrogen carrier gas flow of 20 ml/min was used with a head pressure of 55 to 60 psi. Medical grade air was supplied to the detector at 300 ml/min, and hydrogen was supplied at 30 ml/min. Injections were made using a solvent flush technique (Varian 1993). Reproducibility (standard deviation divided by the mean) of three to four replicates using this technique averaged about 2 percent. Calibration curves were prepared using external standards.

Isotherm Development. Composite and individual uptakes (see definitions, below) of phenol, and the individual uptake of water were measured in completely mixed batch reactors. The conditions of each batch reactor are represented by a single point on the adsorption isotherm. An adsorbent mass of 0.25 g and 10 g of phenol solution were added to 20-ml glass scintillation vials which were sealed with teflon-faced rubber septa and equilibrated at 25 °C on a thermostatted reciprocating shaker. A rate study was conducted to determine the time required to reach equilibrium. The effects of diffusion-controlled mass-transfer rate was separated from that of oxidative coupling reaction rate by conducting the study at pH 2 (Cooney and Xi 1994). F400 carbon was pre-wet by boiling for 30 minutes prior to contacting a 0.4 weight percent solution of phenol. It was found that 100 hours was sufficient time to achieve equilibrium; no further removal from solution was observed for up to 400 hours. All subsequent isotherm experiments were carried out for 120 hours.

Isotherms were measured using adsorbate solutions prepared in Milli-Q filtered water. Solution pH was adjusted with concentrated HCl or NaOH. Low-pH experiments were conducted without a buffer; a pre-wetting step, in which the carbon was equilibrated with pH-adjusted Milli-Q water, was sufficient to maintain pH stability over a relatively narrow range. Most experiments conducted at higher pH values were mildly buffered with 0.015 M ammonium carbonate.

After equilibration, an aliquot of solution was filtered using a hydrophilic modified PTFE filter (Millipore Millex-LCR). Preliminary experiments verified that no loss of phenol occurred on the filter surface.

For most of the isotherms, phenol concentrations were analyzed by GC; some experiments employed UV absorption at 280 nm. Phenol uptake values computed with each method agreed to within 1.5 %. After sampling, adsorbent was subsequently removed from the reactor and centrifuged in a fitted Buchner funnel for 10 minutes at 2000 rpm to remove interstitial water which may have accumulated between adsorbent particles. Total mass uptake (phenol + water) was determined gravimetrically.

Adsorbents were regenerated at ambient temperatures using an excess of acetone, as described by Grant and King (1990). They showed that near-complete regeneration was possible using an acetone-to-carbon ratio of 300 ml/g and a 66.3-hour equilibration period. Recoveries were not increased by additional desorption time (up to 120 hours), additional solvent (946 ml/g) or a second batch regeneration. In this study, the acetone-to-carbon ratio ranged from 500 to 600 ml/g and a minimum desorption period of 120-hours was used.

Analysis and Modeling of Adsorption Data

Composite uptake was computed from measurements made directly in the laboratory:

$$q_e = \frac{W^o(X_p^o - X_p^f)}{M_c} \quad (1)$$

Where q_e is the composite uptake; W^o is the initial solution mass; X_p^o and X_p^f are the initial and final (equilibrium) solute mass fraction in solution, respectively; and M_c is the mass of carbon. It can be shown that the composite uptake is equal to the surface excess, defined as the excess of component in the surface layer compared with the amount present in a quantity of bulk liquid containing the same total mass of all species (Kipling 1965).

The total amount of component i removed from bulk solution is referred to as the individual uptake, Q , and includes the amount of component i within adsorbent pores and held interstitially, in addition to that adsorbed on the surface. Therefore, the mass of solution taken up by the adsorbent must be accounted for:

$$Q_P = \frac{W^o X_P^o - W^f X_P^f}{M_c} \quad (2)$$

$$Q_W = \frac{(W^o X_W^o - W^f X_W^f)}{M_c} = \frac{(W^o(1 - X_P^o) - W^f(1 - X_P^f))}{M_c} \quad (3)$$

where W^f is the mass of solution at equilibrium. Individual uptakes are difficult to measure directly. However, the sum of individual uptakes ($Q_P + Q_W$), referred to as the total mass uptake, M_T , was readily measured gravimetrically. Centrifugation was used to minimize interstitial water which may have accumulated between adsorbent particles. Individual solute uptake was computed by combining the composite uptake expression (Equation 1), the individual uptake expression (Equation 2) and the following mass balance on the solution:

$$W^f = W^o - Q_P M_c - Q_W M_c \quad (4)$$

to yield the following relationship:

$$Q_P = \frac{W^o(X_P^o - X_P^f)}{M_c} + X_P^f M_T \quad (5)$$

Composite uptake of phenolic compounds were modeled using the Freundlich adsorption isotherm:

$$q_e = K_F (X_P^f)^n \quad (6)$$

Where q_e is the composite uptake, and n and K_F are empirical constants. The value of K_F represents the composite uptake at a solution phase concentration equal to unity, and can therefore be interpreted as a measure of adsorption capacity. The parameter n represents the intensity of adsorption; low values are reflected in isotherms

which exhibit high uptake at low solution phase concentrations. It has been shown that the Freundlich isotherm is consistent with a pseudo-exponential site energy distribution; in this interpretation the value of n represents the degree of site energy heterogeneity (Derylo-Marczewska et al., 1984; Cooney, 1990). High values of n reflect relatively uniform surfaces.

Analysis of Regeneration Data

The individual uptake of solute during the adsorption step is redistributed between the adsorbent surface and the solution phase (bulk liquid and adsorbent pore volume) during regeneration. When the solution is sufficiently dilute, the irreversible composite uptake, q_e^i , is approximately equal to the amount of solute remaining on the surface after regeneration, M_p^{si} . The solution phase is comprised of added regenerant, R , and entrained solution from the adsorption step, W_E^f . A solute mass-balance for the regeneration yields the following relationship:

$$Q_p M_c = q_e^i M_c + (W_E^f + R) X_p^{f'} \quad (8)$$

where $X_p^{f'}$ is the weight fraction of solute in the regenerant solution. The weight of the entrained solution, W_E^f cannot be measured directly; therefore, simplifying assumptions must be made to estimate this parameter. In systems which employ large regenerant to adsorbent ratios, $R \gg W_E^f$ and it is thus possible to neglect the entrained solution. Upper and lower bound estimates of the irreversible uptake can be made by setting W_E^f equal to zero and the total mass uptake, M_T , respectively. Equation (8) was solved for q_e^i , and the difference between the total composite uptake, q_e , and the irreversible composite uptake q_e^i , is designated the reversible uptake, q_e^r . Regeneration efficiency was computed as the ration of reversible to total composite uptake.

The following section employs representative data to illustrate observed trends. A complete set of the data collected and additional figures can be found in the appendix.

Results and Discussion

Comparison of As-Received (Washed) Carbons. Phenol uptake and regeneration by the four were measured at several values of pH to provide a comparison among adsorbents under conditions which either suppress (low pH) or promote (high pH) oxidative coupling. Data were fitted with the Freundlich isotherm model, which described data satisfactorily over a range of liquid-phase concentrations from less than 100 ppm

to over 20,000 ppm (10^{-4} to 2 weight percent). Isotherm parameters and confidence limits (95%) were estimated from linear regression of log-transformed data (Table 4).

Figure 1 presents representative isotherm data at low pH. The bituminous-coal-based F400, peat-based RO, and coconut-shell-based CG6 carbons exhibited similar uptakes over a wide range of equilibrium concentrations. The wood-based WVB sample exhibits the lowest uptake in the low concentration region but the highest uptake for solution phase concentrations above 5,000 ppm. Correspondingly, this carbon also has a significantly higher value of the Freundlich n -value, reflecting a lower site energy heterogeneity. A smaller fraction of higher-energy sites is consistent with the lower uptake observed at low solution phase concentrations.

Regeneration efficiencies corresponding to a pre-regeneration loading of approximately $100 \mu\text{g}/\text{m}^2$ ranged from about 83 to 91% for low-pH experiments; these findings are consistent with previous results reported by Grant and King (1990). Under these conditions, which are expected to suppress oxidative coupling reactions, all adsorbents exhibited similar performance with regard to regenerability. Experiments conducted to evaluate the effect of drying the adsorbent under ambient conditions prior to regeneration found that there was no significant benefit to this procedure, and at higher loadings, regeneration efficiency was reduced somewhat (see appendix).

The effect of pH on uptake and regeneration was evaluated by measuring isotherms for the four carbons at pH 9. The relative ordering of uptake for the activated carbons (in both the higher and lower concentration regions) at pH 9 was similar to that found at pH 2. Uptake at pH 9 was either higher (F400, RO, CG6) or remained essentially the same (WVB) as that at pH 2. Representative data for F400 carbon are shown in Figure 2. Uptake would be expected to decrease at the higher pH values because of an increase in the negative charge on the adsorbent surface and an increased degree of phenol ionization (Mueller et al. 1985). Thus, the observed increases were likely due to the effects of oxidative coupling, which is promoted at high pH values. Grant and King (1990) found that reversible adsorption increased with decreasing pH, even for values below the pK of phenol, and concluded that the phenolate ion is more reactive than phenol.

An increase in pH from 2 to 9, expected to increase the rate and extent of oxidative coupling reactions, had a dramatic and carbon-specific effect on regeneration efficiency. The regeneration efficiency of the F400, RO, and CG6 carbons was reduced significantly (by 73, 82 and 50%, respectively), while the acid-activated WVB carbon, which had the highest regeneration efficiency at both pH values investigated, exhibited a reduction of about 10%. Regeneration efficiencies for different carbons are shown in Figure 3. It is likely that the different effects of pH on regeneration efficiency observed for different carbons are caused by properties of the adsorbents which promote catalytic activity. This is supported by the observation that for the F400, RO and CG6 carbons,

the reversible adsorption at pH 9 was lower than that measured at pH 2; conversely the irreversible uptake was higher. Illustrative data for F400 carbon are shown in Figure 4. It can also be noted from Figure 4 that the percentage of reversible adsorption at pH 9 increases with increasing coverage. For the WVB carbon, the irreversible uptake was also higher at pH 9; however, the reversible adsorption was the same at both pH values.

The effect of pH on regeneration efficiency was studied in greater detail using the F400 carbon. As shown in Figure 5, a significant and continuous decline in regeneration efficiency is noted as the pH ranges from about 2 to 5, while a more gradual decrease is noted at higher pH values. This finding supports the observation made by Grant (1988), who noted that small variations in pH are inconsequential, while wider variations markedly affect reversible and irreversible adsorption.

Phenol uptake at pH 9 was measured for two pyrolyzed resins, Amborsorb 572 and 575 (see appendix). The 572 resin is more hydrophobic than the 575 and has a higher surface area (1100 vs. 800 m²/g). The resins exhibited performance quite similar to that of the F400 and RO carbons, but in contrast to these adsorbents, reached more well-defined plateaus at higher solution-phase concentrations. The similar capacities of the two resins on a surface area basis suggest that the adsorbent surfaces are similarly reactive (or non-reactive) toward phenol. Both resins exhibit regenerability at high pH values on the order of 60-70%, significantly higher than the F400 carbon, but below that found for the WVB carbon.

Effects of HCl-washing. The effect of acid-washing adsorbents as a surface treatment prior to conducting the isotherm experiment was investigated for several carbons. The acid-washing procedure (2.0 N HCl) was done to remove alkaline impurities and ash components, such as iron, aluminum, and manganese. It has been shown that metals on the surfaces of activated carbon may contribute to catalytic activity (Grant and King 1990). It was hypothesized, therefore, that removing ash components might reduce the extent of oxidative coupling, and would possibly reduce the uptake at high pH values. As shown in Figure 2, the acid washing treatment did not significantly change the uptake by the F400 carbon in the high concentration region; at low concentrations a slight increase in uptake was observed. Uptake by the WVB carbon was independent of acid washing over the entire concentration range. Uptake by the RO carbon increased slightly at lower concentrations (<1000 ppm) and decreased slightly at concentrations over 5000 ppm.

The acid-washing treatment had little effect on the regeneration efficiency of the F400 and WVB carbons (see appendix), a result consistent with the negligible changes observed in the composite uptake isotherms. HCl washing lowered the ash content of F400 carbon from 6.3 to 4.7%, and atomic absorption spectrophotometry analysis of the F400 acid extract revealed that approximately 11 μmol Fe, 24 μmol Al, 0.04 μmol Mn, 0.03 μmol Cr and 0.01 $\mu\text{mol/g}$ Cu were removed from the surface. Based on the metal content of F400 carbon reported by Karanfil (1995), this represents approximately 18, 37, 28 and 2.8% of the total Fe, Al, Mn and Cu content,

respectively. It is possible that ash content does not dominate the catalytic activity of this carbon; alternatively, it is possible that the acid-washing procedure did not remove enough metals to affect reversible uptake. However, acid washing did increase the regeneration efficiency of the RO carbon somewhat, up to 12% at lower loadings. The WVB and RO carbons have similar ash contents, but exhibit much different degrees of adsorption reversibility. Conversely, the F400 and RO carbons have similar adsorption reversibilities but much different ash content. It is evident that ash content alone is not a good predictor of reversible adsorption, nor is HCl washing effective in increasing reversible adsorption. Nevertheless, considering that the HCl-washing procedure did remove potentially catalytic components, subsequent experiments investigating the effects of heat treatment and surface oxidation employed the acid-washing procedure.

Examination of the carbon characterization data reported in Table 2 reveals that among the as-received carbons, the WVB carbon exhibits the highest oxygen content, at least a factor of two greater than that of other adsorbents. The high NaOH uptake of this carbon (Table 3) suggests that it is likely that much of the oxygen is found as acidic functional groups. The effects of oxygen-containing functional groups on phenol uptake and reversibility were investigated further through a program of heat treatment and surface oxidation. F400 and WVB were chosen as representative adsorbents for these experiments. Prior to oxidation, the carbon was heat treated at 1000 °C to remove oxygen groups which may have formed on the surface during activation or during storage. Based on the data in Tables 2 and 3, it is apparent that the heat treatment effectively reduced the oxygen contents of both adsorbents, and completely removed all strongly acidic groups from the WVB carbon, as evidenced by a lack of NaHCO₃ uptake. The total acidity, measured by NaOH uptake, was reduced completely to zero for the F400 carbon, and reduced by about 50% for the WVB carbon. HCl uptake remained essentially unchanged for the F400 carbon, but increased for the WVB sample.

Heat treatment did not have a significant effect on phenol uptake or regeneration for the F400 carbon. This is consistent with the starting material having a low oxygen content and a low total acidity to begin with. The WVB carbon exhibited similar uptake at higher concentrations, but increased uptake at lower concentrations, a trend reflected in a significantly lower Freundlich n-value. Thus, heat treatment produced a less energetically uniform surface by increasing the proportion of high energy sites. A decrease in regeneration efficiency of about 10% was also observed.

Surface oxidation subsequent to high-temperature heat treatment increased total acidity and decreased HCl uptake for both carbons. Functional group density and the proportion of strong acid functionality (NaHCO₃ uptake) was observed to increase with increasing reaction time and temperature. The relative increase in acidic functional groups was greater for the F400 carbon. However, the absolute effects of surface oxidation were greater for the wood-based WVB carbon; for a given set of oxidation conditions, the resulting acidic functional

group content was greater than for the coal-based F400. This finding is consistent with other reports in the literature (Bandosz et al. 1993) and may reflect a greater starting oxygen content of the wood based material.

Surface oxidation had a significant effect on the uptake of phenol by F400 carbon, as shown in Figure 6. On both a mass and surface area basis, all oxidized carbons exhibited a significant reduction in uptake in the lower concentrations, as seen by a reduction in the Freundlich K_F value, and all but the sample oxidized under the most mild conditions exhibited a reduced uptake at higher concentrations. The sample oxidized for 9 hours at 70 °C did display a statistically significant increase in the Freundlich n -value, supporting the idea that adding hydrophilic centers decreases the energetic heterogeneity of the surface. It is apparent, however, that statistically significant changes in the Freundlich n -value require large changes in surface chemistry. The uptake of phenol by the WVB carbon was reduced somewhat by surface oxidation, particularly at higher concentrations. The effects of oxidation are less than for the F400 carbon, however, which is consistent with a lower relative increase in acidity.

Surface oxidation significantly increased both the absolute reversible adsorption and the regeneration efficiency of the F400 carbon, as shown in Figure 7. An interesting feature of the data shown in Figure 7 is the effect of loading on regeneration efficiency for different degrees of oxidation. The as-received sample shows a continuous increase in regeneration efficiency over the entire range of loading studied, a trend that has been observed previously (Vidic and Suidan 1991). The sample oxidized for 2 hours at 50 °C shows a maximum in regeneration efficiency, while carbons oxidized to a greater degree exhibit a decline in regeneration efficiency with increased loading. A possible explanation is that on oxidized surfaces, phenol must compete with water bound to hydrophilic centers, reducing the extent or rate of coupling reactions. At higher solute activities, water is effectively displaced, increasing the degree of coupling and the relative contribution of irreversible adsorption. This occurs at much lower solute activities on surfaces lacking hydrophilic functional groups. Surface oxidation did not have a significant effect on either absolute reversible adsorption or regeneration efficiency for the WVB carbon, despite an increase in total acidity of about a factor of two. Reasons for this will become apparent in subsequent sections when reversible adsorption is correlated with Boehm acidity measurements.

Heat treatment of oxidized F400 carbons at 650 °C was done to remove strongly acidic and other CO_2 -evolving groups in an attempt to determine whether the type of oxygen-containing functional group or the total functional group density was the most important factor in the regenerability enhancement of oxidized carbons. Heat treatment at 650 °C significantly reduced the total oxygen content (Table 2) and reduced the total acidity by about a factor of three. For the carbon sample oxidized for 2 hours at 70 °C, the ability to neutralize NaHCO_3 and Na_2CO_3 was eliminated upon subsequent heat treatment, returning the carbon to a condition closely approximating the as-received carbon. Heat treatment of the carbon sample oxidized for 9 hours at 70 °C nearly

eliminated the strong-acid functionality, but significant total acidity and some ability to neutralize Na_2CO_3 remained.

As shown in Figure 8, heat treatment of oxidized carbons resulted in a significant recovery in phenol uptake. This observation is consistent with the results of similar heat treatment reported by Puri (1981). Phenol uptake by the heat treated OX 2/50 was similar to the HCl-washed carbon, and uptake by the heat-treated OX 9/70 sample was nearly so. The recovery of phenol uptake was reflected in a significant increase in the Freundlich K_F value for both carbons, and a significant decrease in the n-value for the OX 9/70 sample, again supporting the concept of heat treatment creating a less energetically uniform surface.

As shown in Figure 9, the increase in uptake upon heat treatment was associated with a significant decrease in regeneration efficiency, although reversible uptake was somewhat higher than that found for the as-received, HCl-washed carbon, particularly at lower loadings. Removal of strongly acidic functional groups did not completely eliminate the increases in reversibility due to surface oxidation. Further insight into the effects of surface functional group density and type can be gained by correlating surface acidity with reversible adsorption.

Figure 10 shows the results of a correlation between regeneration efficiency corresponding to a coverage of about $100 \mu\text{g}/\text{m}^2$ (pH 9) and total acidity (NaOH uptake). Correlations as a function of NaHCO_3 and Na_2CO_3 uptake were also evaluated, but were not superior to total acidity; furthermore, the total acidity correlation was more sensitive to small changes at low levels of acidity, as some carbons had no NaHCO_3 or Na_2CO_3 uptake. Figure 10 shows a clear trend of increasing reversibility with increasing surface acidity; however, a plateau is reached at approximately 1 meq/g. In the plateau region, the regeneration efficiencies of the coal- and wood-based carbons are essentially equivalent, leading to the conclusion that regenerability is more a function of carbon surface chemistry than source material or pore structure. However, the heat-treated WVB carbon exhibits greater regeneration efficiency than the F400 carbons having similar total acidity. Furthermore, the F400 OX2/50 sample has a higher oxygen content, total acidity and Na_2CO_3 uptake. While this is only one data point, there is a suggestion that some other carbon property is influencing reversibility. The heat-treated F400 carbons having low acidity appear to follow the same trend as oxidized F400 carbons; however, the heat treated carbon having the highest acidity appears less effective for suppressing oxidative coupling. This carbon is otherwise similar to the OX 2/50 sample, suggesting that the removal of strongly acidic groups from the F400 surface is detrimental for minimizing the effect of oxidative coupling.

The increased regenerability of oxidized carbons suggests that the extent of oxidative coupling reactions is significantly reduced; however, phenol polymerization products were found in the acetone extracts of both heat treated (1000°C) and oxidized carbons, suggesting that oxidized surfaces inhibit, but do not completely

eliminate, the coupling reaction. The data presented in this work is consistent with several mechanisms which may contribute to the suppression of oxidative coupling by oxidized carbons. Karanfil (1995) has proposed that acidic surface groups may inhibit polymerization reactions by accepting electrons released during the activation and radical formation steps, reducing the formation of hydroxy and phenoxy radicals. This explanation is consistent with the findings of Bandosz et al. (1992) who showed that oxidation increased the carboxylic acid content and electron-acceptor capacity of carbon surfaces, as measured by relative gas-chromatographic retention times of propene and propane. Harbour et al. (1986) found that oxidation of carbon blacks with peracetic acid generated electron-accepting groups as measured by electron spin resonance spectroscopy. An alternative explanation relates to an increased selectivity between phenol and water on oxidized surfaces.

As proposed by Mahajan et al. (1980), chemisorbed oxygen may form sites that preferentially adsorb water, possibly leading to the formation of water clusters. As a result, part of the adsorbent surface area may become unavailable, or the interaction energy between phenol and the surface may be reduced. Changes in the affinity of oxidized surfaces for water was evaluated by measuring the uptake of water vapor corresponding to a relative humidity of 22.5% (at 25 °C). Water vapor adsorption by activated carbon depends on both surface chemistry and pore structure, and has been used to evaluate the hydrophilic character of carbon surfaces (Bansal et al. 1988). Water uptake is thought to occur primarily on active (hydrophilic) sites, and has been correlated with the enthalpy of immersion, NaOH uptake, and the amount of CO₂-evolving groups on the surface (Bansal et al. 1988). As shown in Figure 11, a correlation between water vapor uptake and surface acidity, as measured by NaOH uptake, was found for the surface treated carbons employed in this work. This result suggests that oxidized carbons have a higher affinity for water, primarily through association with acidic sites. Thus, increased selectivity for water on oxidized carbons is likely, and may contribute, in part, to the increased regenerability of these adsorbents.

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Table 1. Adsorbent Starting Materials and Activation

Manufacturer	Starting Material	Activation Method	Code
Calgon	Bituminous Coal	Steam	F400
Westvaco	Wood	Acid/catalyst	WVB
Norit	Extruded Peat	Steam	RO
Cameron	Coconut Shell	Steam	CG6
Rohm & Haas	Sulfonated Styrene Divinyl Benzene	Pyrolysis	AMB

Table 2. Carbon Characterization by Elemental Analysis

Carbon Type	Surface Treatment	Elemental Analysis, Percent by Weight				
		C	H	N	O + S	Ash
F400	As-Received	92.85	<0.2	0.80	0.05	6.30
F400	AW	91.21	0.20	0.61	3.28	4.70
F400	AW, H1	92.76	<0.2	0.64	1.30	5.30
F400	OX 2/50	89.32	<0.2	0.71	5.27	4.70
F400	OX 2/70	88.03	<0.2	0.82	6.05	5.10
F400	OX 9/70	86.48	<0.2	0.85	7.17	5.50
F400	OX 2/70, H6	91.18	<0.2	0.75	2.77	5.30
F400	OX 9/70, H6	88.77	<0.2	0.91	4.92	5.40
WVB	AW	87.57	1.77	0.27	8.59	1.80
WVB	AW, H1	93.42	<0.2	0.28	3.20	3.10
WVB	OX 2/50	92.29	<0.2	0.42	3.99	3.30
WVB	OX 2/70	89.08	<0.2	0.46	7.36	3.10
RO	AW	93.98	<0.2	0.62	3.70	1.70
CG6	AW	91.97	<0.2	0.57	2.66	4.80

Notes. Symbols: AW means HCl washed for 42 hours in a sohxdet extractor; H1 means heat treated at 1000 °C for 24 hours under nitrogen, H6 means heat treated at 650 °C for 24 hours under nitrogen; "OX" refers to carbon first treated by acid washing and heat treatment at 1000 °C, followed by oxidation in concentrated (70%) HNO₃; "OX" is followed by the reaction time in hours/reaction temperature in degrees centigrade.

Table 3. Carbon Pore Structure and Surface Chemistry

Carbon Type	Surface Treatment	Physical Analysis			Chemical Analysis			
		Surface Area, m ² /g	Water Uptake g/g	Water Vapor Uptake μg/m ²	HCl Uptake μeq/m ²	NaOH Uptake μeq/m ²	Na ₂ CO ₃ Uptake μeq/m ²	NaHCO ₃ Uptake μeq/m ²
F400	AW	1044	0.63	5.60	0.34	0.14	0.00	0.00
F400	AW, H1	1055	0.64	1.85	0.37	0.00	0.00	0.00
F400	OX 2/50	968	0.66	9.84	0.29	0.60	0.19	0.05
F400	OX 2/70	1041	0.67	15.00	0.22	0.94	0.40	0.22
F400	OX 9/70	1031	0.68	31.08	0.11	1.71	0.96	0.61
F400	OX 2/70, H6	1029	0.67	3.40	0.29	0.26	0.00	0.00
F400	OX 9/70, H6	1066	0.72	6.43	0.24	0.55	0.22	0.05
WVB	AW	1369	1.55	ND	0.18	0.57	0.24	0.12
WVB	AW, H1	ND	1.13	13.94	0.26*	0.31*	0.09*	0.00
WVB	OX 2/50	1272	1.14	12.91	0.17	0.76	0.40	0.19
WVB	OX 2/70	1295	1.13	21.79	0.13	1.14	0.62	0.35
RO	AW	1103	0.98	54.34	0.39	0.27	ND	ND
CG6	AW	941	0.64	ND	0.34	0.28	0.00	0.00

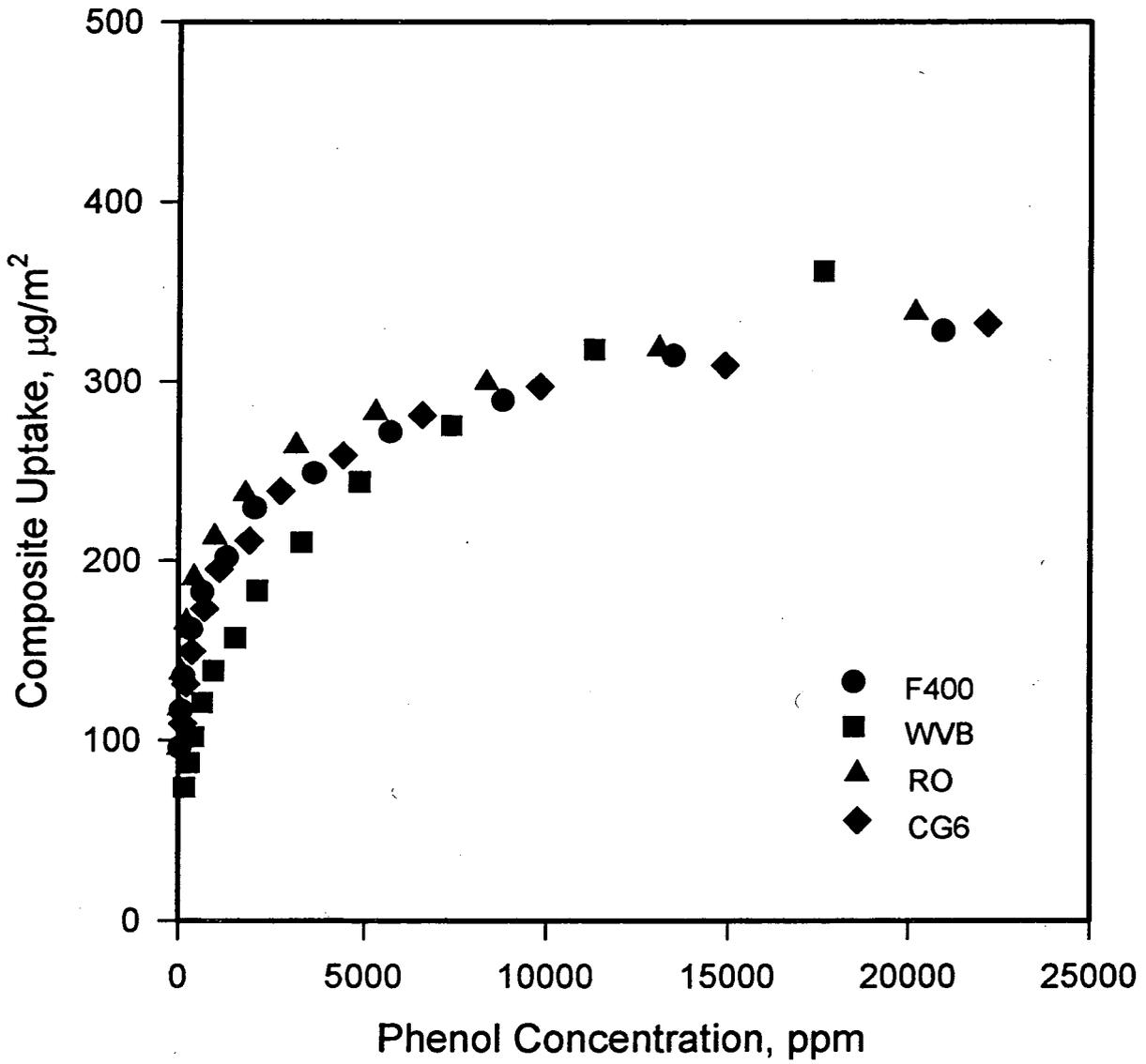
Notes. Values reported are averages of at least two replicates. Water vapor uptake measured at a relative humidity of 0.225. Symbols: AW means HCl washed for 42 hours in a sohxlet extractor; H1 means heat treated at 1000 C for 24 hours under nitrogen, H6 means heat treated at 650 C for 24 hours under nitrogen; "OX" refers to carbon first treated by acid washing and heat treatment at 1000 °C, followed by oxidation in concentrated (70%) HNO₃; "OX" is followed by the reaction time in hours/reaction temperature in degrees centigrade. ; ND means not determined. Negative values for uptakes are reported as zero. *Assuming a surface area of 1300 m²/g.

Table 4. Freundlich Parameters for Phenol Uptake

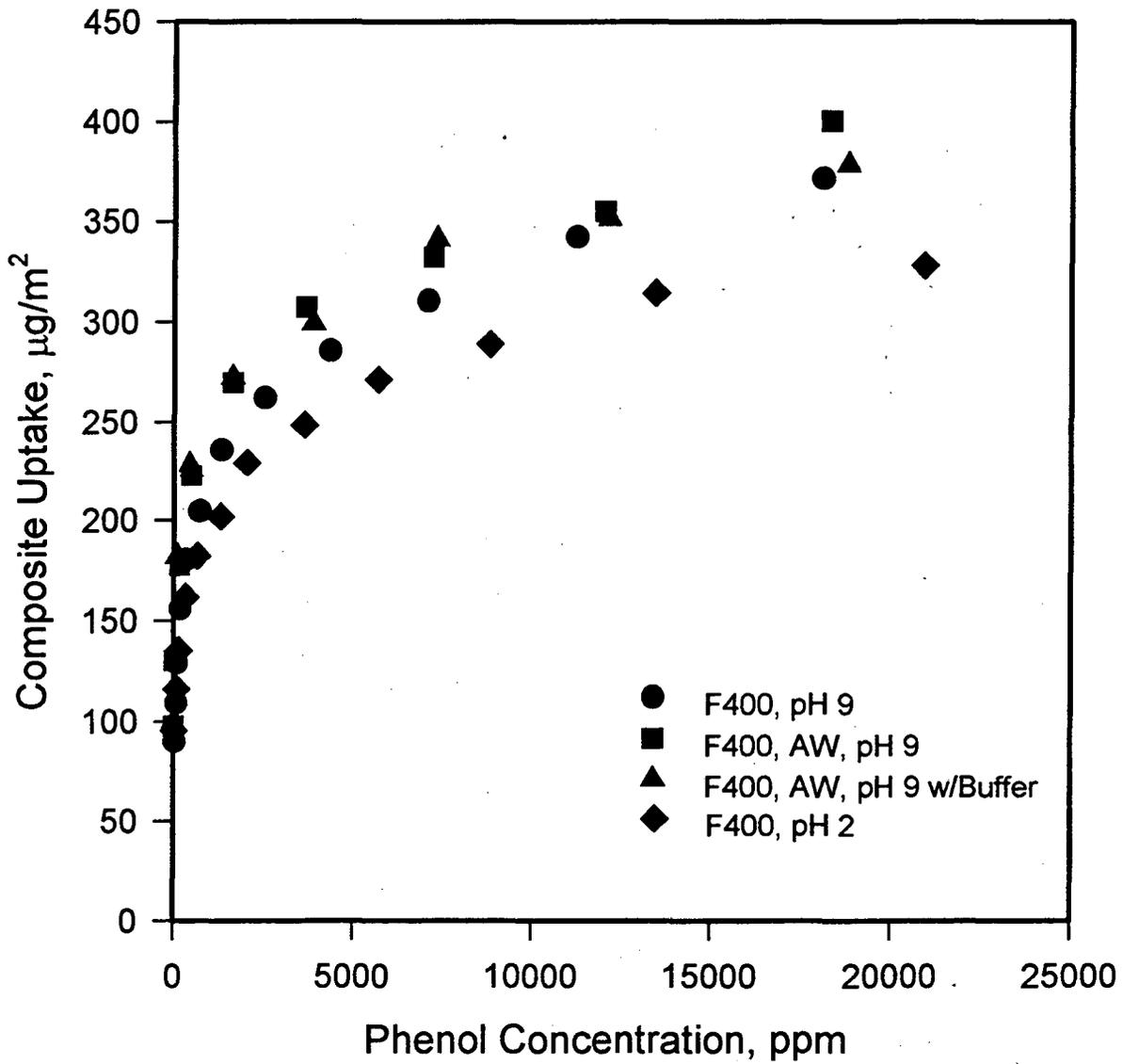
Sorbent	Treatment	pH	Freundlich Isotherm Parameters	
			K_F	n
F400	As-Received	2	51.1 (45.9, 57.1)	0.198 (0.183, 0.213)
F400	As-Received	9	47.1 (39.4, 56.4)	0.223 (0.197, 0.248)
F400	Acid-Washed	9	75.9 (72.0, 79.9)	0.168 (0.161, 0.176)
F400	AW, H1	9	60.7 (54.2, 67.8)	0.183 (0.168, 0.198)
F400	OX 2/50	9	56.1 (49.0, 64.4)	0.207 (0.189, 0.225)
F400	OX 2/70	9	46.3 (41.5, 51.7)	0.199 (0.185, 0.213)
F400	OX 9/70	9	28.6 (25.2, 32.3)	0.235 (0.220, 0.250)
F400	OX 2/70, H6	9	64.5 (58.9, 70.7)	0.196 (0.183, 0.208)
F400	OX 9/70, H6	9	57.7 (54.7, 60.8)	0.189 (0.182, 0.196)
WVB	As-Received	2	12.7 (11.8, 13.7)	0.345 (0.336, 0.355)
WVB	As-Received	9	11.5 (10.7, 12.5)	0.353 (0.343, 0.364)
WVB	Acid-Washed	9	14.2 (12.6, 16.0)	0.338 (0.322, 0.354)
WVB	AW, H1	9	40.7 (38.2, 43.5)	0.207 (0.199, 0.216)
WVB	OX 2/50	9	38.4 (35.8, 41.1)	0.212 (0.203, 0.221)
WVB	OX 2/70	9	36.3 (32.4, 40.8)	0.208 (0.193, 0.223)
RO	As-Received	2	57.4 (50.0, 66.0)	0.185 (0.166, 0.204)
RO	As-Received	7	84.7 (75.8, 94.6)	0.158 (0.142, 0.175)
RO	As-Received	9	68.7 (56.7, 83.3)	0.179 (0.151, 0.208)
RO	Acid-Washed	9	97.0 (83.9, 112)	0.137 (0.116, 0.158)
CG6	As-Received	2	42.6 (37.4, 48.6)	0.211 (0.194, 0.228)
CG6	As-Received	9	41.3 (35.4, 48.4)	0.231 (0.210, 0.252)
AM572	As-Received	9	62.5 (54.0, 72.5)	0.190 (0.170, 0.211)
AM575	As-Received	9	74.0 (58.0, 94.5)	0.191 (0.144, 0.239)

Note: Parameters based on regressing uptake values in units of $\mu\text{g}/\text{m}^2$, and phenol concentration in units of ppm. Values in parentheses are 95% confidence intervals determined from regression analyses.

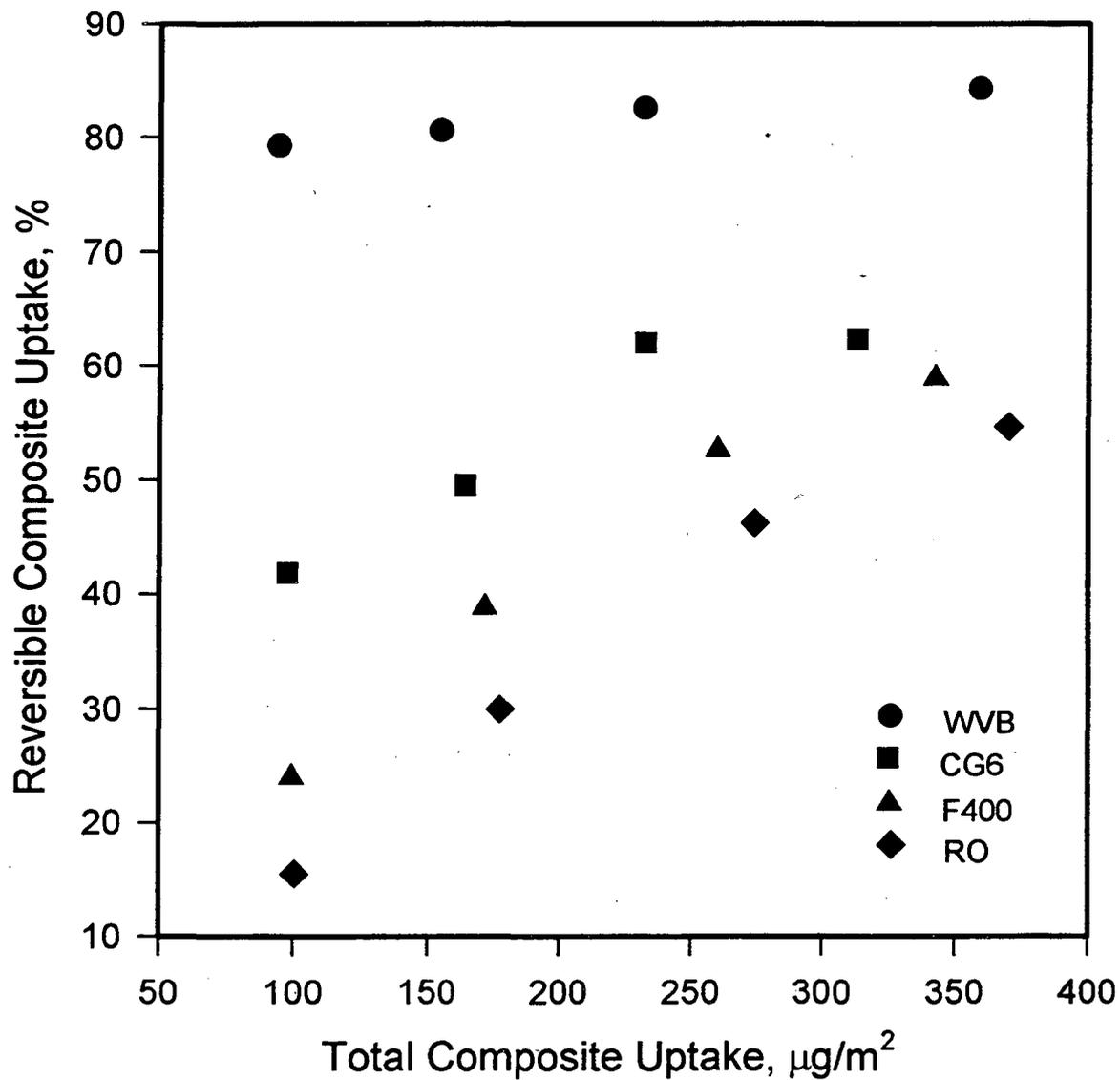
Effect of Carbon Type on Phenol Uptake, pH 2



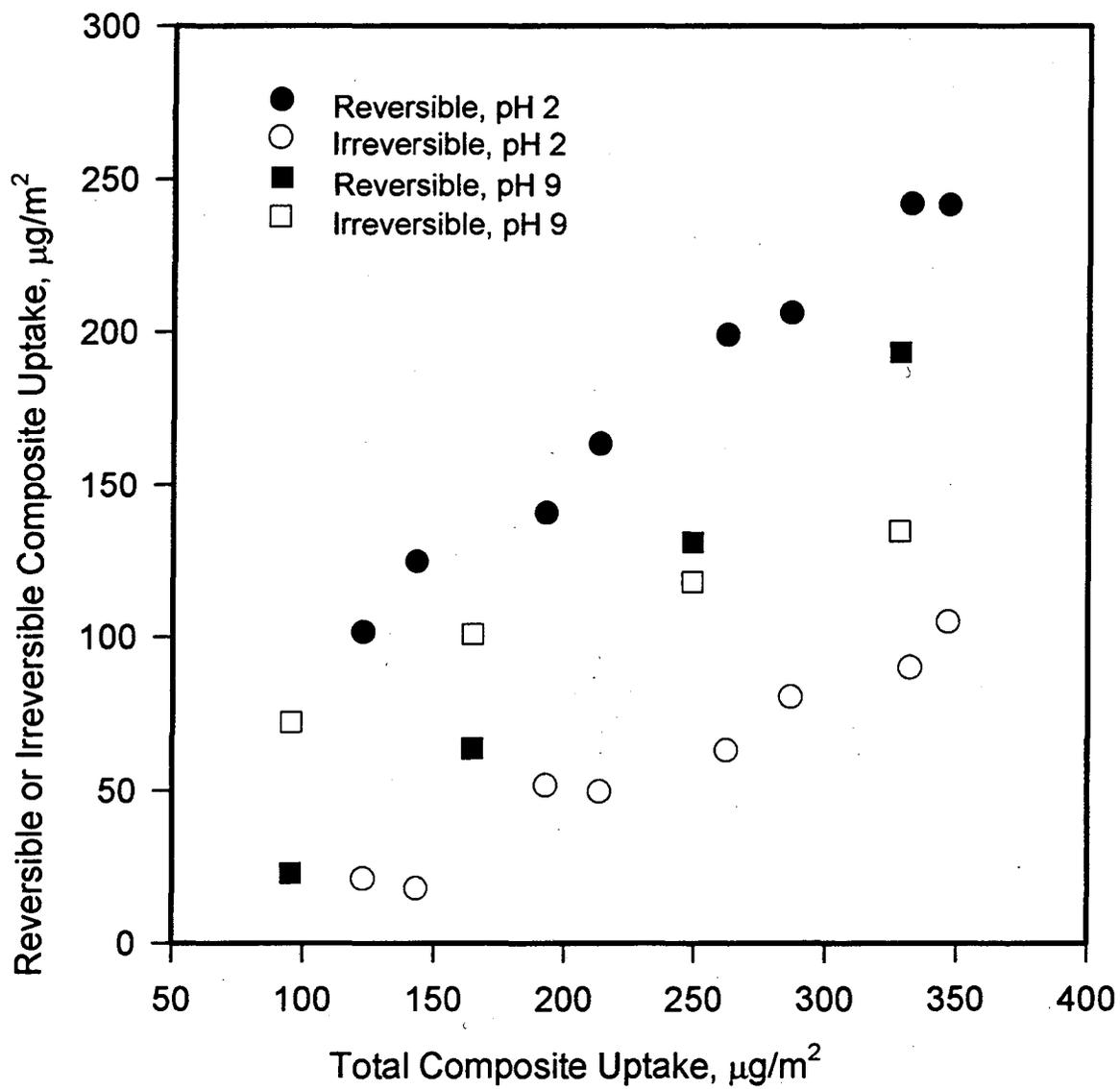
Effect of pH and HCl-Washing on Phenol Uptake by F400 Carbo



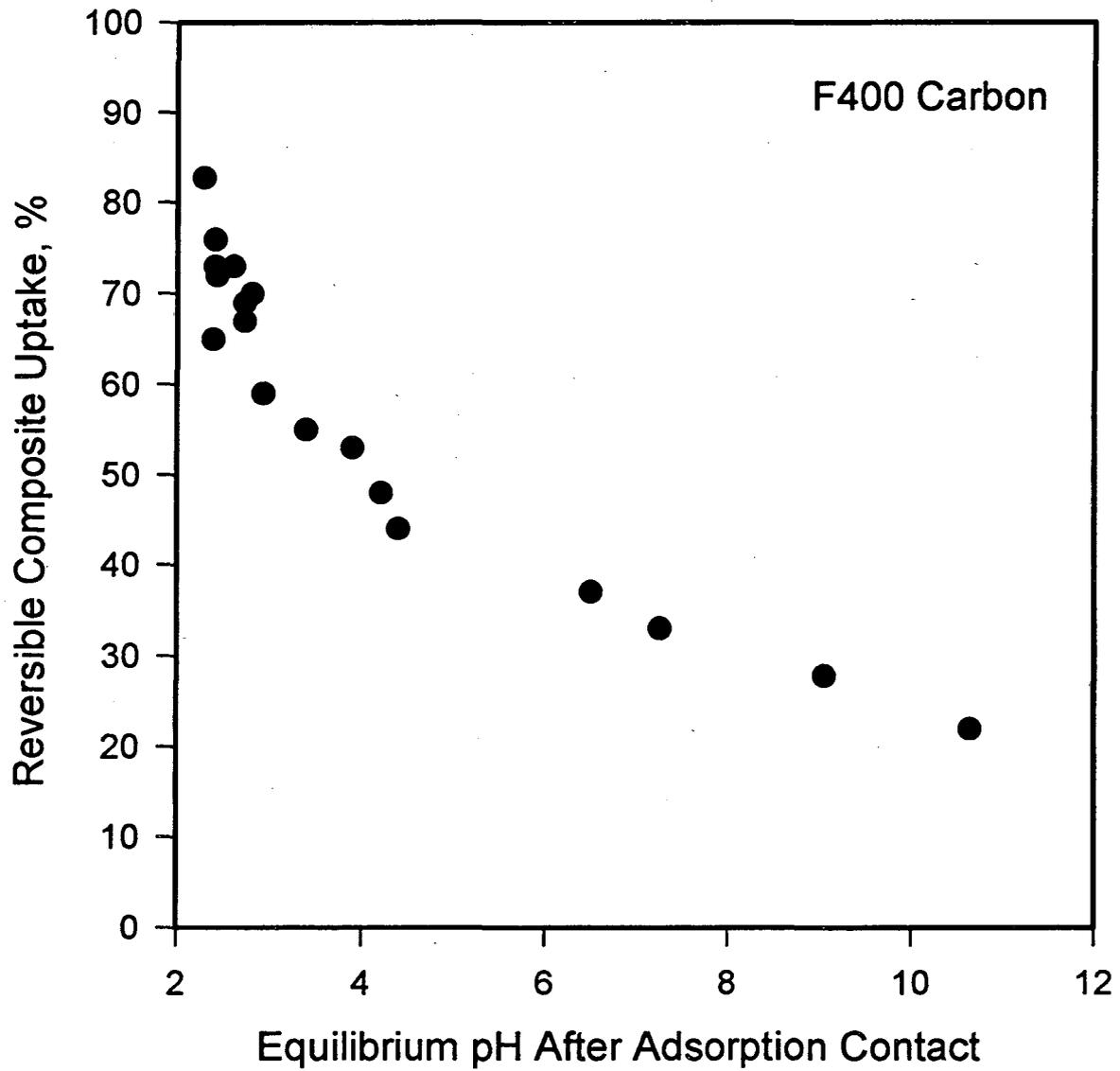
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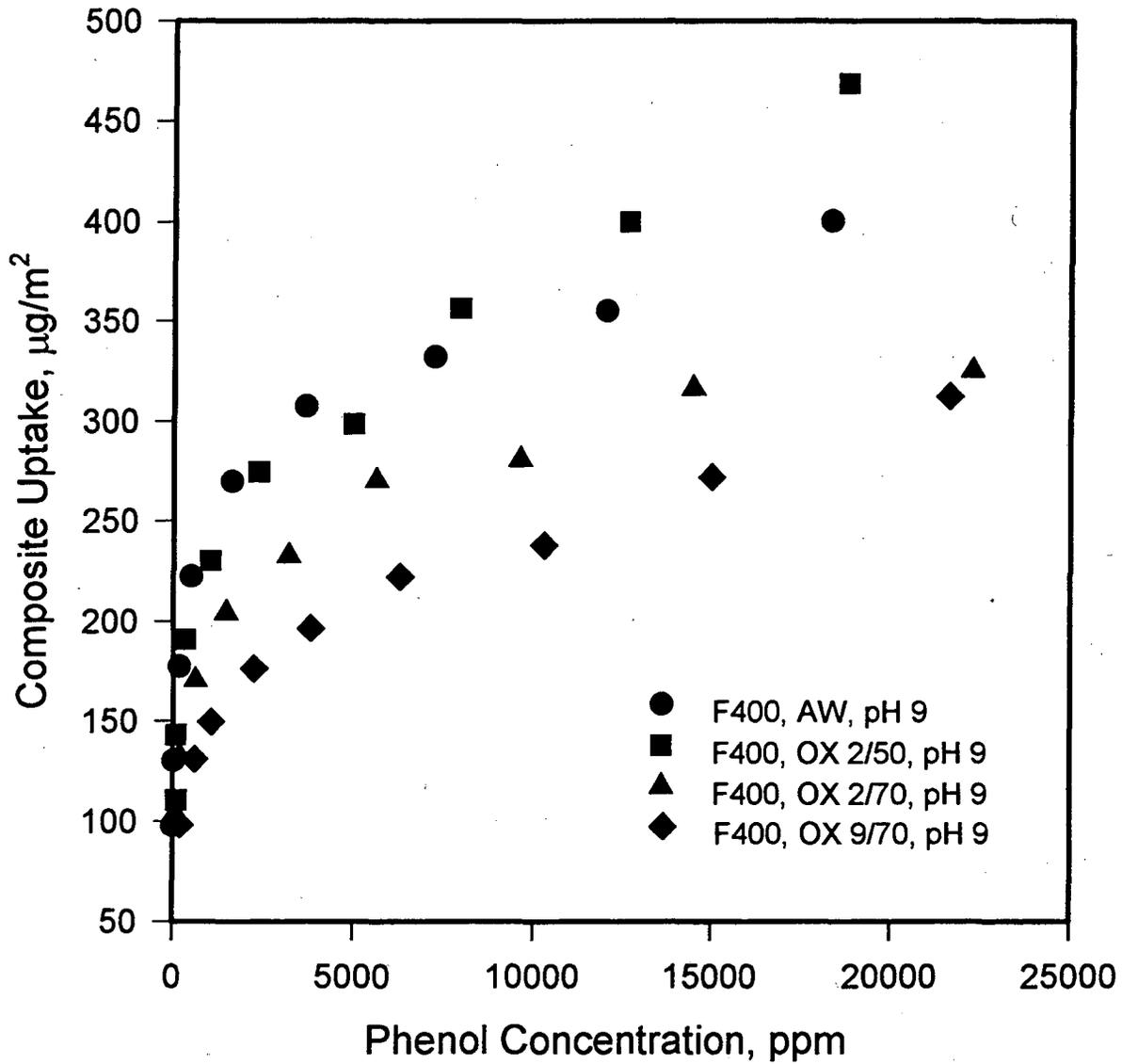
Effect of pH on Phenol Uptake by F400 Carbon



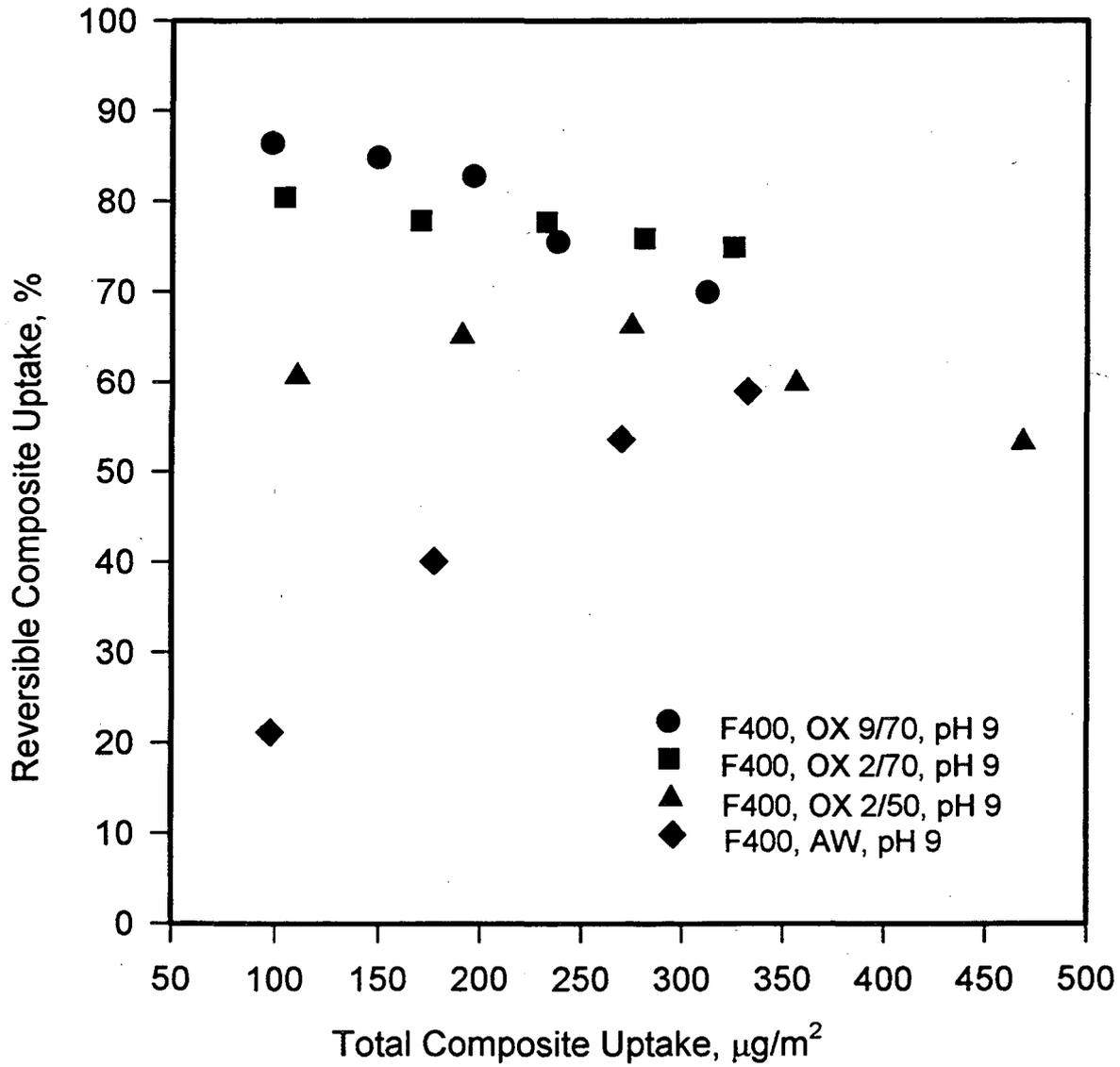
Effect of pH on Regeneration of Phenol



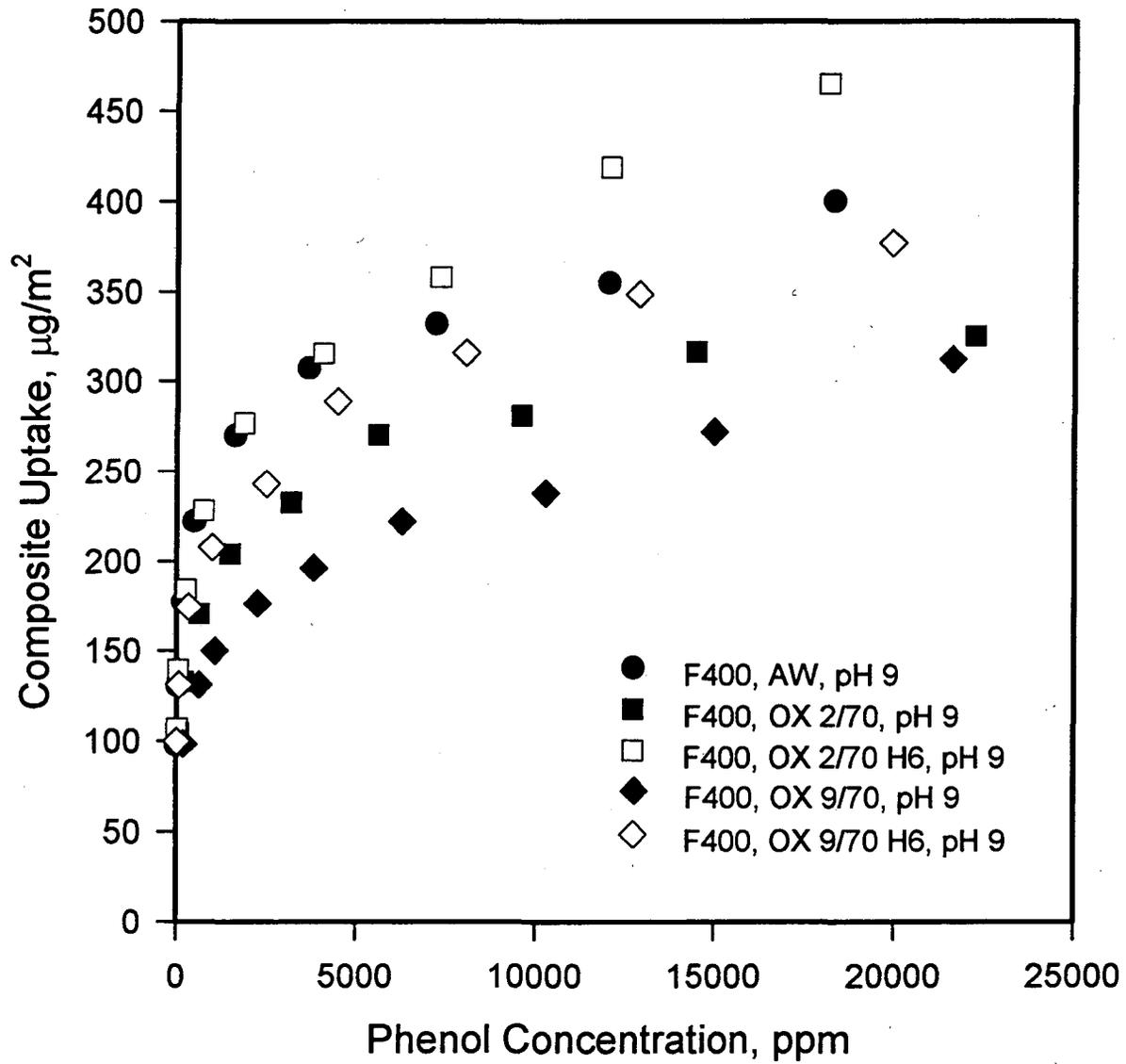
Effect of Surface Oxidation on Phenol Uptake



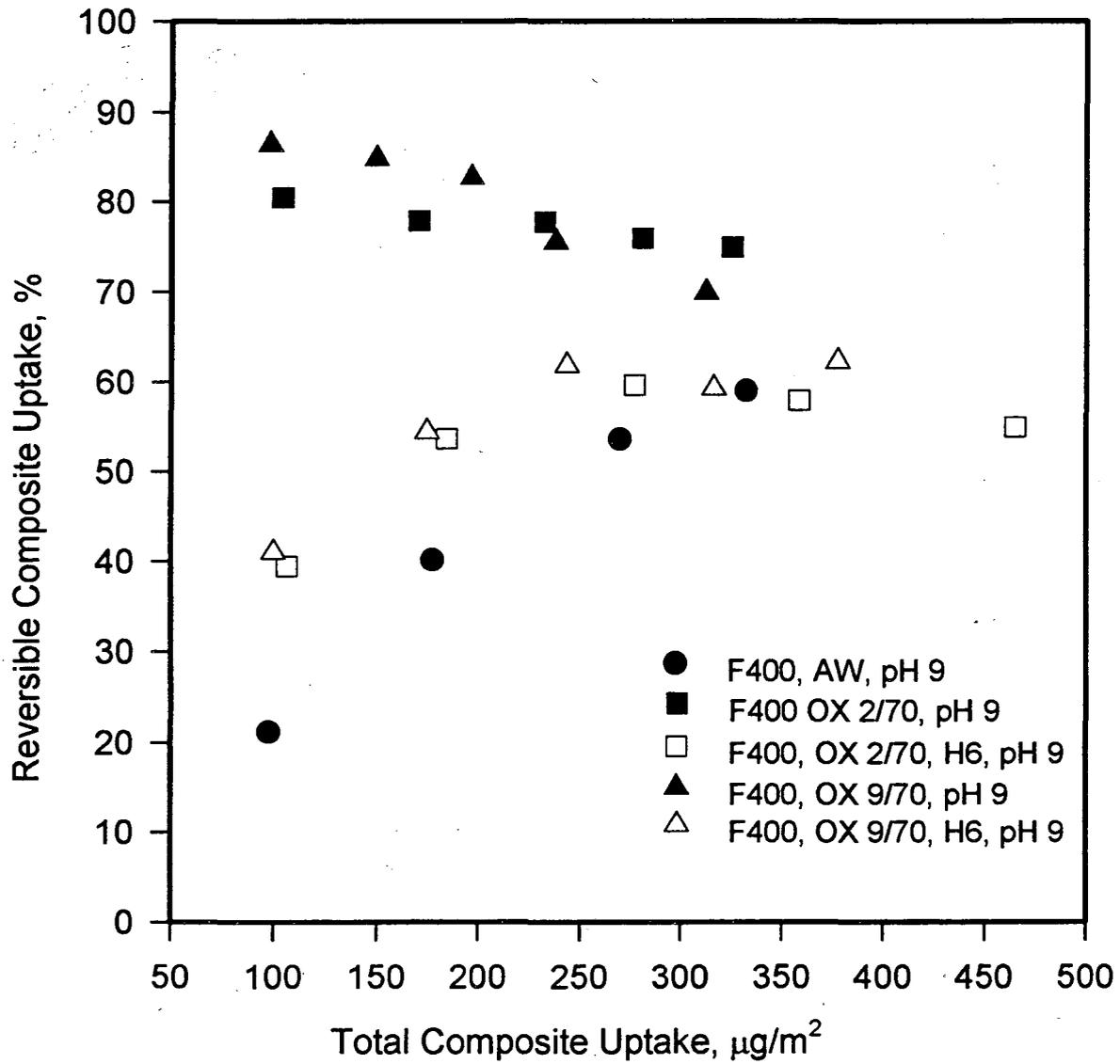
Effect of Surface Oxidation on Reversible Uptake of Phenol



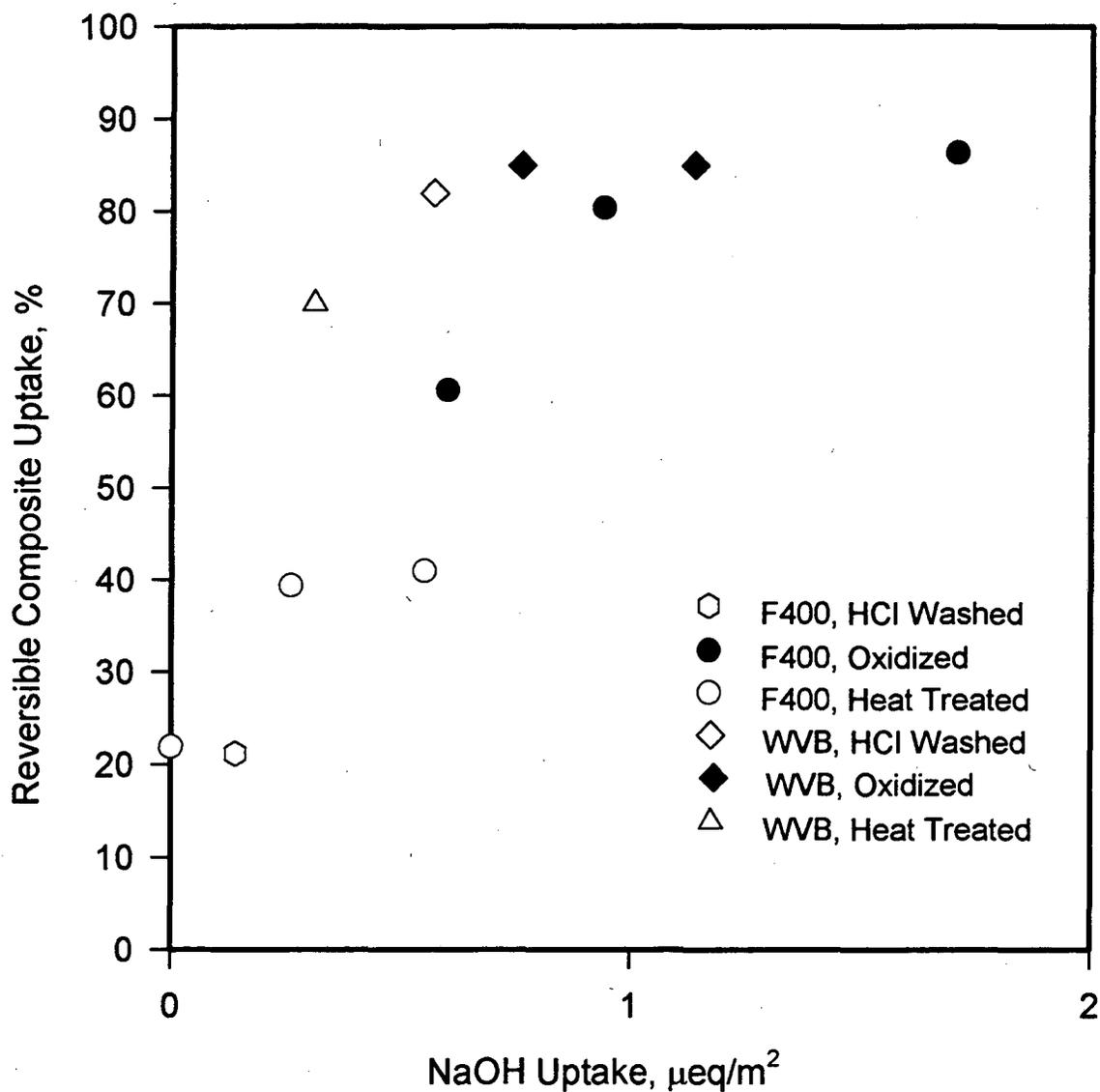
Effect of Surface Oxidation and Heat Treatment on Phenol Uptake



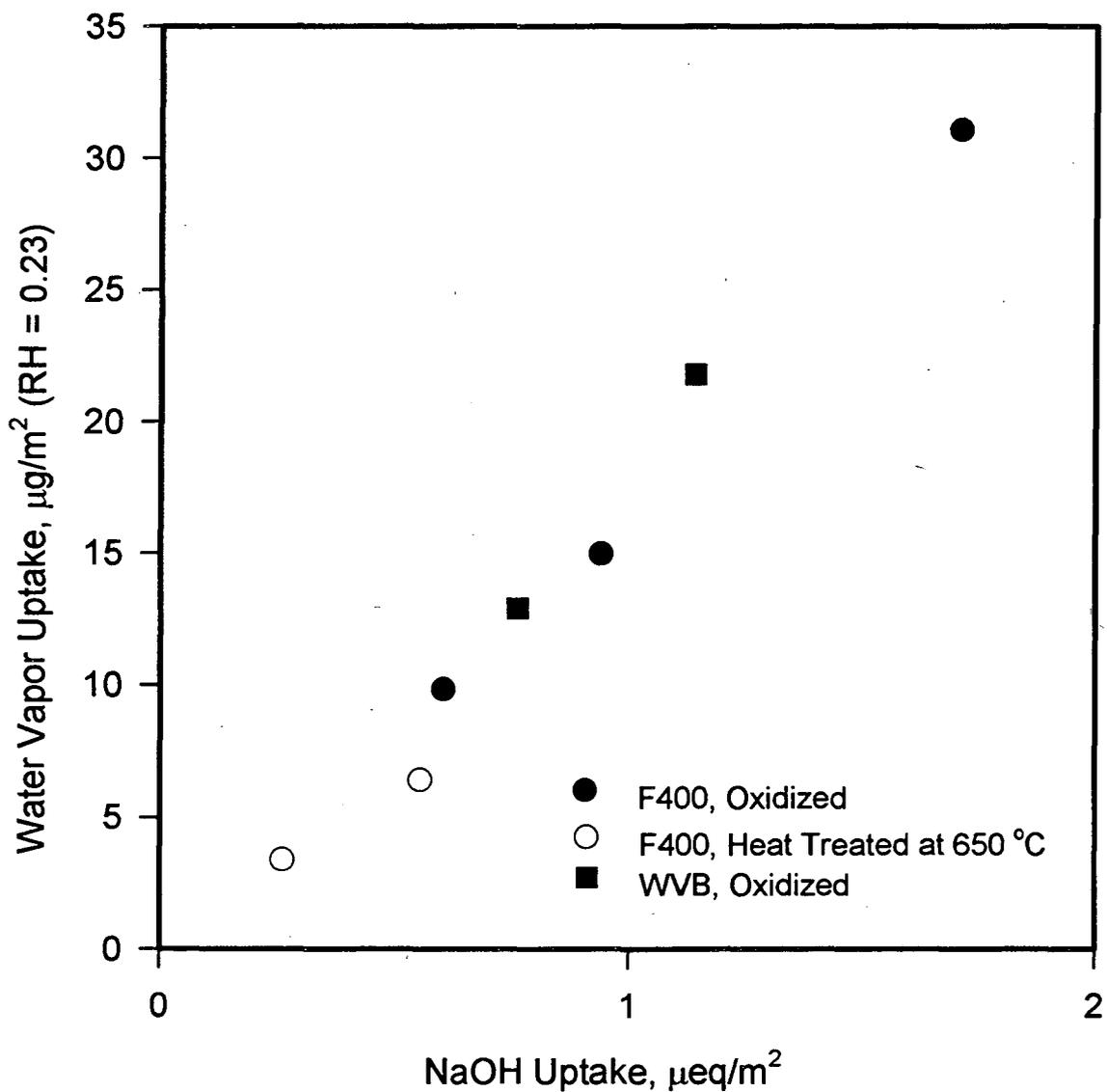
Effect of Surface Oxidation and Heat Treatment on Reversible Uptake of Phenol



Effect of Surface Treatment on Reversible Adsorption



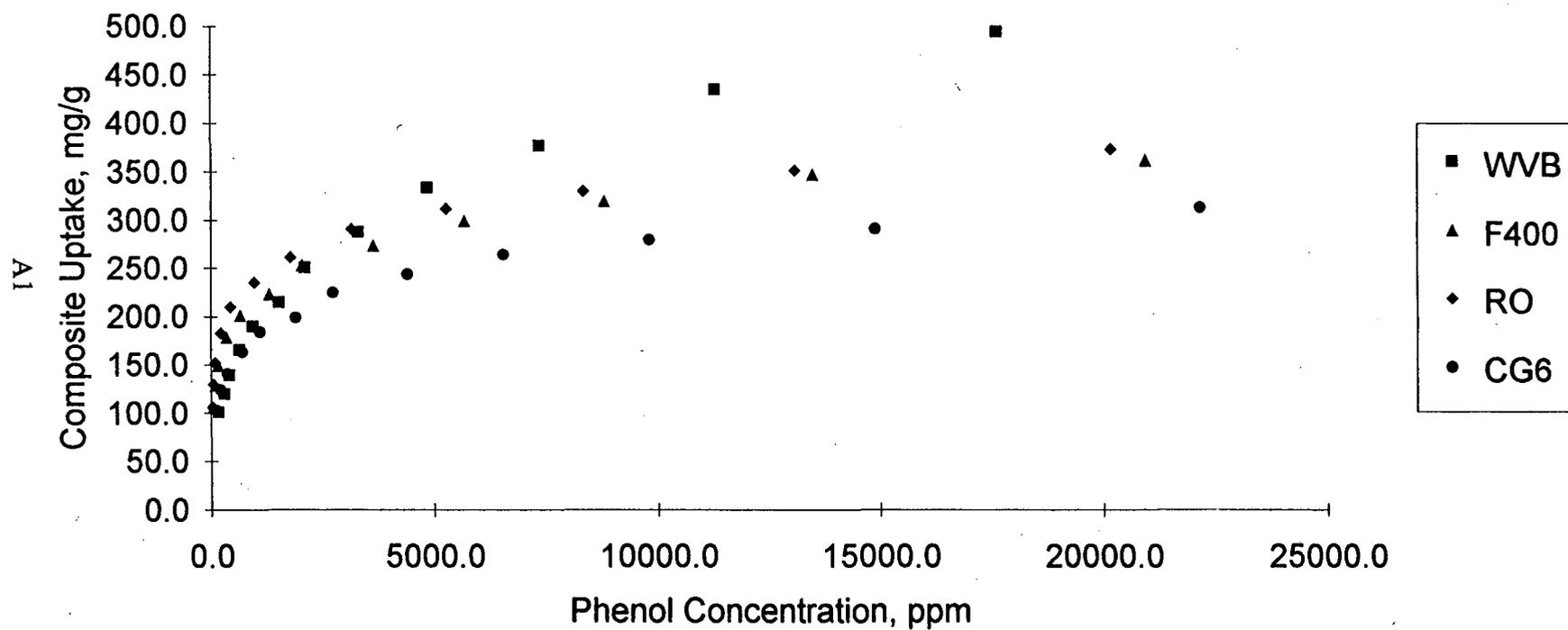
Effect of Surface Treatment on Water Vapor Uptake



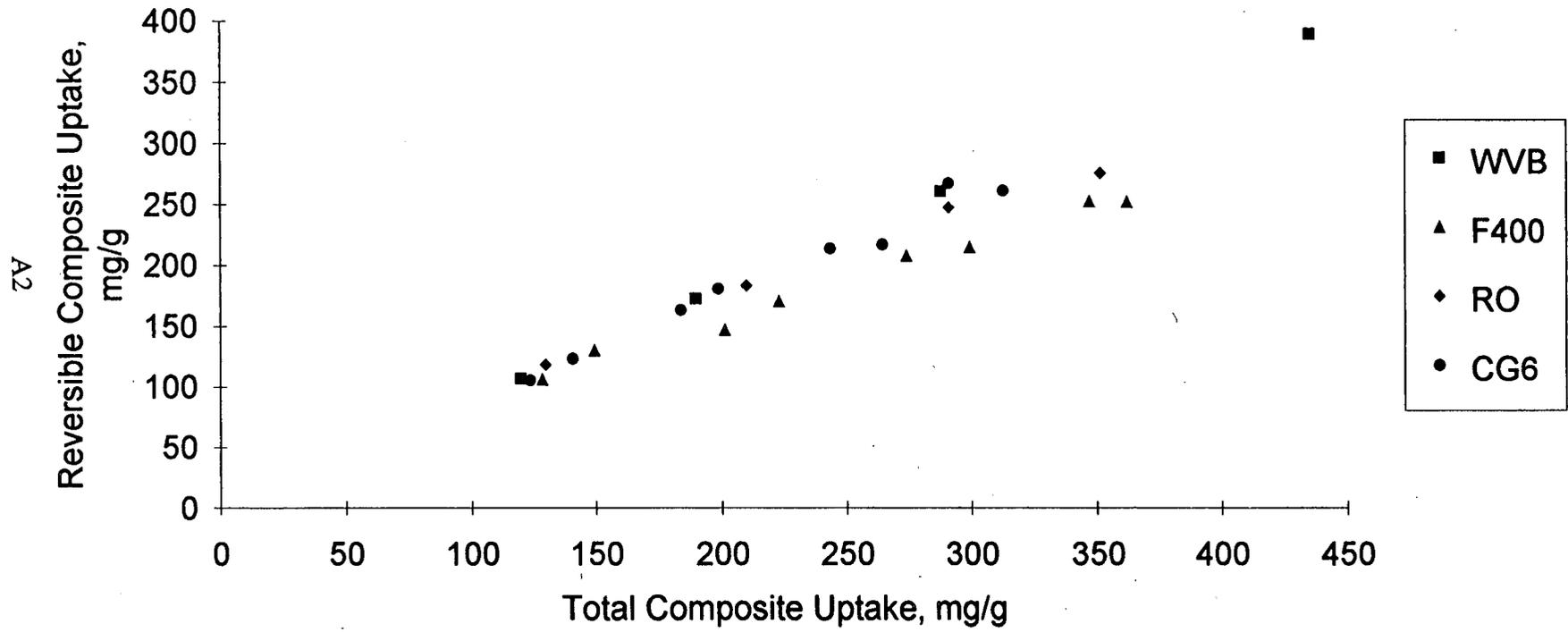
APPENDIX

Additional Figures	A1-A36
Isotherm Data	A37-A41
Regeneration Data	A42-A45
Water Uptake Data	A46
Ambersorb Literature	A47
Mass spectrometry results	A48-A52

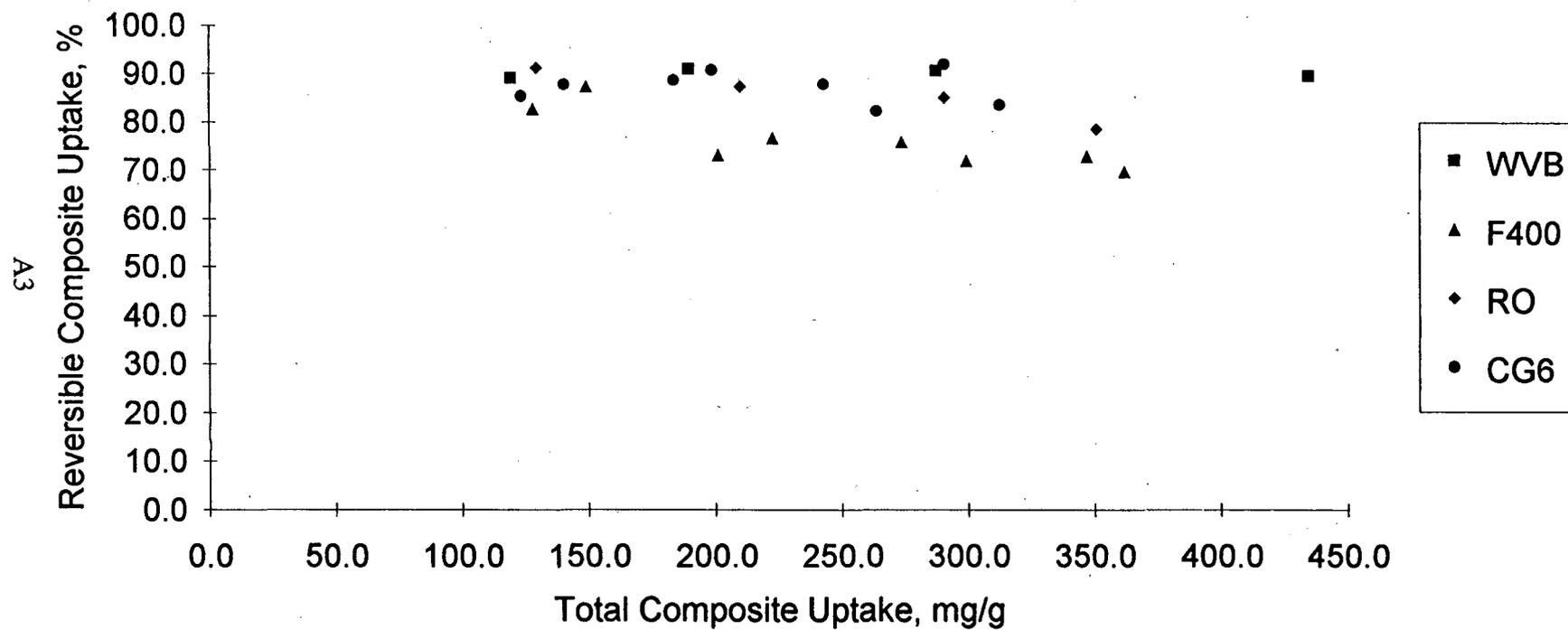
Effect of Carbon Type on Phenol Uptake, pH 2



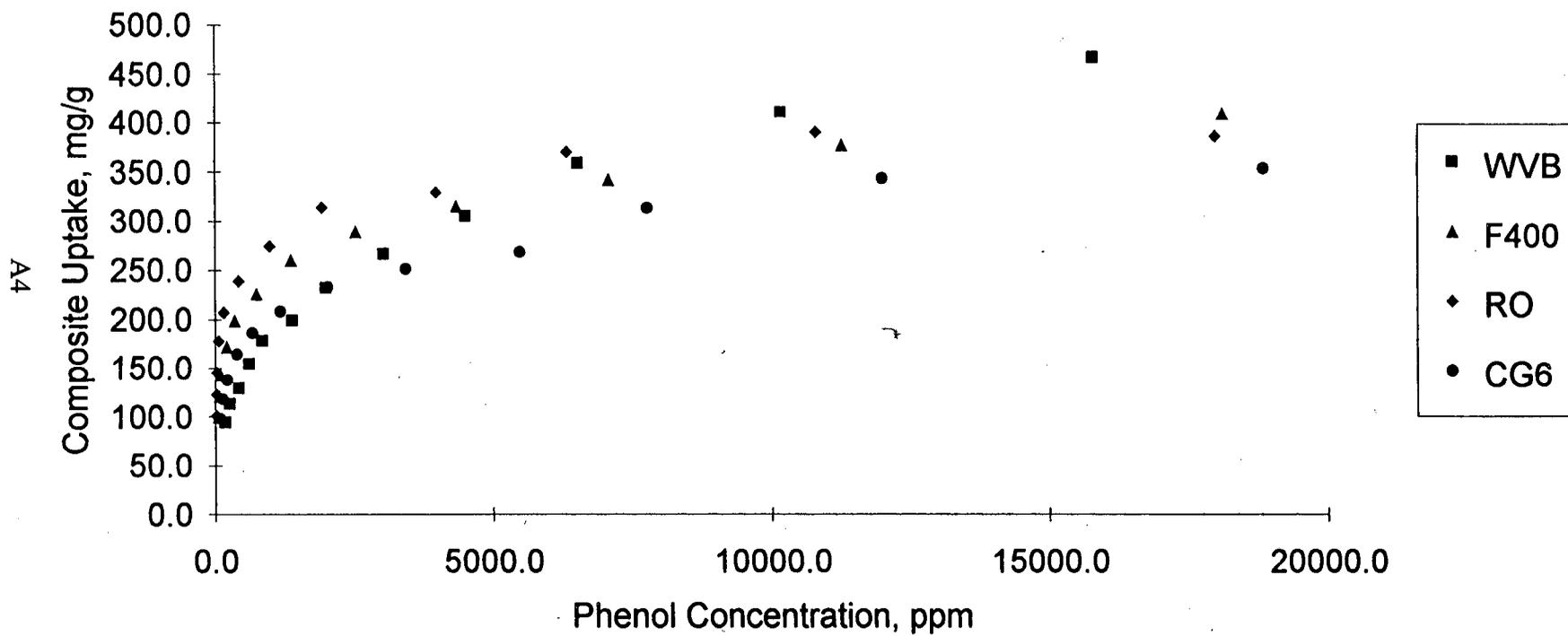
Effect of Carbon Type on Reversible Phenol Uptake, pH 2



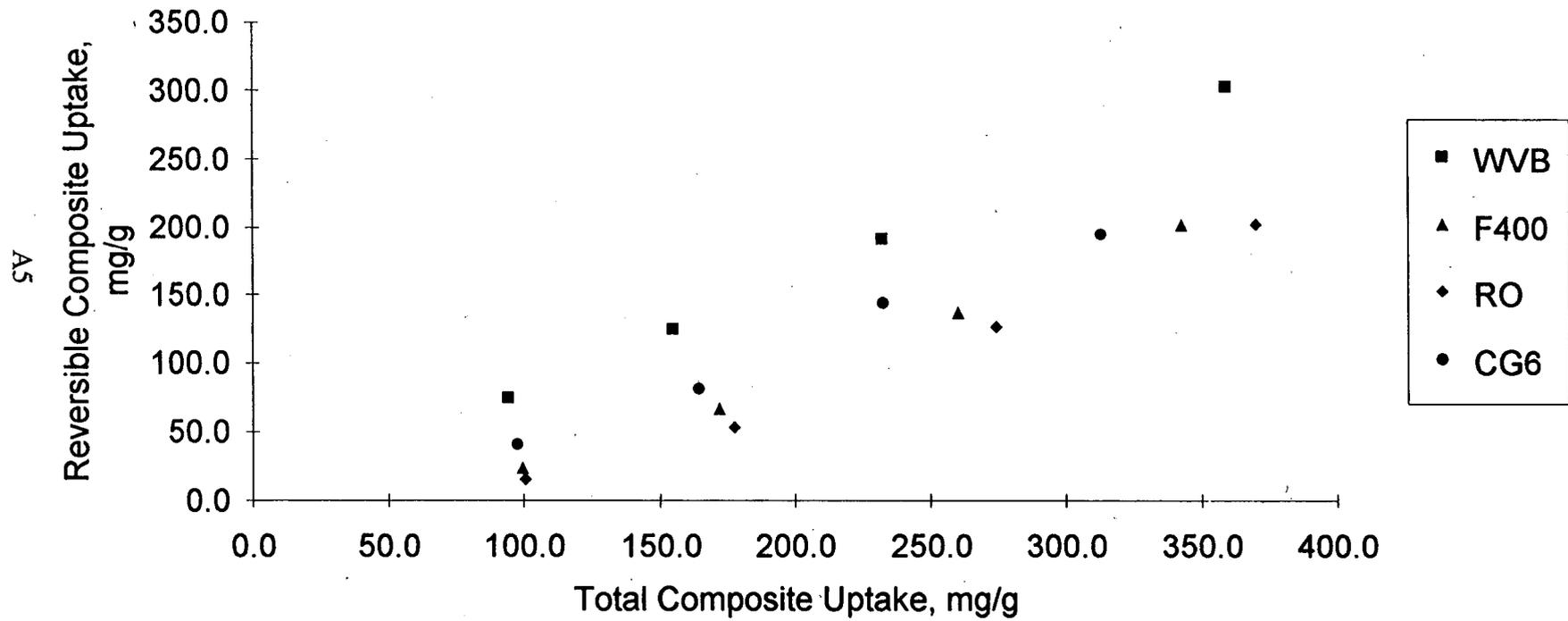
Effect of Carbon Type on Reversible Phenol Uptake, pH 2



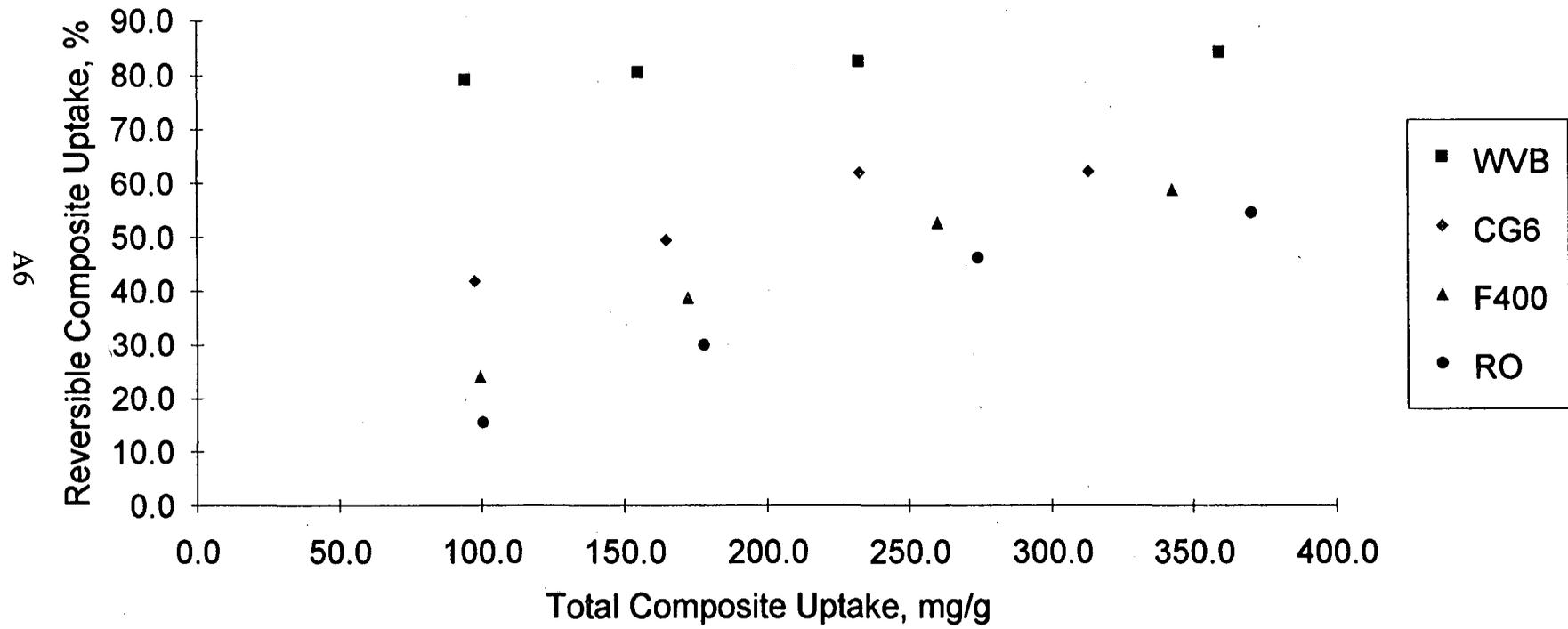
Effect of Carbon Type on Phenol Uptake, pH 9



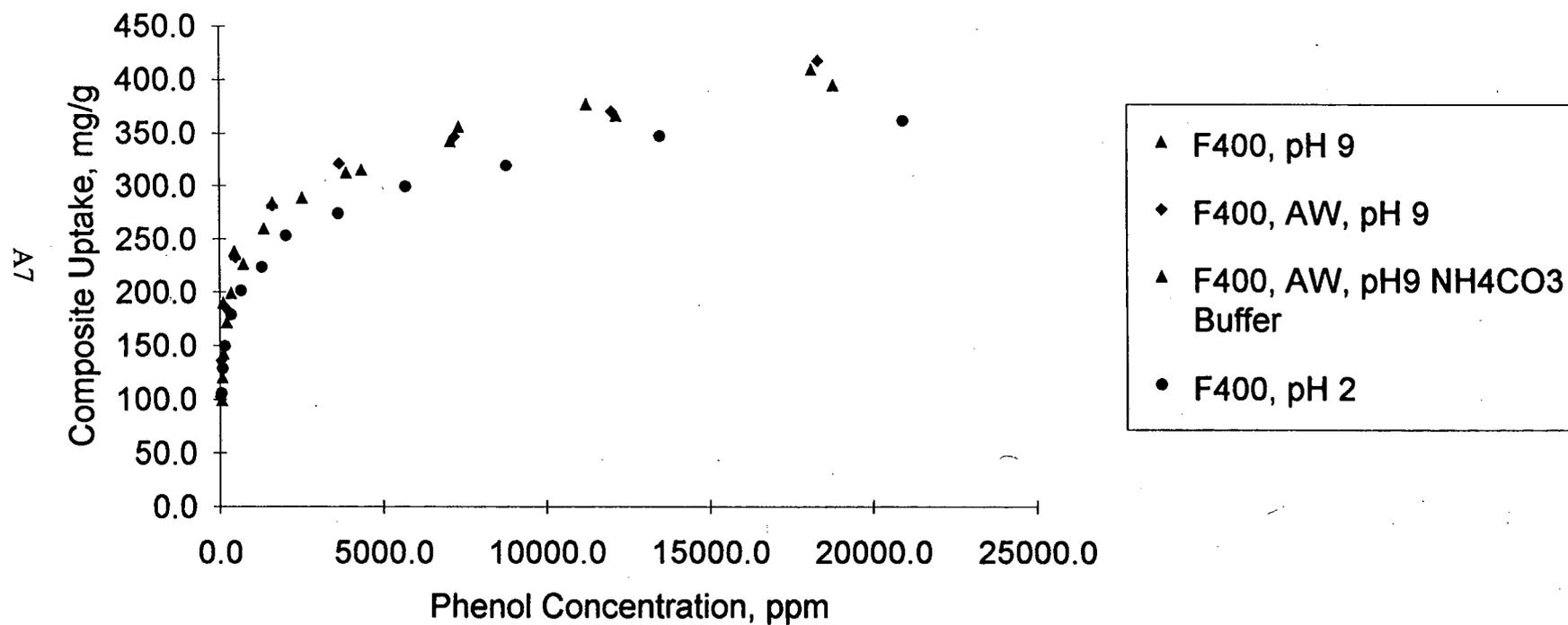
Effect of Carbon Type on Reversible Phenol Uptake, pH 9



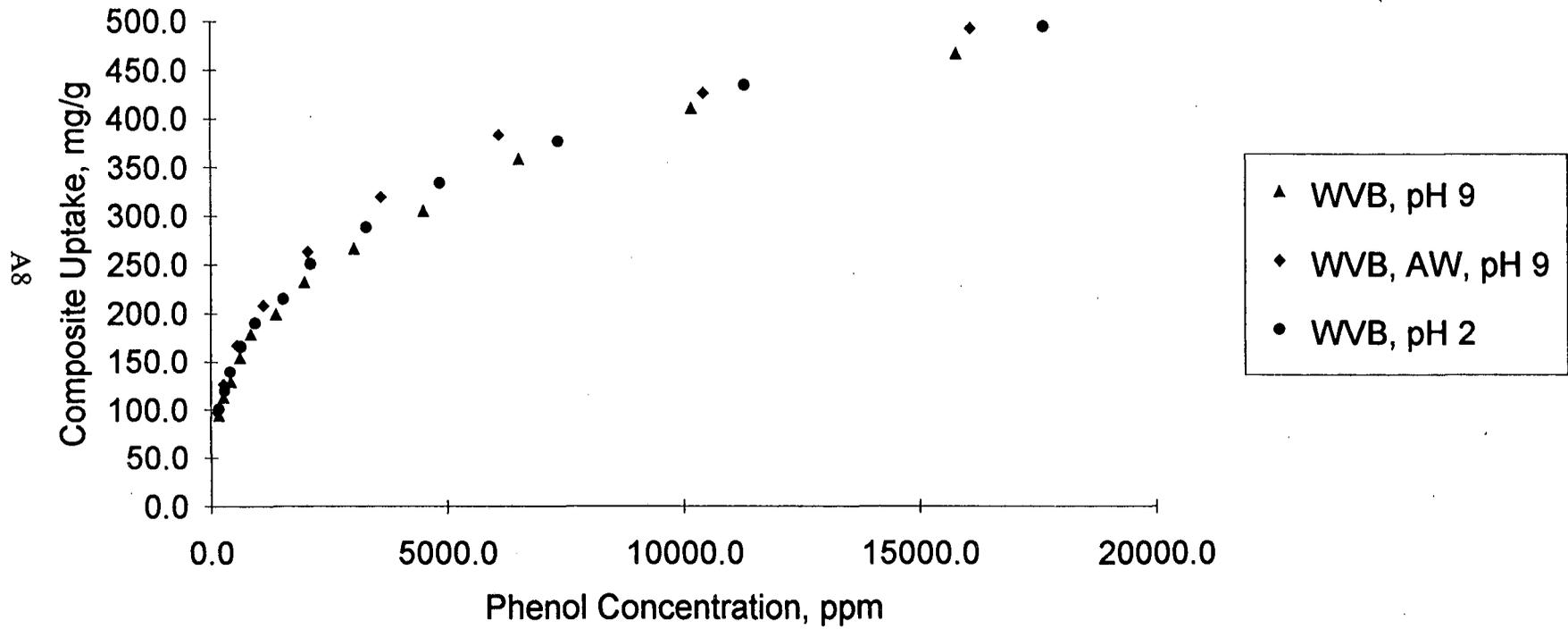
Effect of Carbon Type on Reversible Phenol Uptake, pH 9



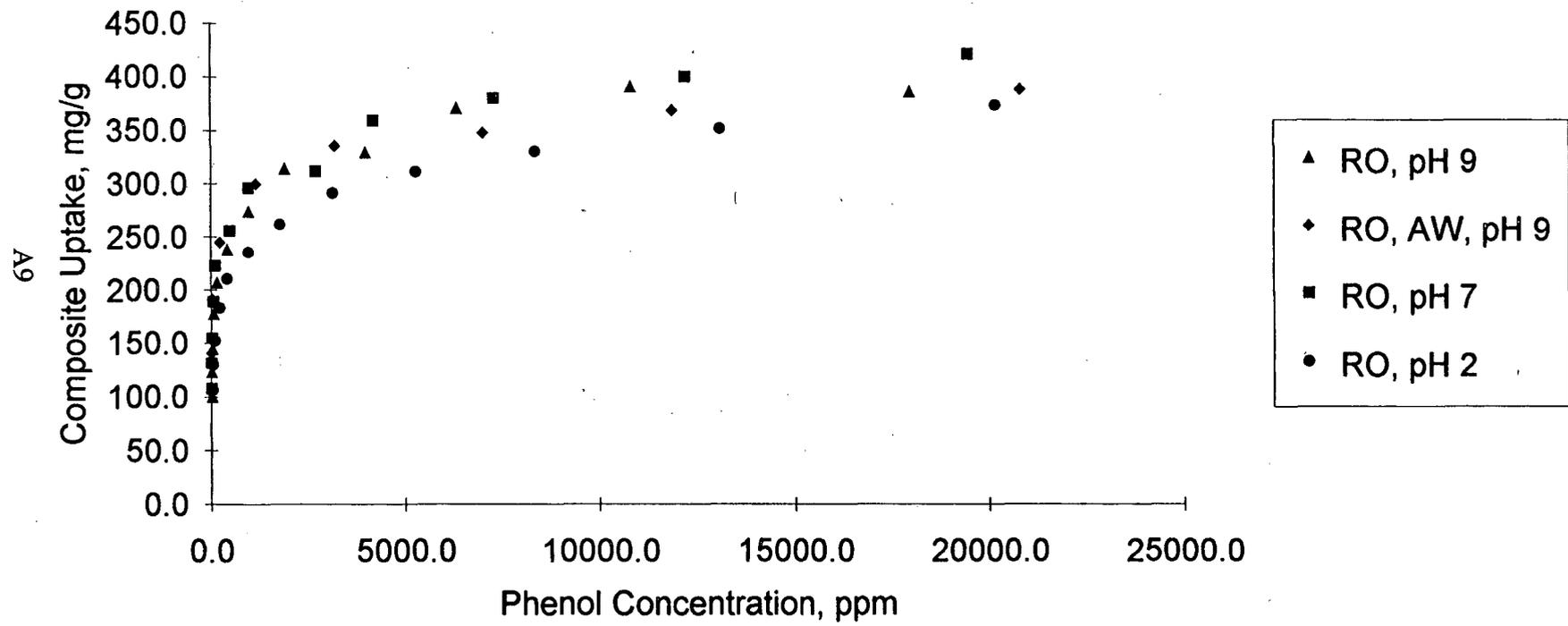
Effect of pH and Acid-Washing on Phenol Uptake by F400 Carbon



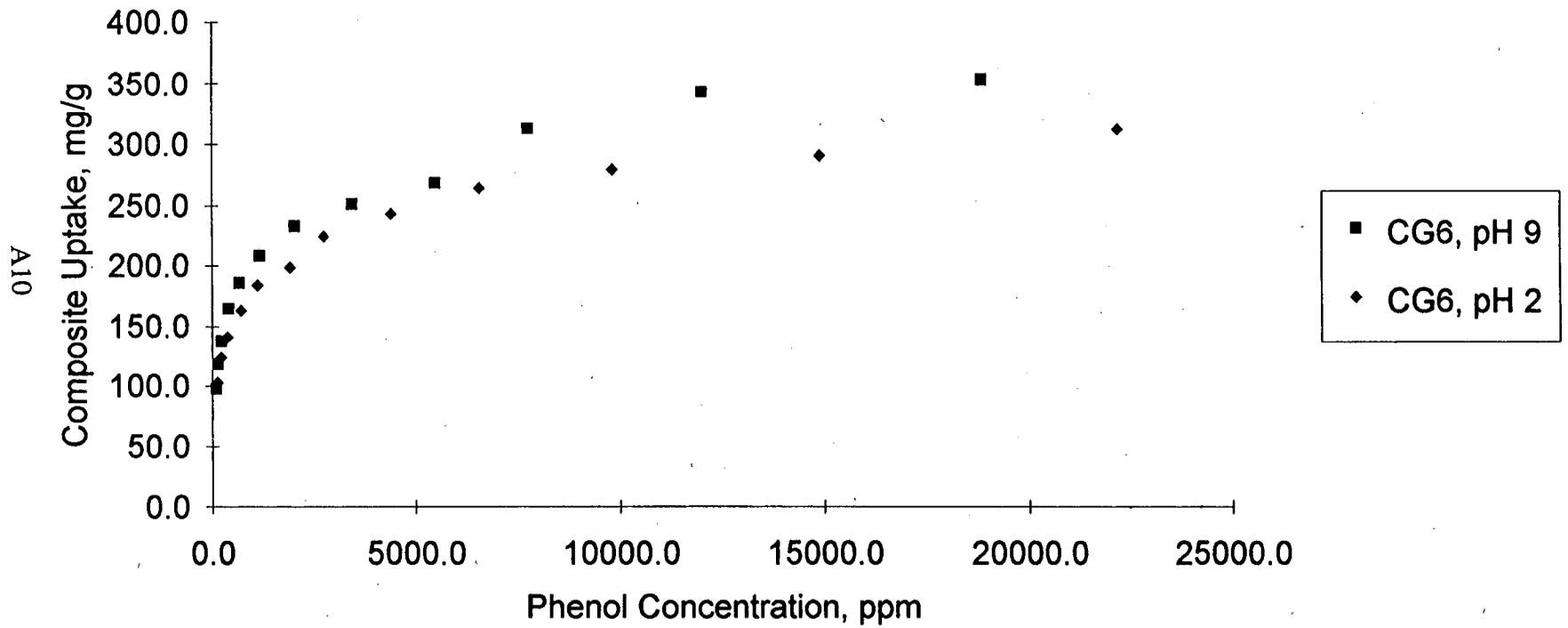
Effect of pH and Acid-Washing on Phenol Uptake by WVB Carbon



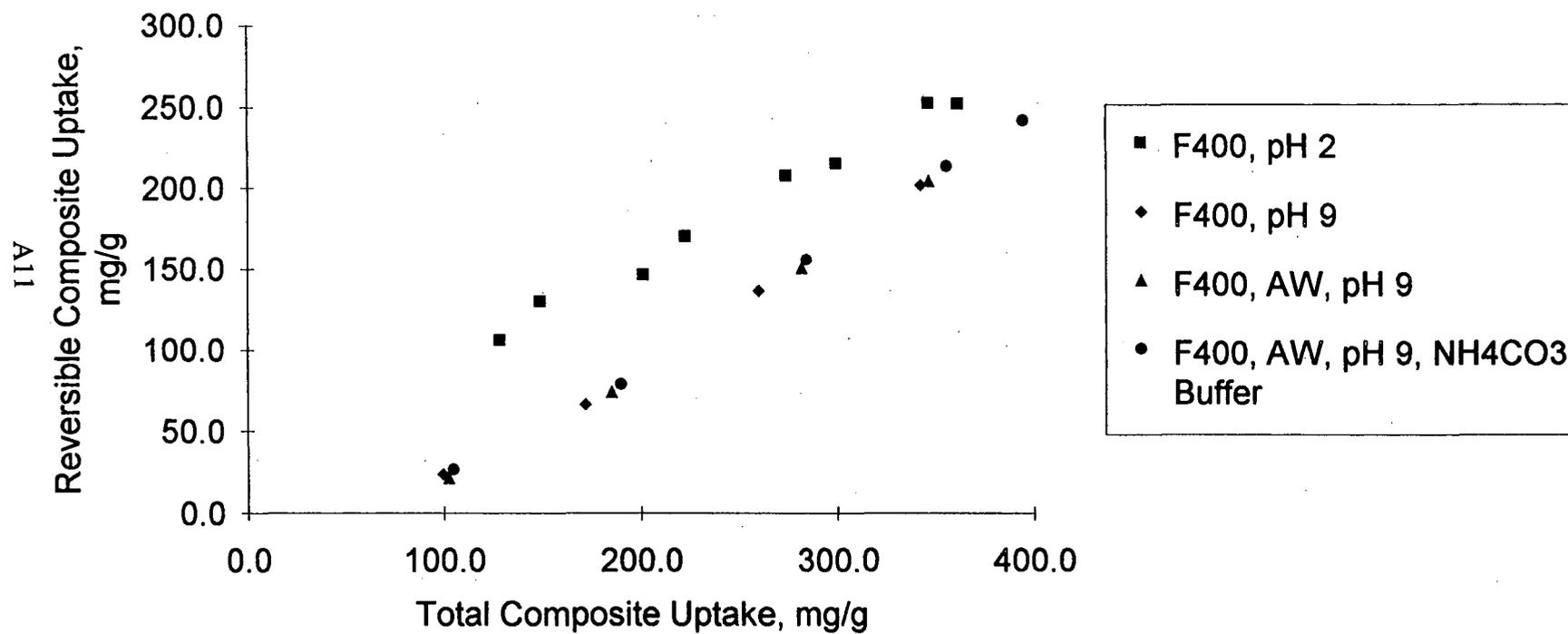
Effect of pH and Acid-Washing on Phenol Uptake by RO Carbon



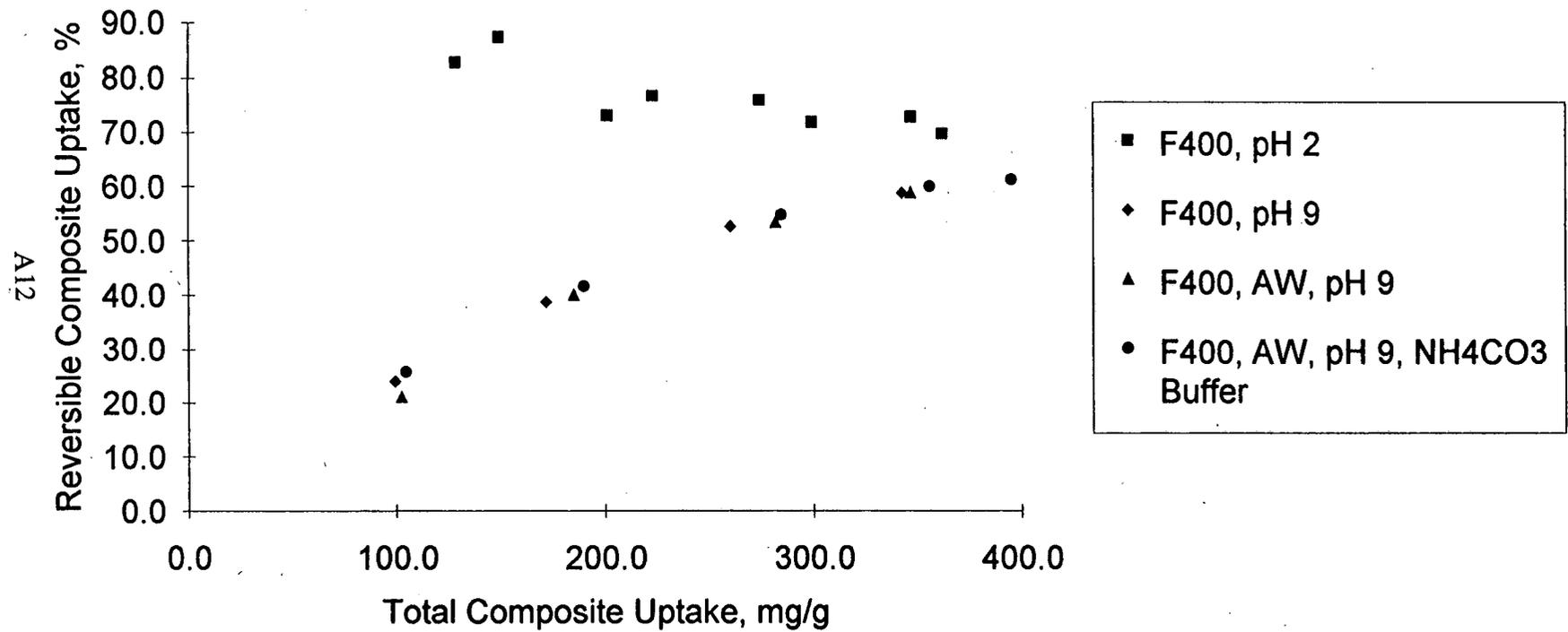
Effect of pH on Phenol Uptake by CG6 Carbon



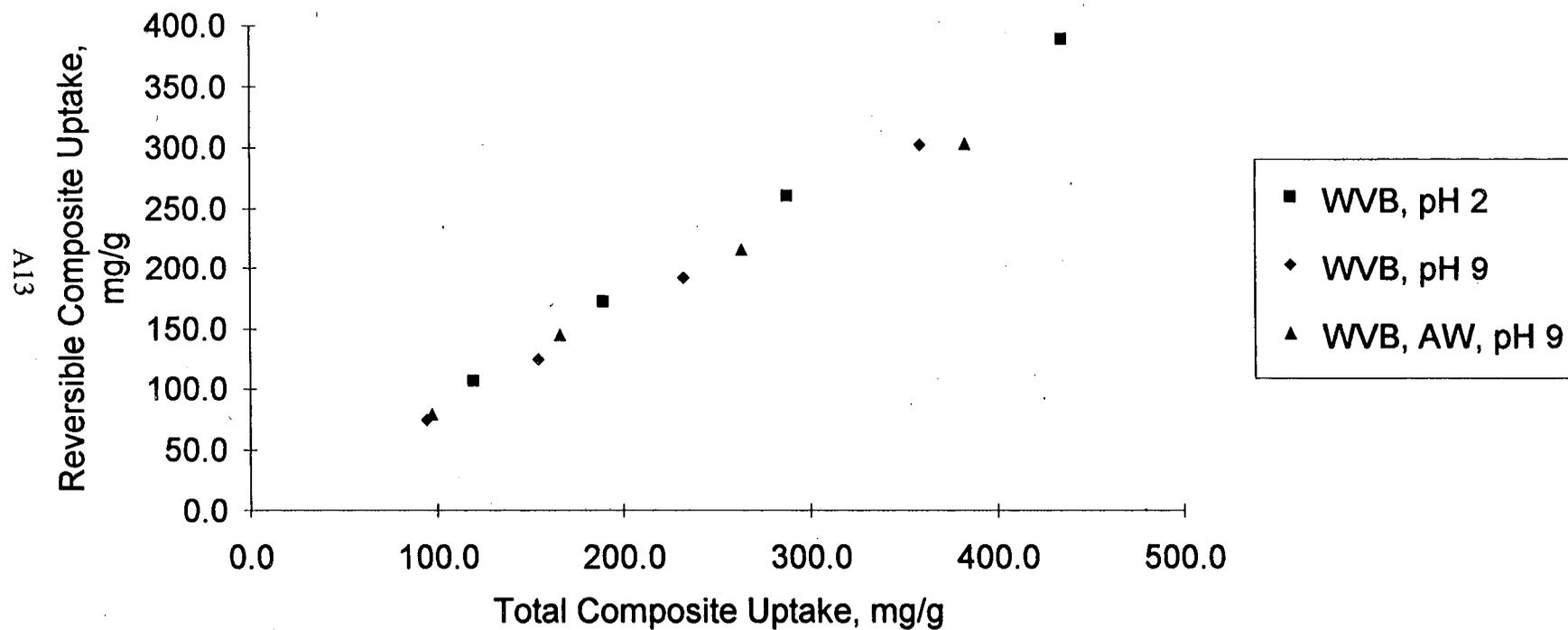
Effect of pH and Acid-Washing on Reversible Phenol Uptake by F400 Carbon



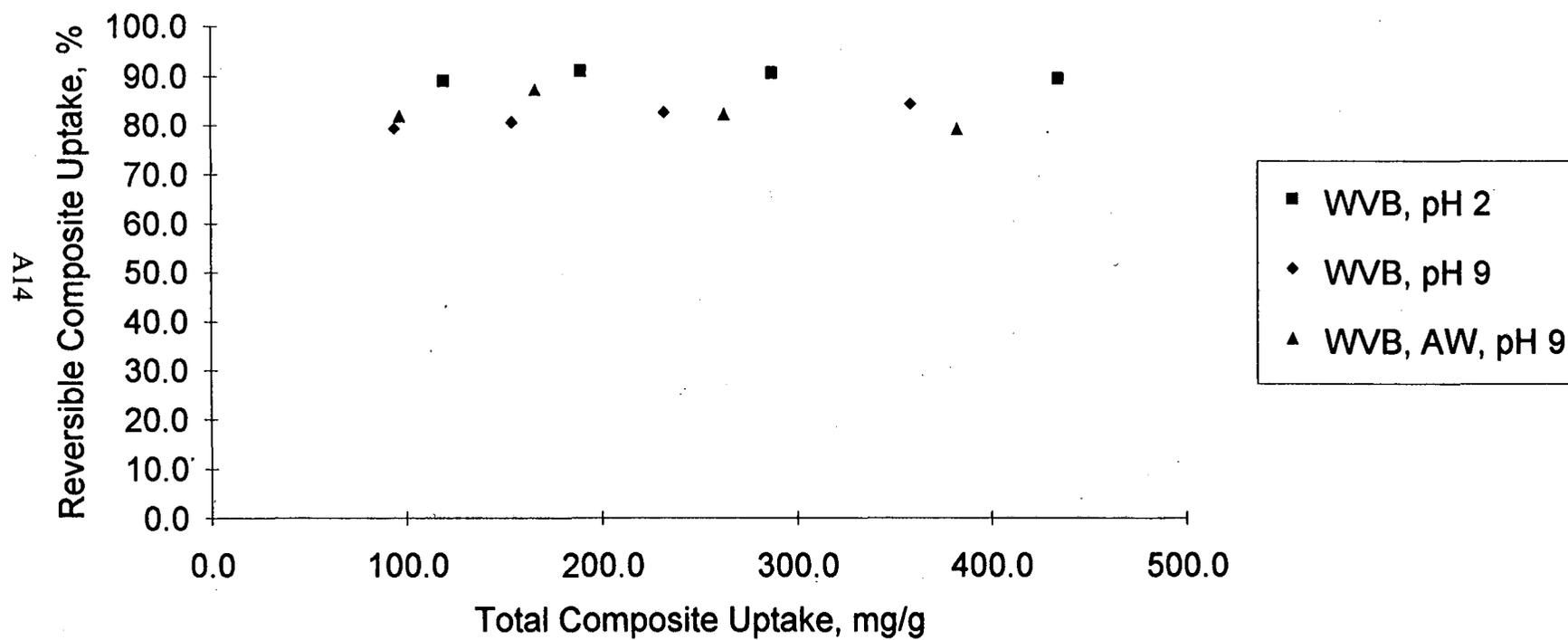
Effect of pH and Acid-Washing on Reversible Phenol Uptake by F400 Carbon



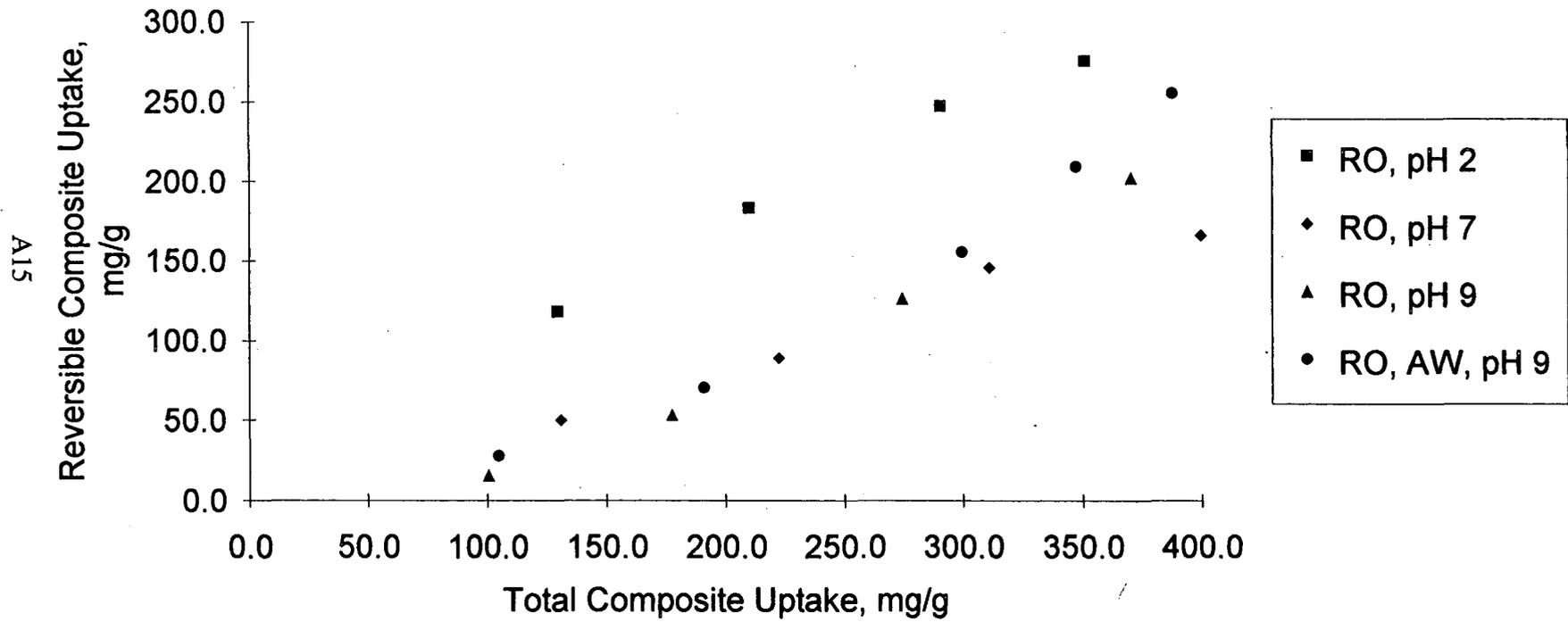
Effect of pH and Acid-Washing on Reversible Phenol Uptake by WVB Carbon



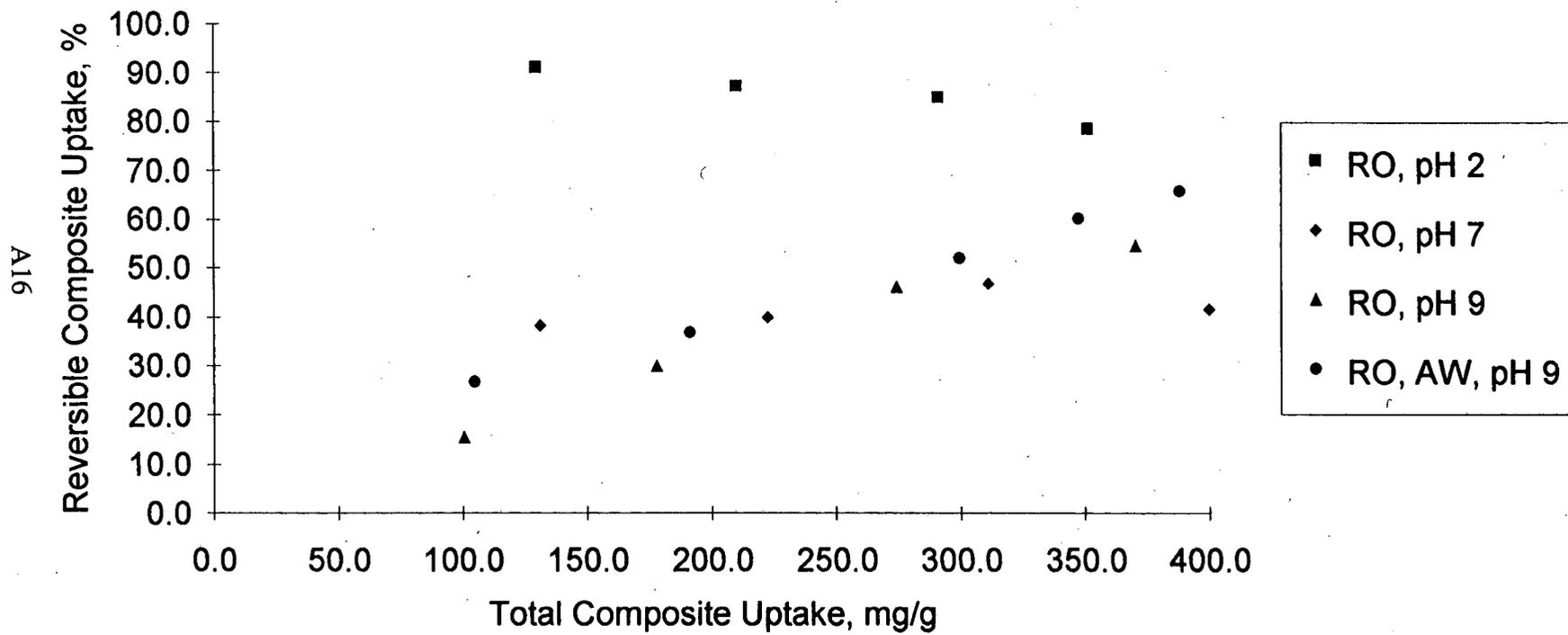
Effect of pH and Acid-Washing on Reversible Phenol Uptake by WVB Carbon



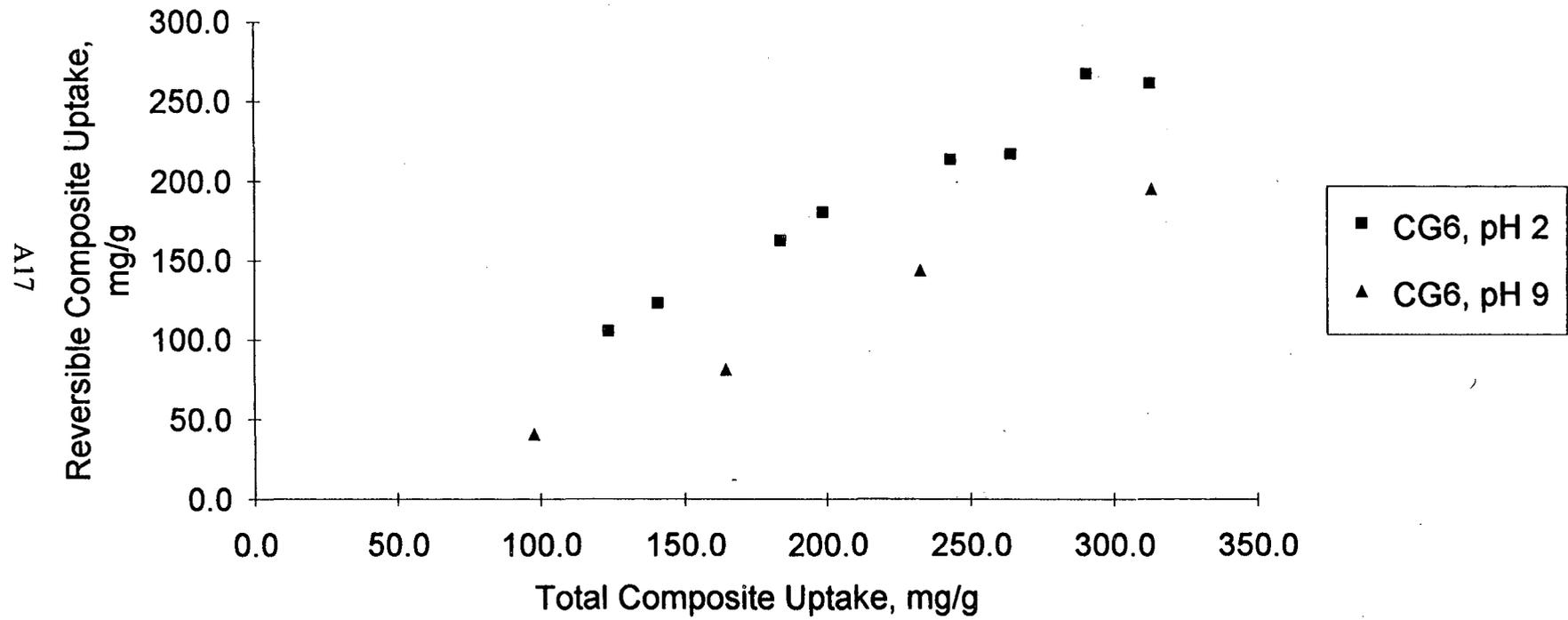
Effect of pH and Acid-Washing on Reversible Phenol Uptake by RO Carbon



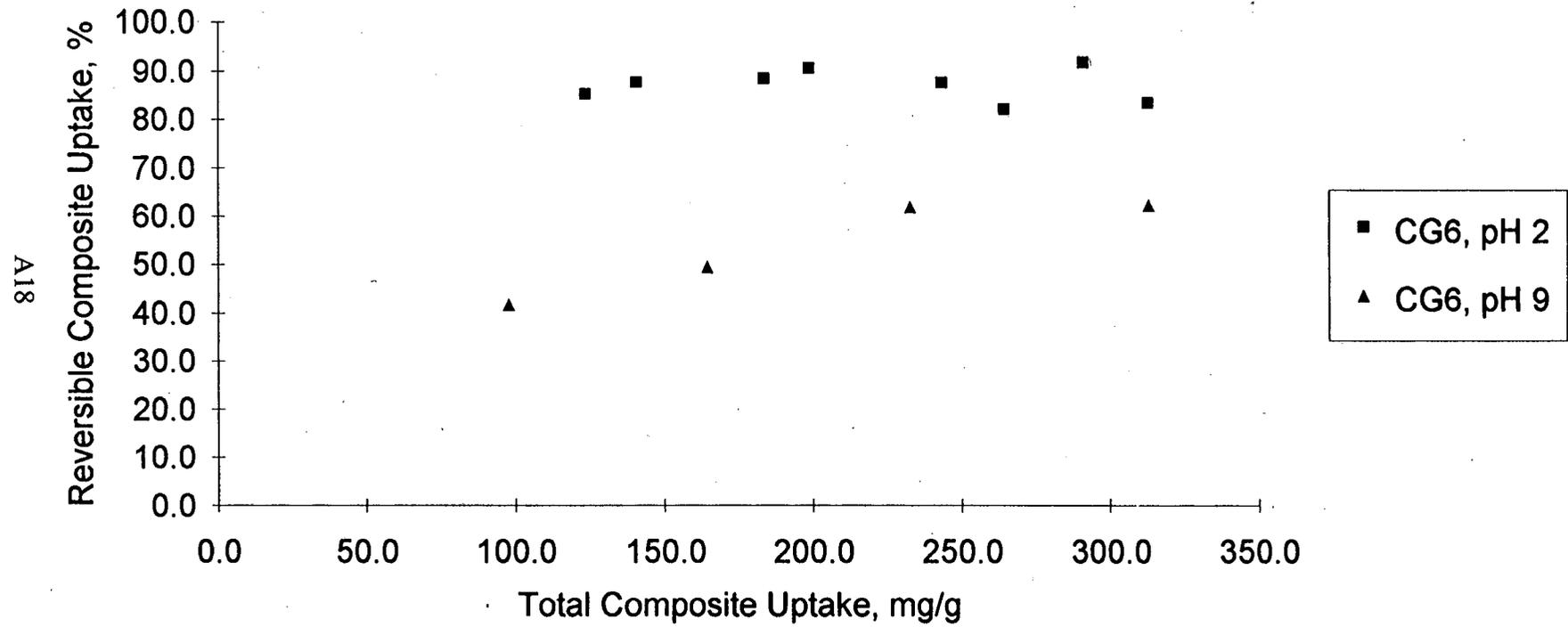
Effect of pH and Acid-Washing on Reversible Phenol Uptake by RO Carbon



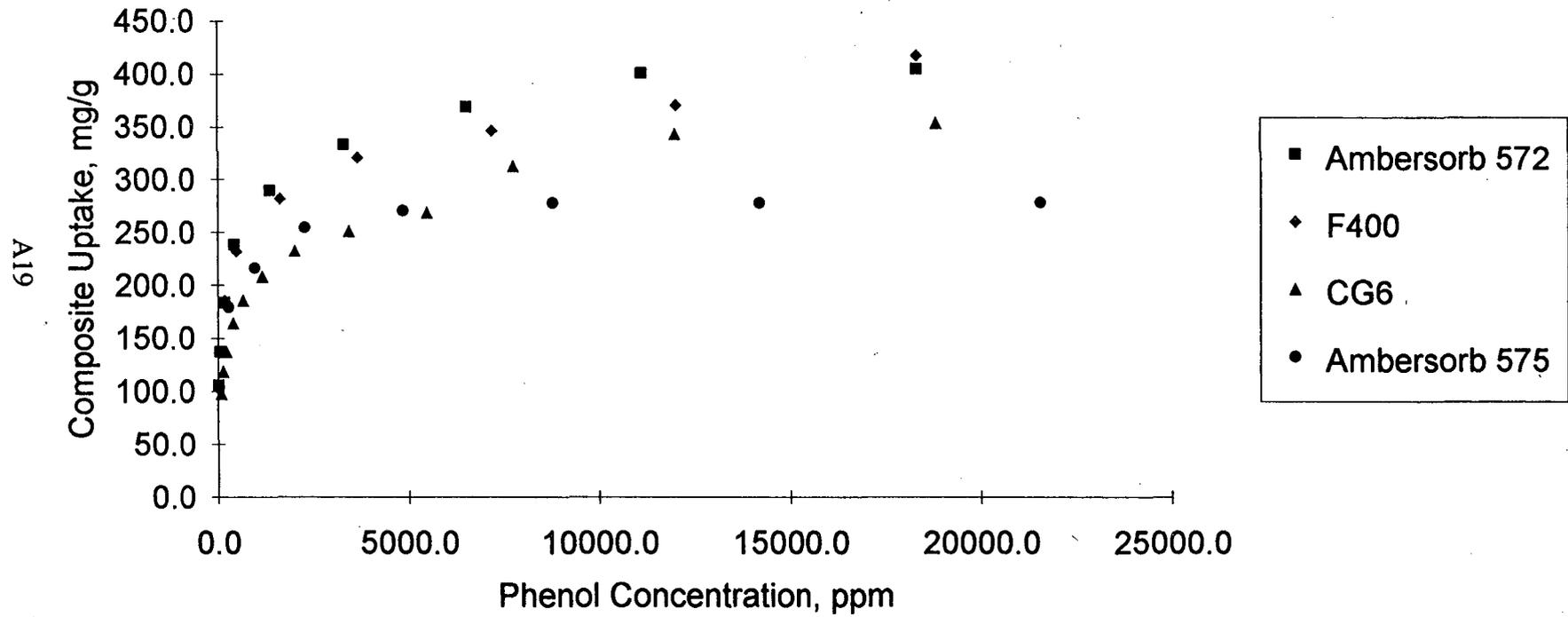
Effect of pH on Reversible Phenol Uptake by CG6 Carbon



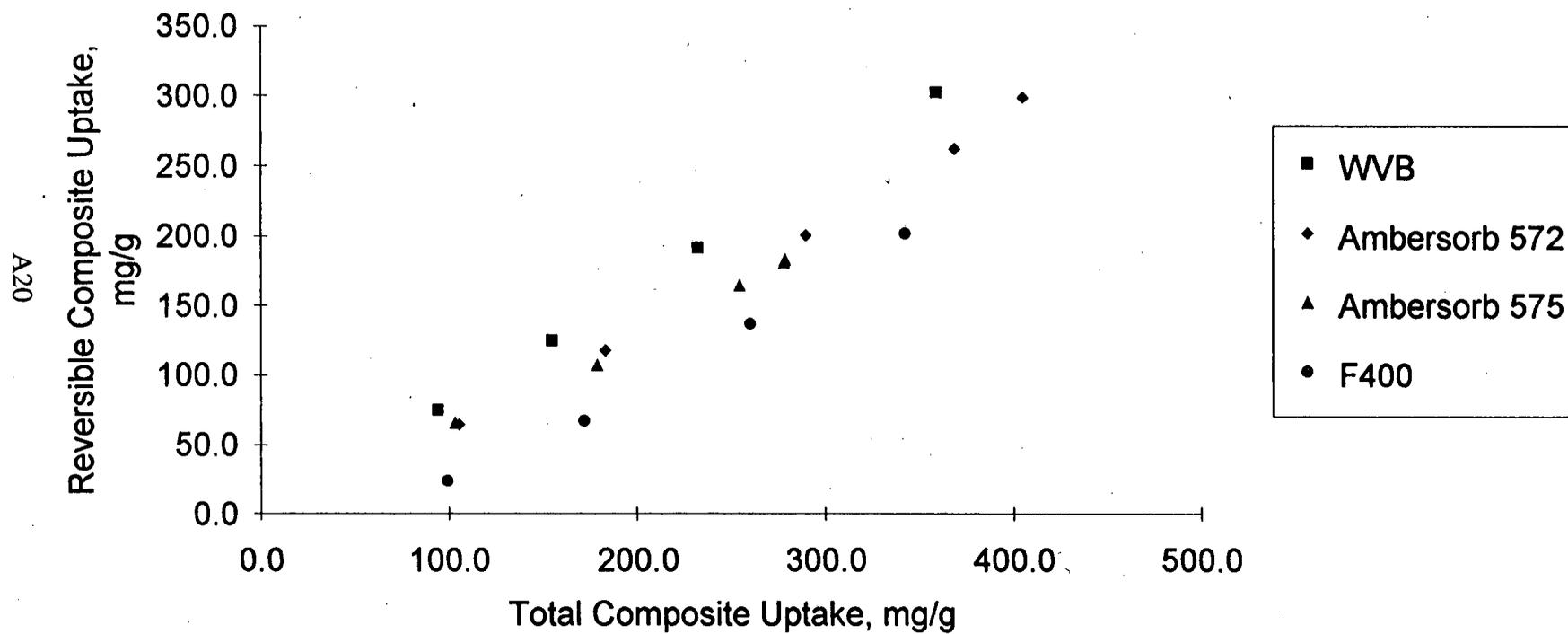
Effect of pH on Reversible Phenol Uptake by CG6 Carbon



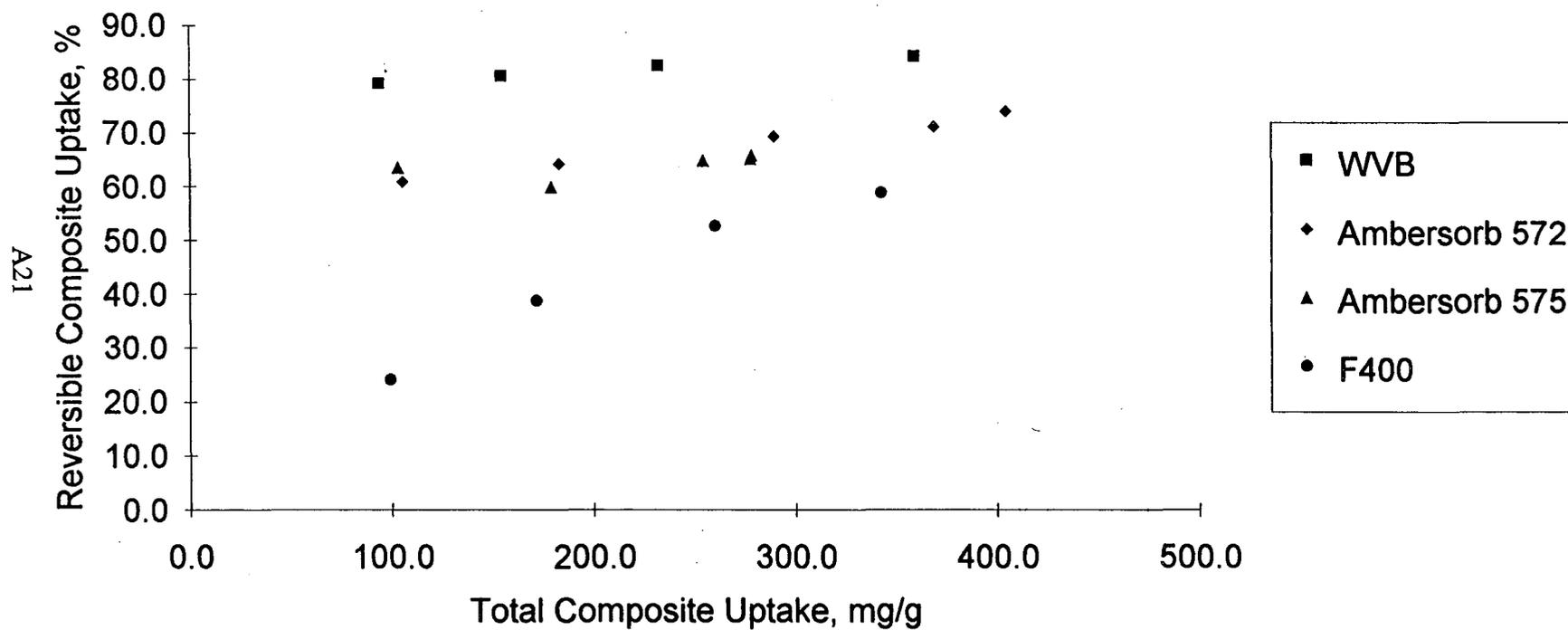
Phenol Uptake by Carbons and Ambersorb Resins, pH 9



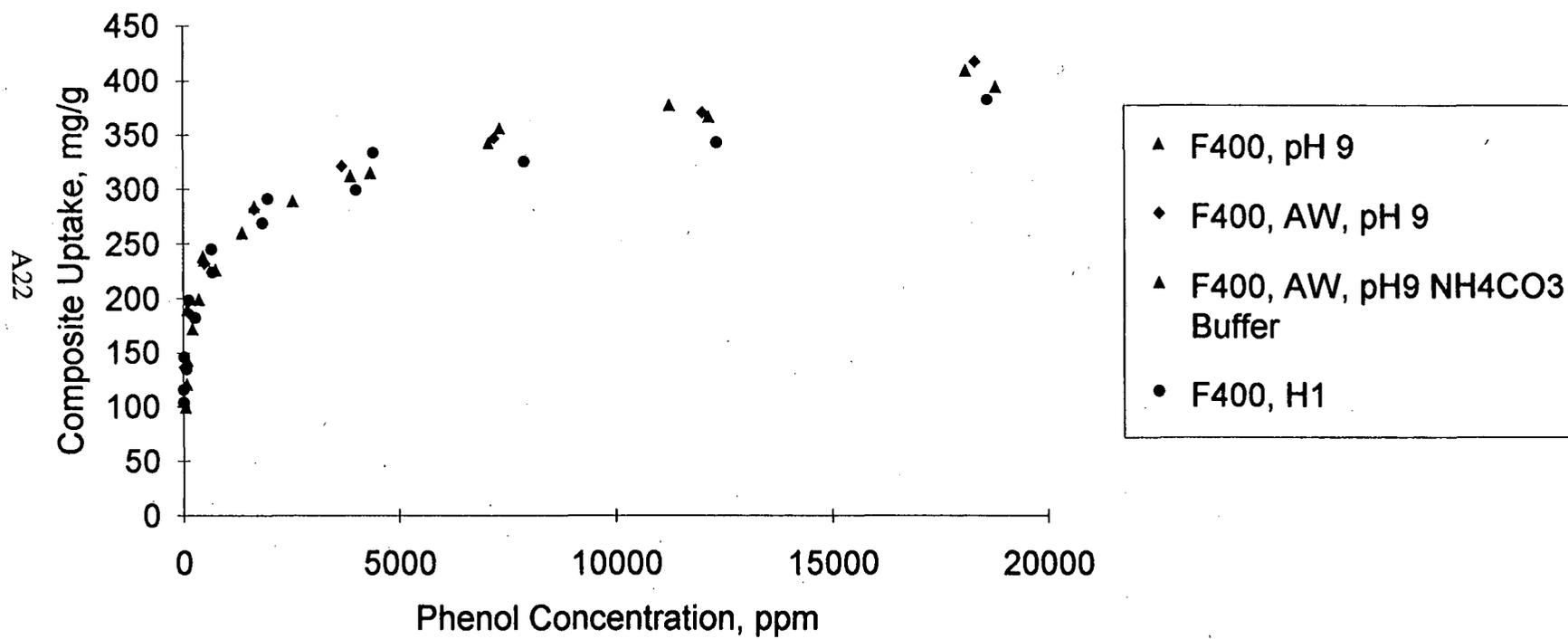
Reversible Phenol Uptake by Carbons and Ambersorb Resins, pH 9



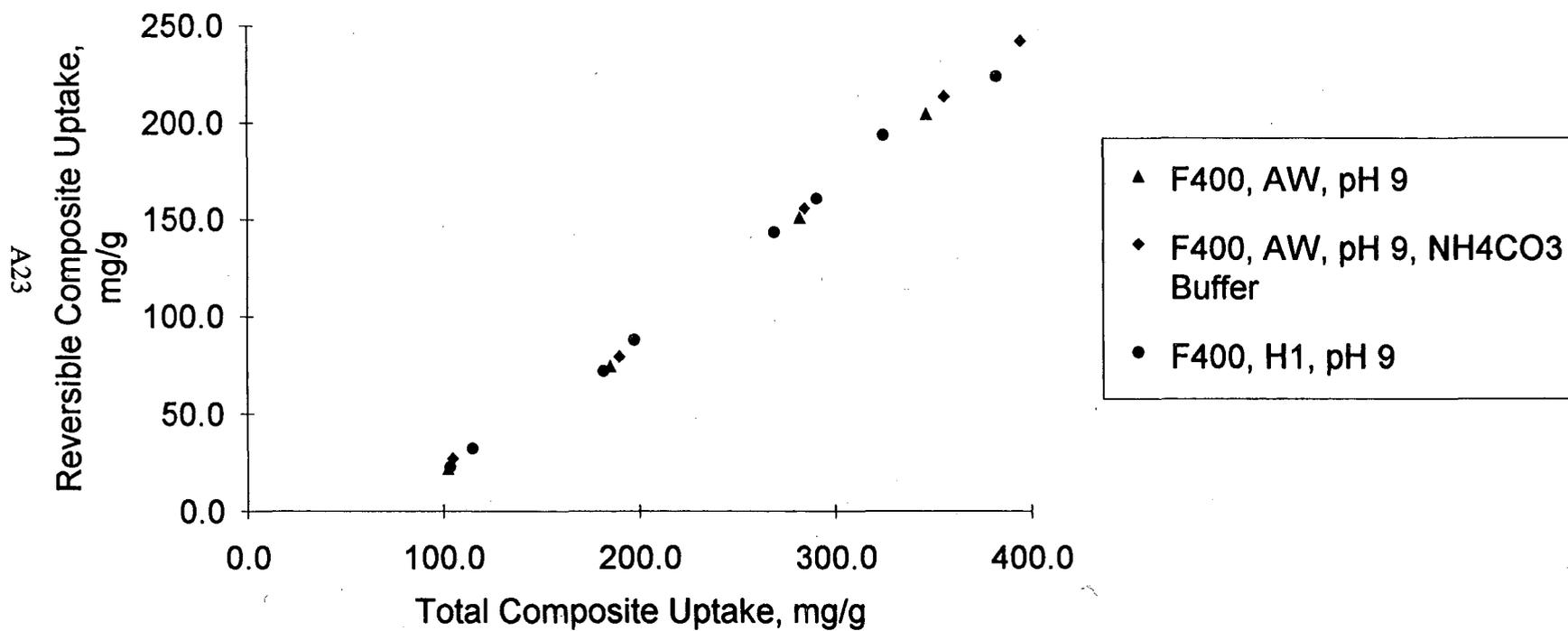
Reversible Phenol Uptake by Carbons and Ambersorb Resins, pH 9



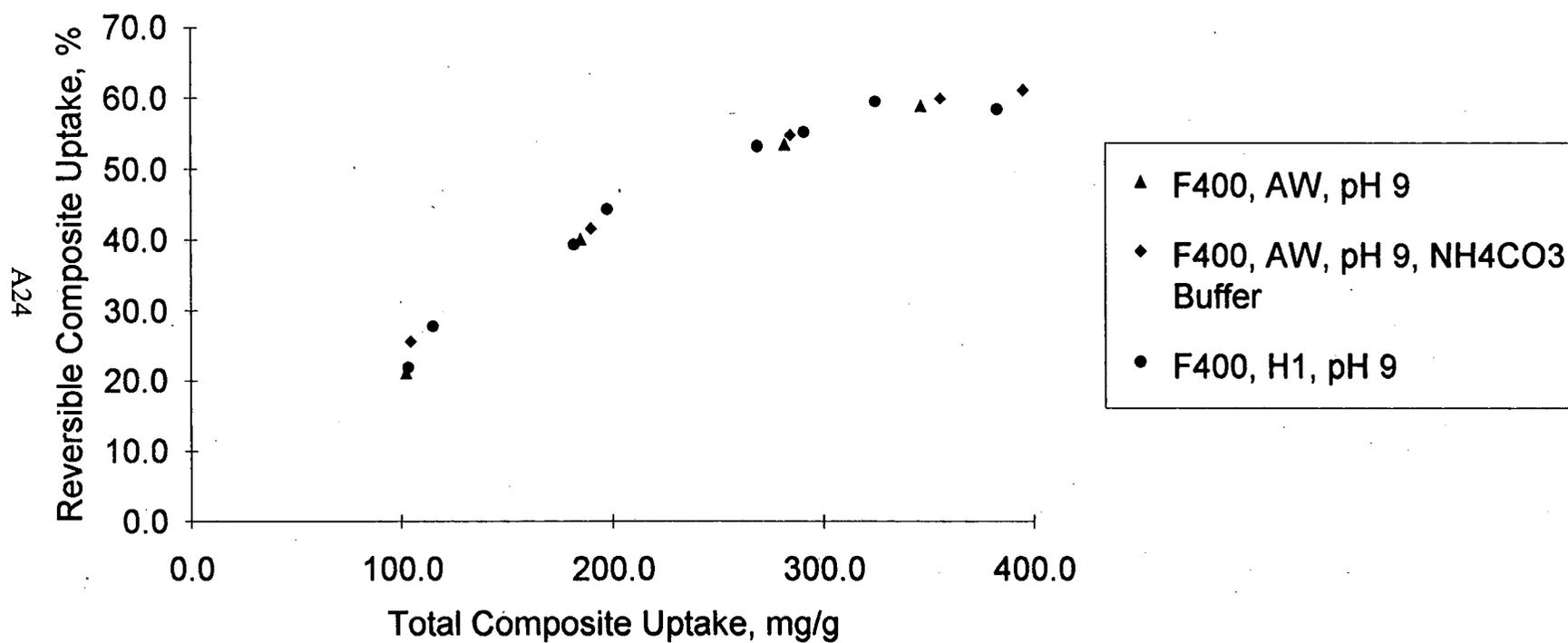
Effect of Heat Treatment on Phenol Uptake by F400 Carbon



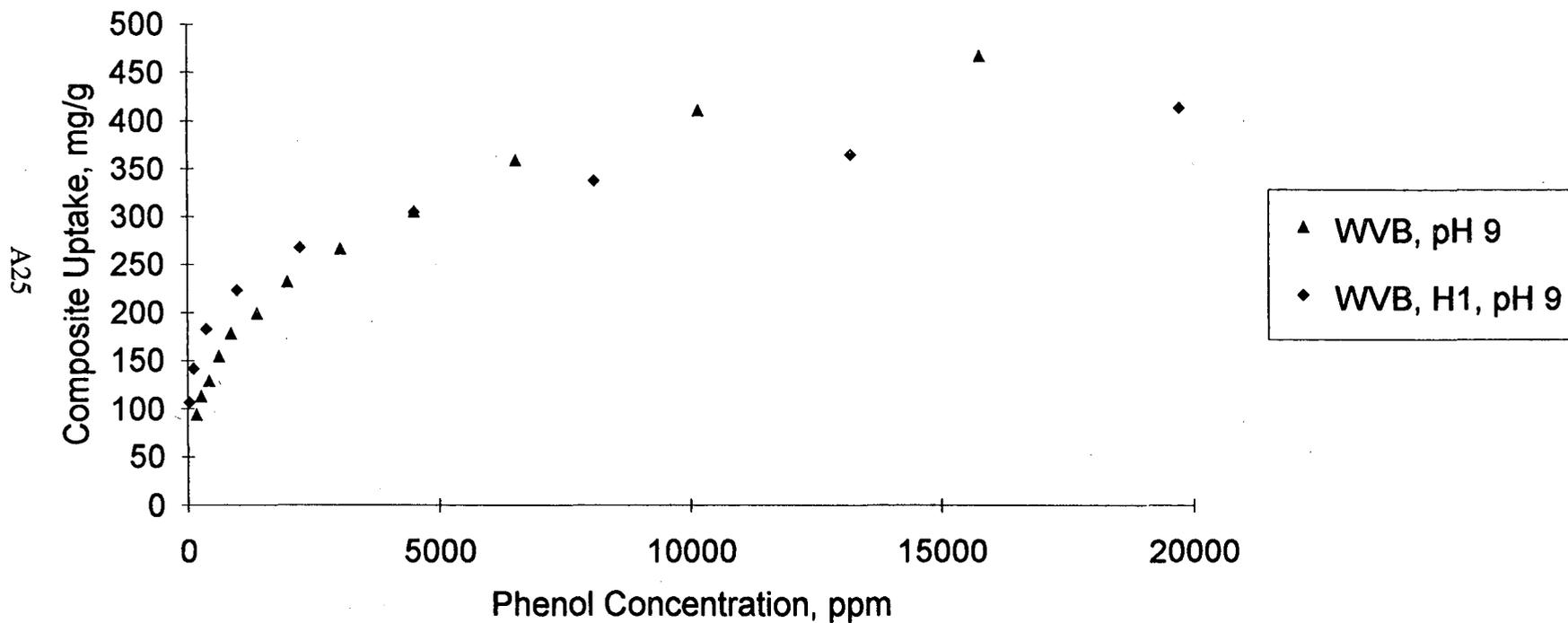
Effect of Heat Treatment on Reversible Phenol Uptake by F400 Carbon



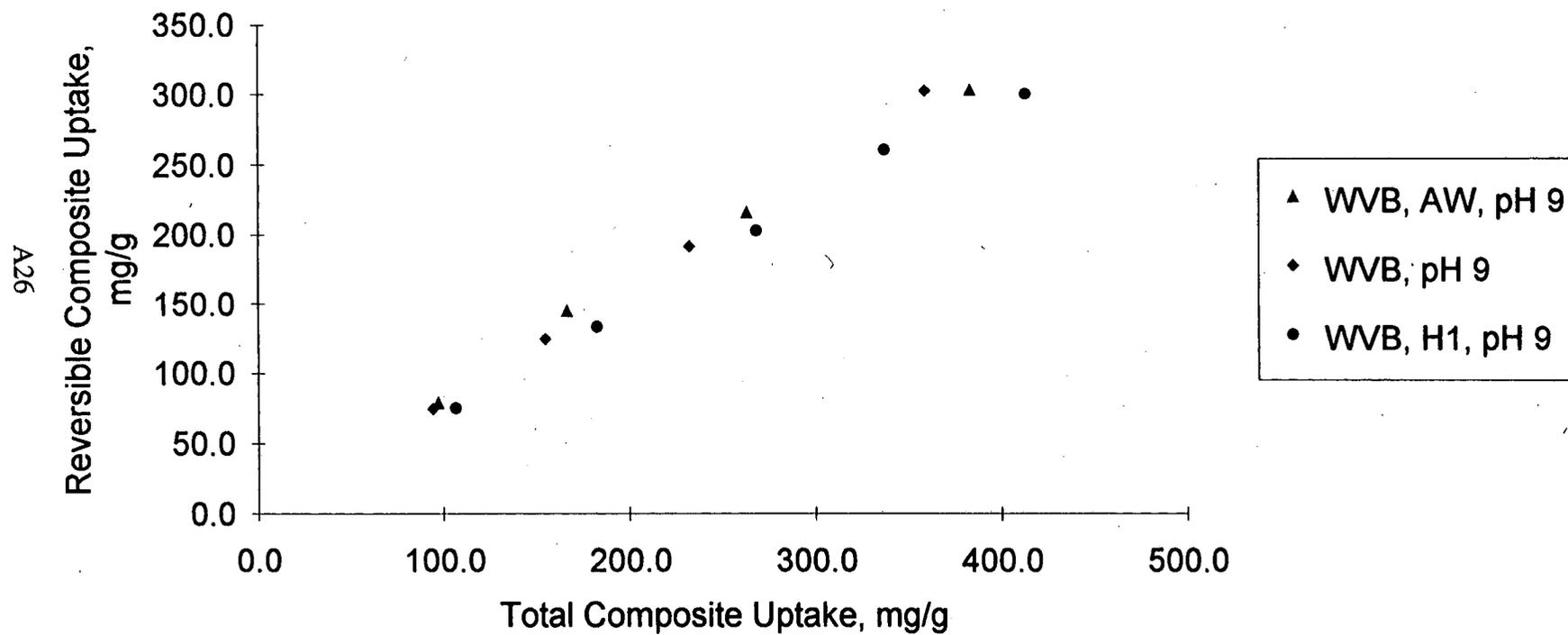
Effect of Heat Treatment on Reversible Phenol Uptake by F400 Carbon



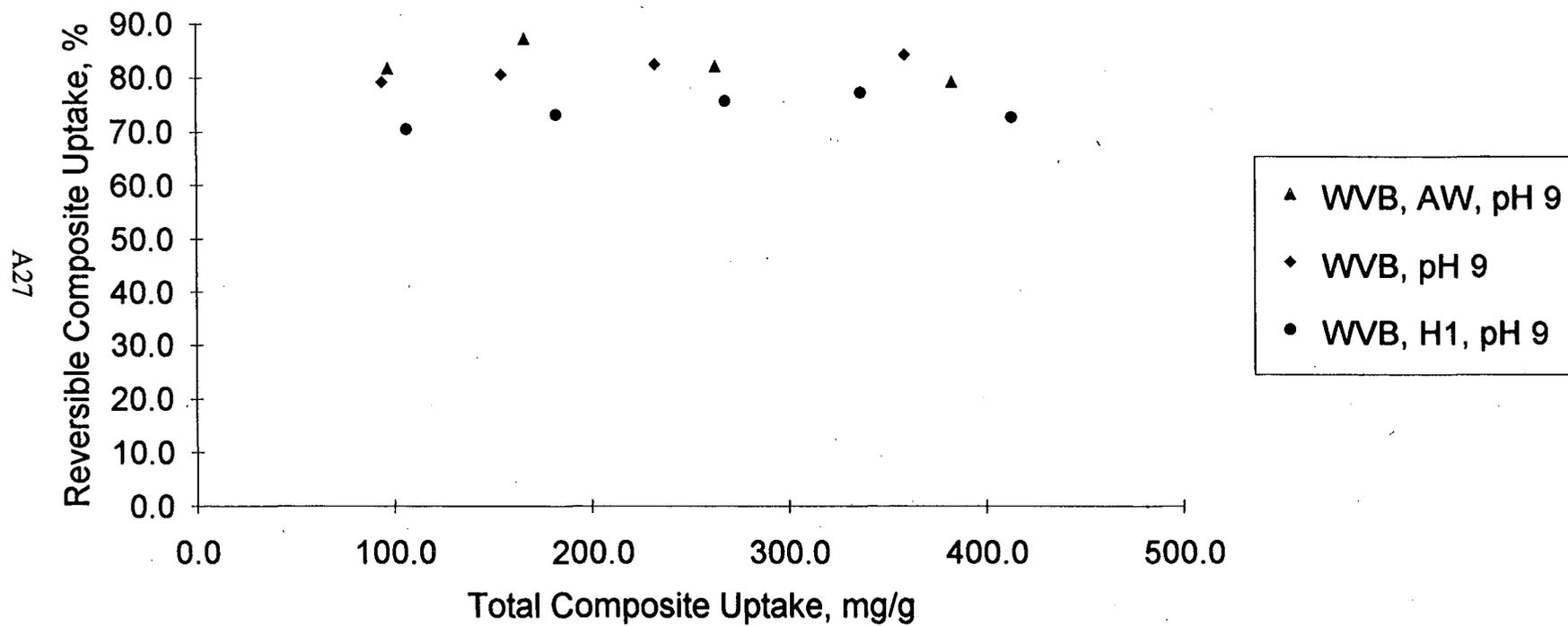
Effect of Heat Treatment on Phenol Uptake by WVB Carbon



Effect of Heat Treatment on Reversible Phenol Uptake by WVB Carbon



Effect of Heat Treatment on Reversible Phenol Uptake by WVB Carbon



Effect of Surface Oxidation on Phenol Uptake by F400 Carbon

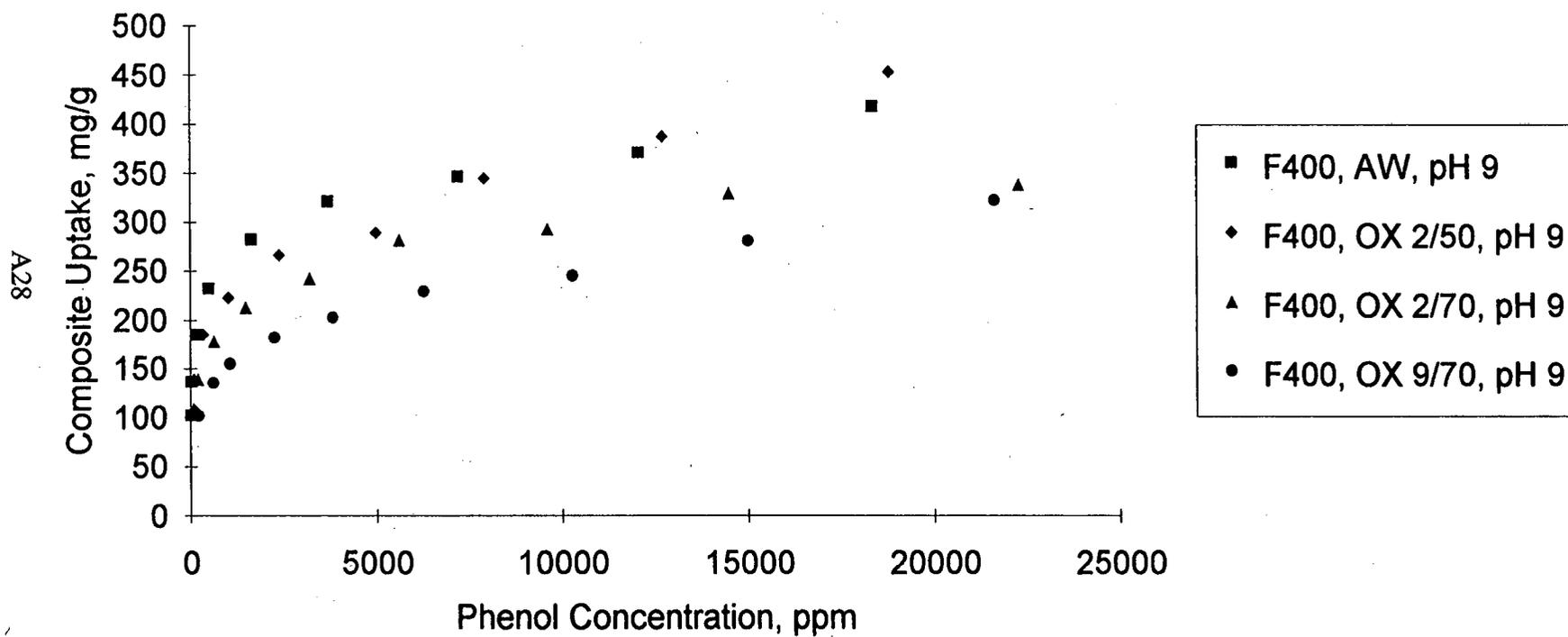
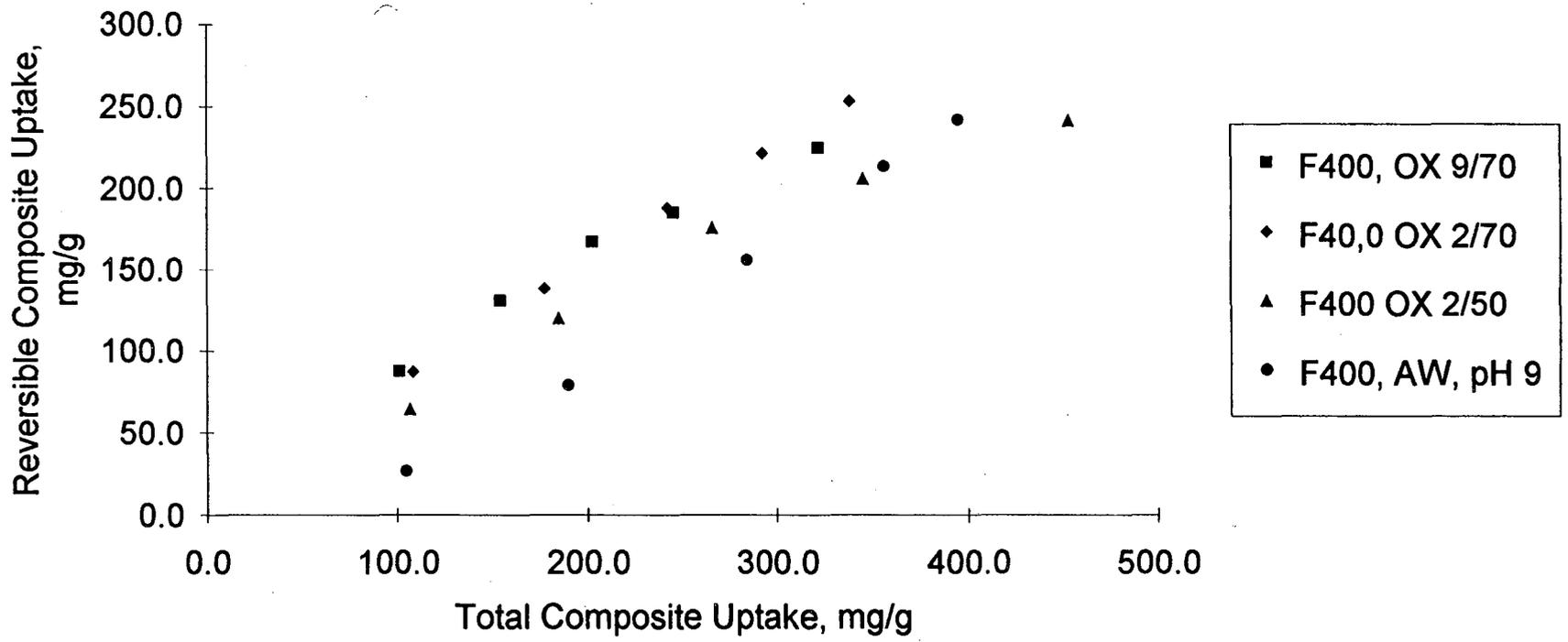


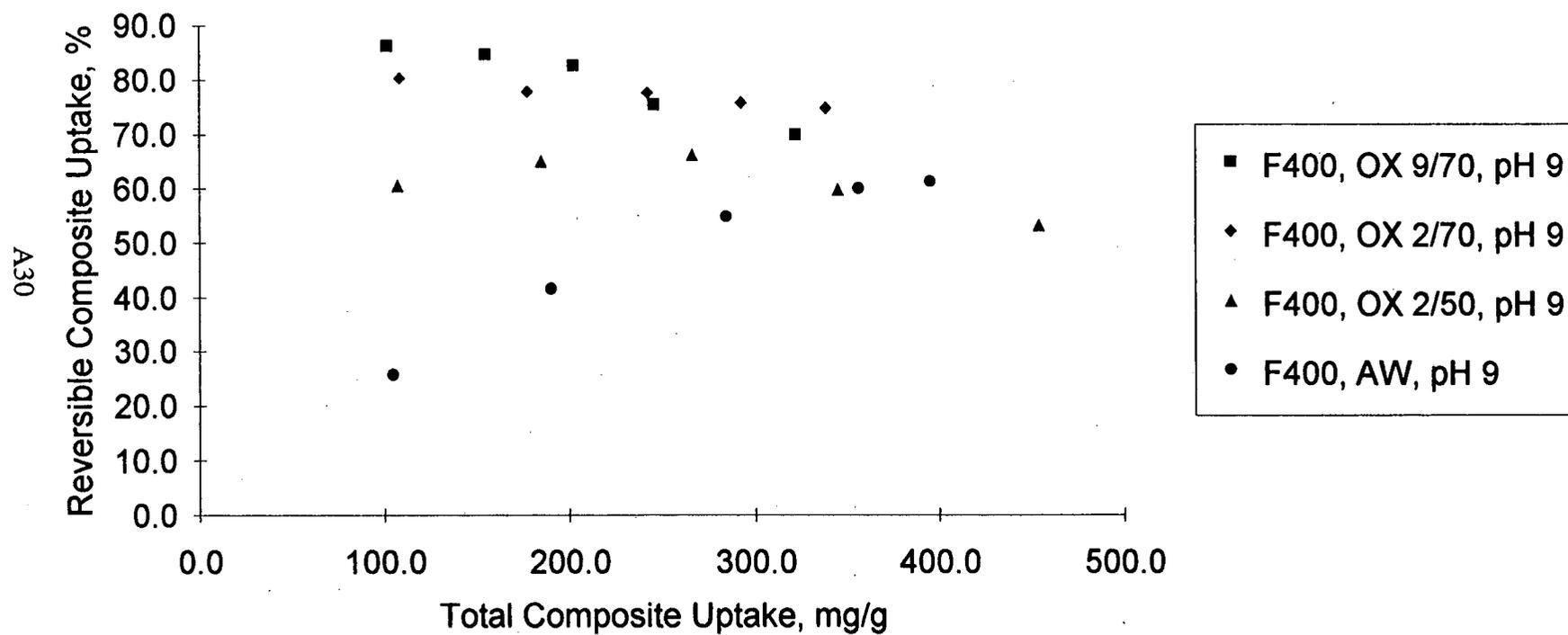
Figure 6

A29

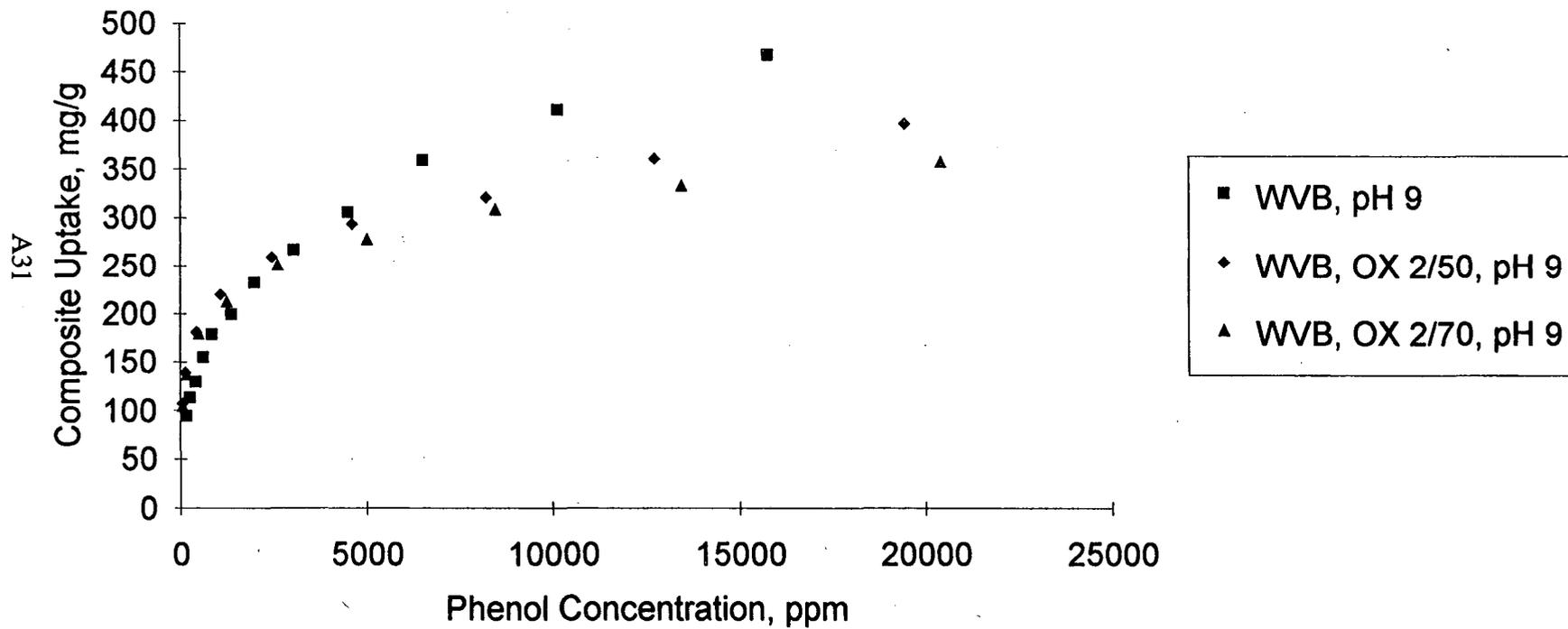
Effect of Surface Oxidation on Reversible Phenol Uptake by F400 Carbon, pH 9



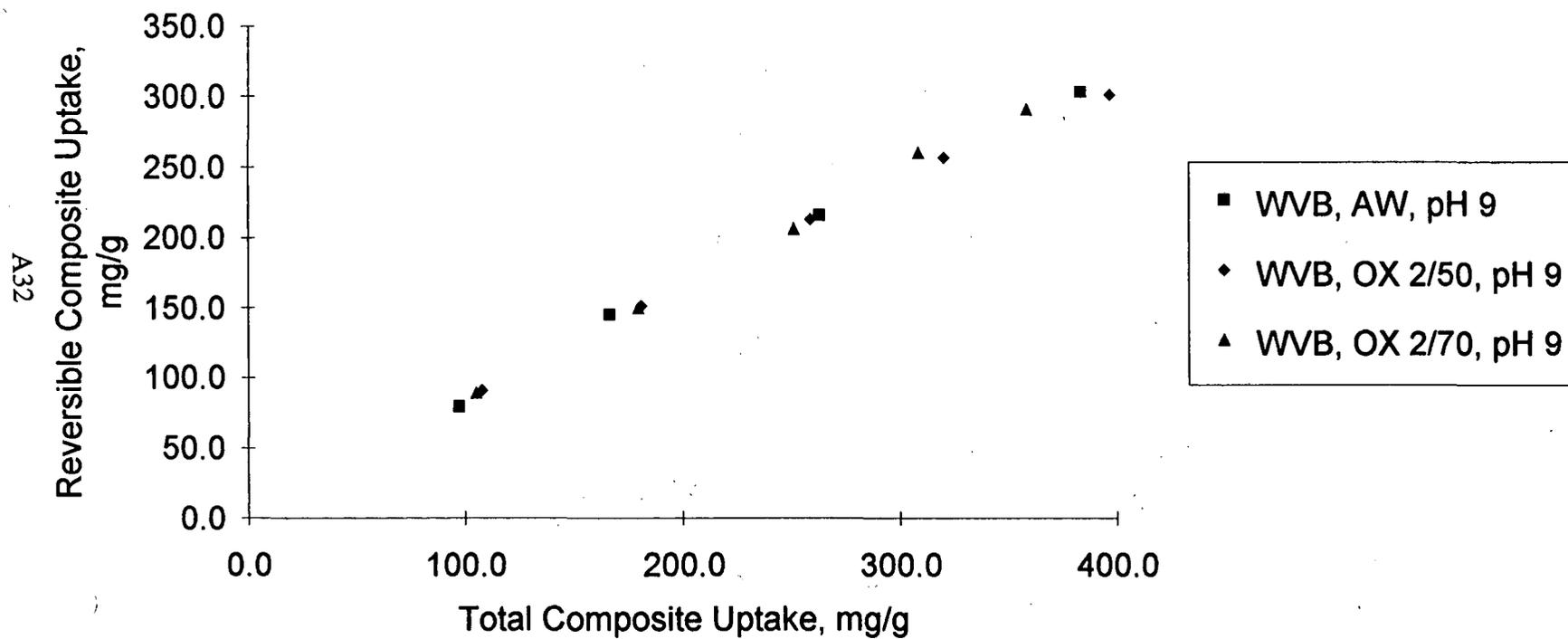
Effect of Surface Oxidation on Reversible Phenol Uptake by F400 Carbon



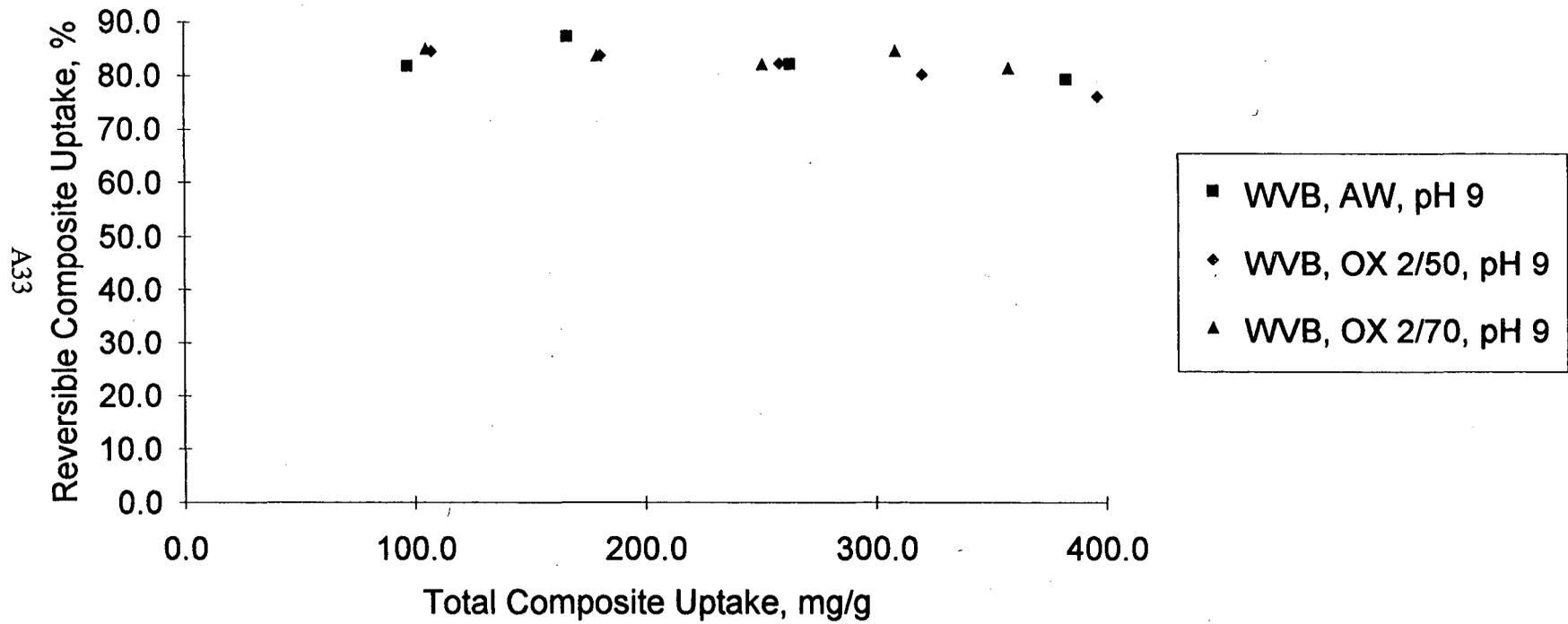
Effect of Surface Oxidation on Phenol Uptake by WVB Carbon



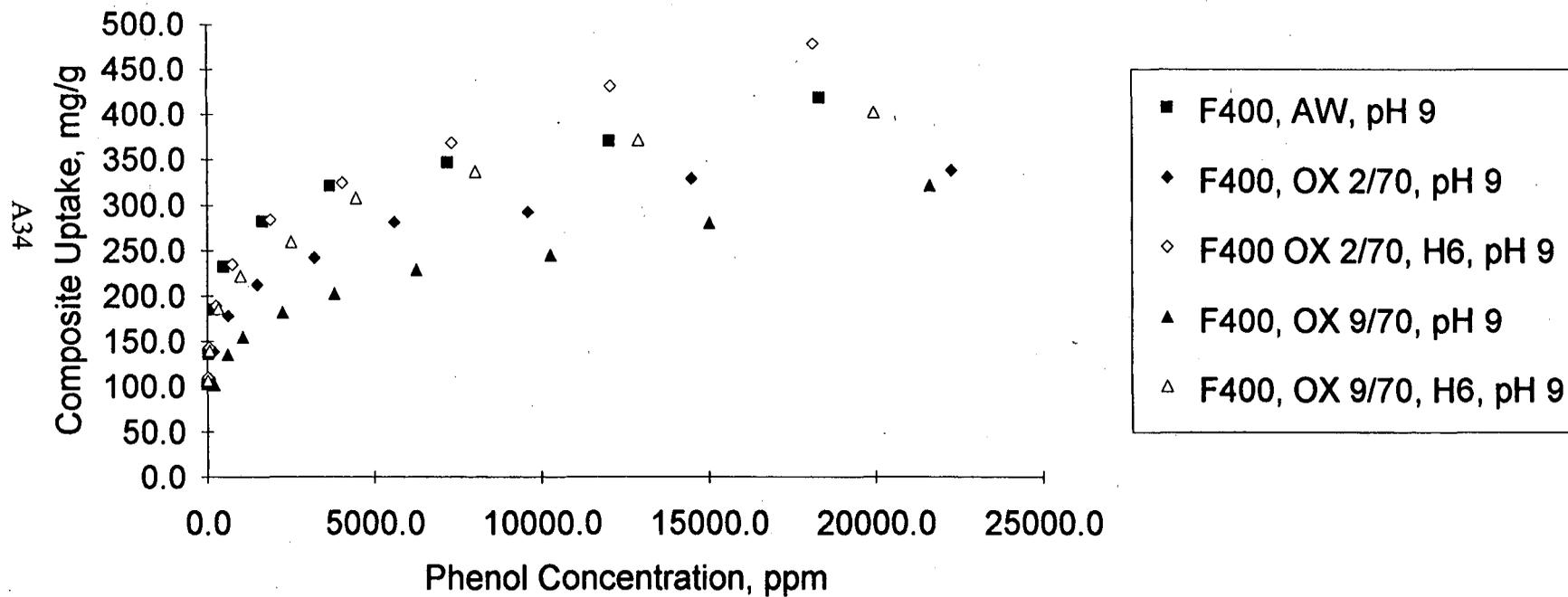
Effect of Surface Oxidation on Reversible Phenol Uptake by WVB Carbon



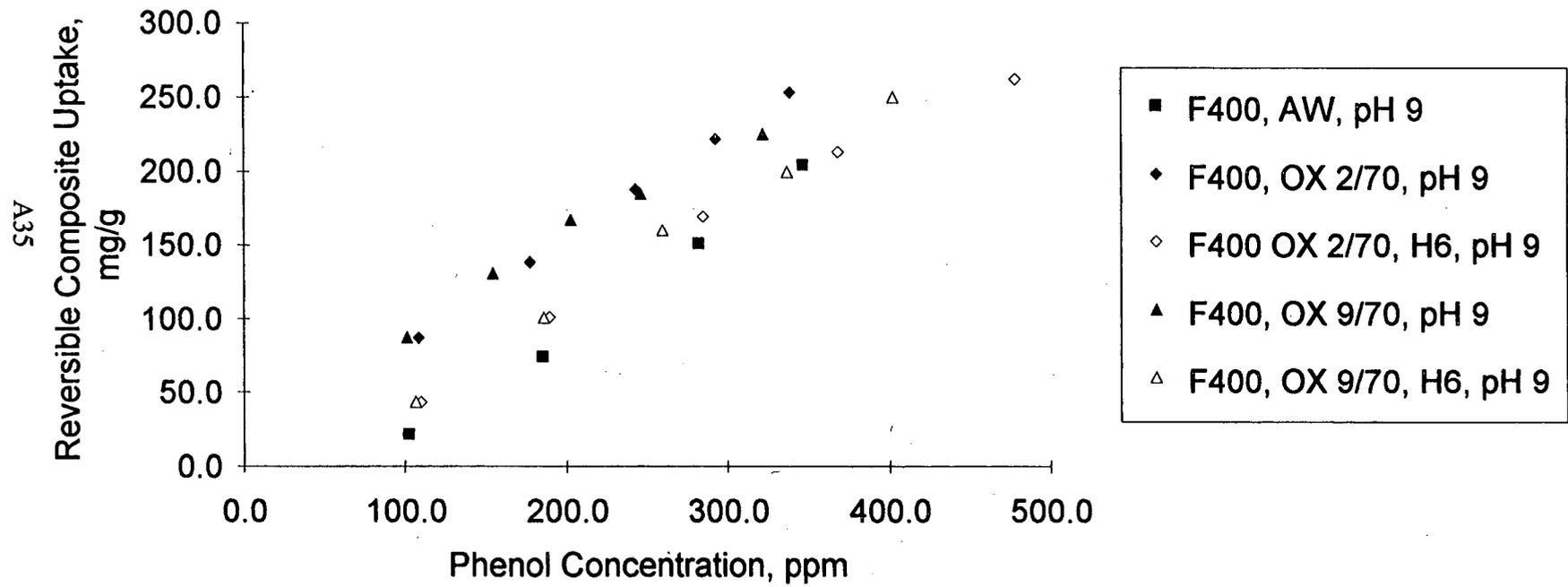
Effect of Surface Oxidation on Reversible Phenol Uptake by WVB Carbon



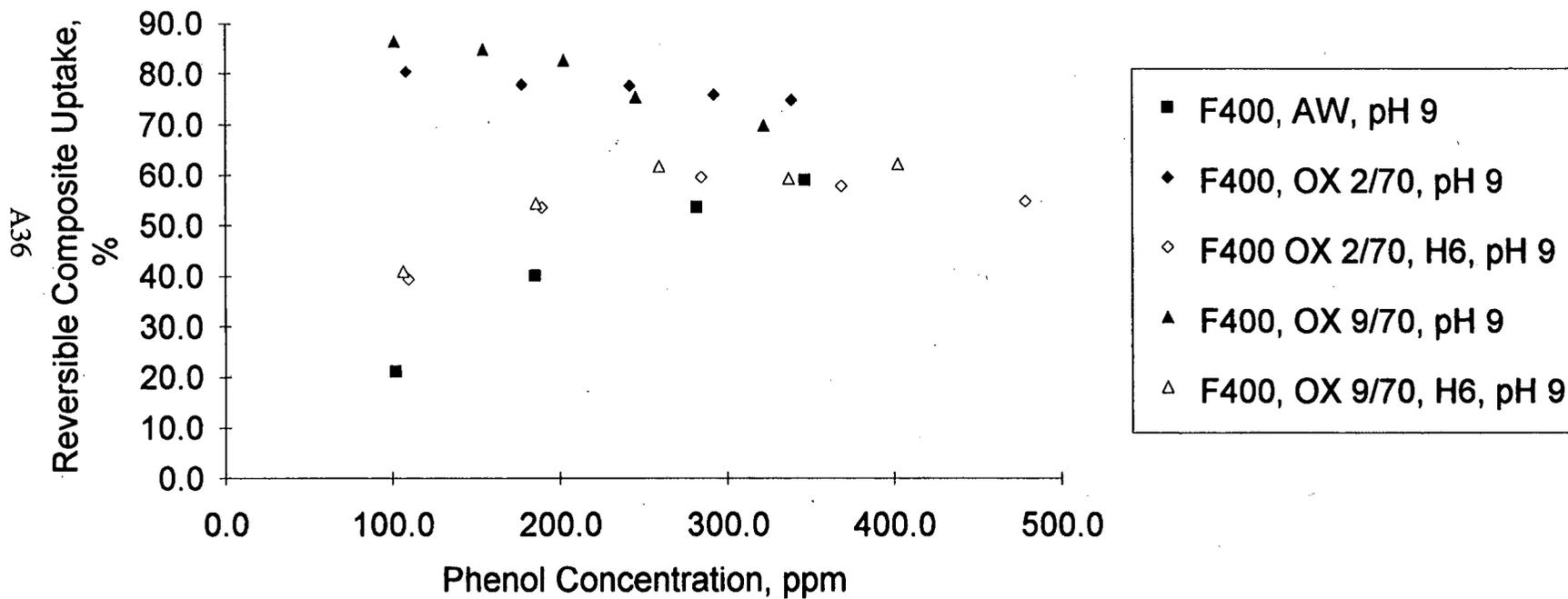
Effect of Surface Oxidation and Subsequent Heat Treatment on Phenol Uptake by F400 Carbon



Effect of Surface Oxidation and Subsequent Heat Treatment on Reversible Phenol Uptake by F400 Carbon



Effect of Surface Oxidation and Subsequent Heat Treatment on Reversible Phenol Uptake by F400 Carbon



Summary of F400 Isotherms

IF2W As-Received pH 2			IF9W As-Received pH 9			IF9A Acid-Washed pH 9		
Ce ppm	qe mg/g	qe ug/m2	Ce ppm	qe mg/g	qe ug/m2	Ce ppm	qe mg/g	qe ug/m2
49.8	105.7	95.8	50.5	99.4	90.1	4.7	102.2	97.897
89.4	128.4	116.4	70.5	120.8	109.5	26.0	136.1	130.407
152.7	149.2	135.3	96.2	142.6	129.3	172.5	185.2	177.395
341.5	178.4	161.8	203.3	172.0	155.9	487.2	232.1	222.363
657.0	201.1	182.3	351.2	198.7	180.2	1631.7	281.7	269.843
1307.6	222.8	202.0	737.8	225.9	204.8	3669.7	321.0	307.426
2041.2	253.0	229.4	1355.0	260.1	235.8	7205.7	346.7	332.128
3641.1	274.0	248.4	2531.9	289.3	262.3	12025.4	370.6	354.986
5691.4	299.4	271.4	4347.8	315.3	285.9	18327.2	418.1	400.479
8806.7	319.0	289.2	7073.5	342.6	310.6			
13492.2	346.9	314.5	11253.3	377.4	342.2			
20944.4	362.0	328.2	18104.9	410.0	371.7			

IF9N Acid-Washed pH 9, Buffered			IF9H1 HT 1000 C pH 9			IF9H1(b) HT 1000 C pH 9		
Ce ppm	qe mg/g	qe ug/m2	Ce ppm	qe mg/g	qe ug/m2	Ce ppm	qe mg/g	qe ug/m2
8.8	104.6	100.2	14.3	103.4	98.0	6.0	115.3	109.3
483.0	235.3	225.4	77.7	134.1	127.1	19.4	145.7	138.1
92.9	189.9	181.9	273.5	182.1	172.6	129.4	197.7	187.3
451.7	238.2	228.2	681.9	223.7	212.1	650.2	244.9	232.1
1630.9	284.4	272.4	1833.1	269.0	254.9	1961.4	291.1	275.9
3875.3	312.7	299.5	4009.5	298.9	283.3	4406.9	333.3	315.9
7321.8	356.1	341.1	7883.5	325.0	308.0			
12165.0	366.9	351.4	12359.6	343.0	325.1			
18799.3	395.1	378.5	18619.7	382.8	362.9			

IF250
AW, H1, OX 2/50
pH 9

IF270
AW, H1, OX 2/70
pH 9

IF270H6
AW, H1, OX 2/70, H6
pH 9

Ce ppm	qe mg/g	qe ug/m2	Ce ppm	qe mg/g	qe ug/m2	Ce ppm	qe mg/g	qe ug/m2
99.0	107.0	110.5	71.7	108.4	104.2	12.2	109.7	106.6
82.0	138.6	143.2	190.3	138.4	132.9	41.8	143.5	139.4
336.4	184.7	190.8	622.9	177.5	170.5	251.6	189.5	184.1
1013.0	222.7	230.1	1478.5	212.5	204.2	732.2	234.7	228.1
2360.1	265.8	274.6	3193.7	242.2	232.6	1872.5	284.6	276.6
4992.8	289.0	298.6	5616.5	281.3	270.2	4051.8	324.7	315.5
7911.9	345.0	356.4	9607.0	292.4	280.9	7325.4	368.4	358.1
12657.8	387.2	400.0	14474.0	329.2	316.3	12071.5	431.1	418.9
18774.9	453.7	468.7	22264.8	338.5	325.1	18155.4	478.5	465.0

IF970
AW, H1, OX 9/70
pH 9

IF970H6
AW, H1, OX 9/70, H6
pH 9

Ce ppm	qe mg/g	qe ug/m2	Ce ppm	qe mg/g	qe ug/m2
204.2	101.4	98.4	18.7	106.6	100.0
609.8	135.1	131.1	71.3	139.8	131.1
1058.3	154.4	149.8	330.2	186.0	174.5
2250.4	182.0	176.5	977.9	222.0	208.3
3820.8	202.6	196.5	2497.2	259.2	243.2
6281.2	229.2	222.3	4458.2	308.0	288.9
10276.5	245.4	238.0	8045.7	336.7	315.9
15002.3	280.5	272.1	12884.4	371.9	348.9
21620.4	321.9	312.3	19941.5	402.2	377.3

Summary of WVB Isotherms

IW2W
As-Recieved
pH 2

IW9W
As-Recieved
pH 9

IW9A
Acid-Washed
pH 9

Ce mg/L	qe mg/g	qe ug/m2	Ce mg/L	qe mg/g	qe ug/m2	Ce mg/L	qe mg/g	qe ug/m2
169.2	100.7	73.6	169.0	94.2	68.8	126.4	97.0	70.9
288.0	119.7	87.4	257.4	112.9	82.5	263.0	126.0	92.1
403.7	139.4	101.8	415.2	129.2	94.4	557.6	166.4	121.5
643.1	165.3	120.8	610.3	154.8	113.1	1110.6	208.0	152.0
940.1	189.7	138.5	846.6	178.3	130.3	2051.9	263.1	192.2
1524.2	214.7	156.8	1375.3	198.9	145.3	3612.5	319.2	233.1
2109.7	250.7	183.1	1981.7	232.2	169.6	6105.7	383.2	279.9
3301.8	287.6	210.1	3039.1	266.6	194.8	10419.0	426.6	311.6
4852.4	333.4	243.5	4514.4	305.0	222.8	16087.4	492.8	360.0
7365.6	376.5	275.0	6530.7	359.2	262.4			
11290.7	435.1	317.8	10169.5	411.3	300.5			
17628.3	494.6	361.3	15783.9	467.3	341.4			

IW9H1
HT 1000 C
pH 9

IW250
H1, OX 2/50
pH 9

IW270
H1, OX 2/70
pH 9

Ce ppm	qe ug/m2	qe m2/g	Ce ppm	qe mg/g	qe ug/m2	Ce ppm	qe mg/g	qe ug/m2
34.3	106.6	82.0	48.4	107.5	84.5	61.7	105.0	81.1
109.0	141.6	108.9	131.8	138.5	108.9	169.4	136.8	105.6
368.0	182.7	140.5	425.5	180.7	142.1	495.8	179.4	138.5
980.7	223.5	171.9	1073.0	219.7	172.7	1245.9	212.4	164.0
2234.3	268.1	206.2	2454.8	258.7	203.4	2605.0	251.1	193.9
4508.7	304.7	234.4	4614.1	293.2	230.5	5026.7	277.8	214.5
8101.2	337.1	259.3	8231.7	320.3	251.8	8485.7	308.5	238.3
13196.4	365.0	280.8	12716.8	360.7	283.6	13450.1	333.0	257.1
19743.6	413.3	317.9	19449.1	396.6	311.8	20410.3	358.0	276.4

Summary of RO Isotherms

IR2W As-Received pH 2			IR7W As-Received pH 7			IR9W As-Received pH 9		
Ce mg/L	qe mg/g	qe ug/m2	Ce mg/L	qe mg/g	qe ug/m2	Ce mg/L	qe mg/g	qe ug/m2
33.6	106.0	96.1	5.7	107.3	97.3	20.0	100.5	91.1
54.6	129.6	117.5	10.4	131.2	119.0	16.7	122.9	111.5
92.3	151.8	137.6	19.6	154.6	140.1	29.6	145.2	131.7
211.2	182.7	165.6	58.9	188.8	171.2	62.8	177.7	161.1
429.9	209.9	190.3	115.5	222.3	201.5	154.3	206.7	187.4
972.8	235.0	213.1	491.7	255.3	231.5	418.8	238.5	216.3
1793.1	261.2	236.8	970.4	295.9	268.3	979.7	274.3	248.6
3154.2	290.9	263.8	2715.6	311.2	282.1	1916.6	314.1	284.8
5280.9	311.4	282.4	4220.9	358.8	325.3	3988.4	329.3	298.5
8339.5	330.0	299.2	7295.8	379.6	344.2	6333.3	370.3	335.7
13080.8	351.2	318.4	12194.4	399.9	362.6	10791.6	390.7	354.2
20175.9	373.0	338.2	19471.8	421.1	381.8	17971.9	386.3	350.2

Summary of CG6 Isotherms

IR9A Acid-Washed pH 9			IC2W As-Received pH 2			IC9W As-Received pH 9		
Ce mg/L	qe mg/g	qe ug/m2	Ce mg/L	qe mg/g	qe ug/m2	Ce mg/L	qe mg/g	qe ug/m2
2.2	104.7	94.9	123.0	102.7	109.1	87.5	97.7	103.8
8.2	140.8	127.7	211.5	123.7	131.4	133.2	118.2	125.6
32.0	191.1	173.2	366.3	140.7	149.5	218.2	137.3	145.9
234.2	244.9	222.1	705.8	163.2	173.4	394.9	164.4	174.7
1169.5	299.6	271.6	1101.5	183.7	195.3	663.4	185.8	197.4
3202.0	335.6	304.3	1902.2	198.8	211.2	1168.8	208.2	221.2
7017.1	347.5	315.0	2741.1	224.4	238.4	2018.5	232.6	247.2
11850.6	368.2	333.8	4410.0	243.3	258.5	3444.0	251.4	267.2
20806.1	388.2	351.9	6566.9	264.3	280.9	5486.8	268.5	285.4
			9810.5	279.7	297.2	7759.1	313.1	332.7
			14891.2	290.9	309.1	11991.6	343.5	365.1
			22170.8	312.8	332.4	18842.8	353.9	376.1

Summary of Ambersorb Resin Isotherms

I729W
As-Received 572
pH 9

I759W
As-Received 575
pH 9

Ce mg/L	qe mg/g	qe ug/m2	Ce mg/L	qe mg/g	qe ug/m2
11.2	105.5	95.9	20.4	103.4	129.2
51.0	137.1	124.7	71.7	136.3	170.3
167.6	183.2	166.5	279.1	179.1	223.8
422.2	238.3	216.6	980.7	216.0	270.0
1366.0	289.7	263.4	2292.8	254.2	317.7
3323.6	333.1	302.8	4851.4	270.5	338.2
6529.7	368.8	335.3	8793.2	278.1	347.6
11106.0	400.9	364.5	14199.2	277.7	347.1
18334.1	405.1	368.2	21576.3	278.4	348.0

Regeneration of F400 Carbon
Composite Uptake in ug/m2

IF2W
As-Recieved
pH 2

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
89.4	123.0	21.2	101.7	82.7
152.7	142.9	18.1	124.9	87.3
657.0	192.6	51.9	140.8	73.1
1307.6	213.4	49.8	163.6	76.6
3641.1	262.4	63.3	199.1	75.9
5691.4	286.8	80.6	206.2	71.9
13492.2	332.3	90.2	242.1	72.9
20944.4	346.7	105.1	241.6	69.7

IF9W
As-Recieved
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
50.5	95.2	72.3	22.9	24.0
203.3	164.7	100.9	63.8	38.8
1355.0	249.1	118.0	131.1	52.6
7073.5	328.2	134.8	193.3	58.9

IF9A
Acid-Washed
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
4.7	97.9	77.2	20.7	21.2
172.5	177.4	106.2	71.2	40.1
1631.7	269.8	125.2	144.6	53.6
7205.7	332.1	136.1	196.0	59.0

IF9N
Acid Washed, NH4CO3 Buffer
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
8.8	100.2	74.5	25.7	25.7
92.9	181.9	106.2	75.7	41.6
1630.9	272.4	123.0	149.3	54.8
7321.8	341.1	136.4	204.7	60.0
18799.3	378.5	146.4	232.0	61.3

IF9H1
Heat Treated, 1000 C
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
14.3	98.0	76.6	21.4	21.9
273.5	172.6	104.7	67.9	39.3
1833.1	254.9	119.1	135.8	53.3
7883.5	308.0	124.5	183.5	59.6
18619.7	362.9	150.6	212.3	58.5
6.0	109.3	78.9	30.3	27.8
129.4	187.3	104.2	83.1	44.4
1961.4	275.9	123.4	152.4	55.3

IF9H1(b)
Heat Treated, 1000 C
pH 9 (Replicate)

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
6.0	109.3	78.9	30.3	27.8
129.4	187.3	104.2	83.1	44.4
1961.4	275.9	123.4	152.4	55.3

IF250
H1, OX2/50
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
26.1	110.5	43.5	67.0	60.6
336.4	190.8	66.6	124.2	65.1
2360.1	274.6	92.8	181.8	66.2
7911.9	356.4	143.3	213.1	59.8
18774.9	468.7	219.2	249.6	53.2

IF270
H1, OX 2/70
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
71.7	104.2	20.4	83.7	80.4
622.9	170.5	37.8	132.7	77.8
3193.7	232.6	52.0	180.7	77.7
9607.0	280.9	67.8	213.1	75.9
22264.8	325.1	81.8	243.4	74.9

Regeneration of F400 Carbon, cont'd
 Composite Uptake in mg/g

IF270H6
 H1, OX 2/70, H6
 pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
12.2	106.6	64.6	42.0	39.4
251.6	184.1	85.5	98.6	53.6
1872.5	276.6	111.7	164.9	59.6
7325.4	358.1	150.7	207.4	57.9
18155.4	465.0	209.8	255.3	54.9

IF970
 H1, OX 9/70
 pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
204.2	98.4	13.4	85.0	86.4
1058.3	149.8	22.8	127.0	84.8
3820.8	196.5	34.0	162.5	82.7
10276.5	238.0	58.4	179.6	75.5
21620.4	312.3	93.9	218.4	69.9

IF970H6
 H1, OX 9/70, H6
 pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
18.7	100.0	59.0	41.0	41.0
330.2	174.5	79.6	94.9	54.4
2497.2	243.2	92.9	150.2	61.8
8045.7	315.9	128.4	187.5	59.3
19941.5	377.3	142.4	234.8	62.2

Regeneration of WVB Carbon
Composite Uptake in ug/m2

IW2W
As-Recieved
pH 2

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	% Reversible
288.0	87.4	9.6	77.9	89.1
940.1	138.5	12.4	126.1	91.0
3301.8	210.1	19.7	190.4	90.6
11290.7	317.8	33.2	284.6	89.6

IW9W
As-Recieved, pH 9
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	% Reversible
169.0	68.8	14.3	54.5	79.3
610.3	113.1	22.0	91.1	80.6
1981.7	169.6	29.6	140.1	82.6
6530.7	262.4	41.1	221.3	84.3

IW9A
Acid-washed, pH 9
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	% Reversible
126.4	70.9	12.9	58.0	81.8
557.6	121.5	15.5	106.1	87.3
2051.9	192.2	34.2	158.0	82.2
6105.7	279.9	58.0	221.9	79.3

IW9H1
Heat Treated 1000 C
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	% Reversible
34.3	82.0	24.2	57.8	70.5
368.0	140.5	37.8	102.7	73.1
2234.3	206.2	50.2	156.1	75.7
8101.2	259.3	58.8	200.5	77.3
19743.6	317.9	86.7	231.2	72.7

IW250
H1, OX 2/50
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
48.4	84.5	13.1	71.5	84.5
425.5	142.1	23.0	119.1	83.8
2454.8	203.4	35.9	167.5	82.3
8231.7	251.8	49.8	202.0	80.2
19449.1	311.8	74.3	237.4	76.2

IW270
H1, OX 2/70
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
61.7	81.1	12.1	69.0	85.1
495.8	138.5	22.4	116.1	83.8
2605.0	193.9	34.5	159.4	82.2
8485.7	238.3	36.7	201.6	84.6
20410.3	276.4	51.3	225.2	81.5

Regeneration of RO Carbon
Composite Uptake in ug/m2

IR2W
As-Received
pH 2

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
54.6	117.5	10.3	107.3	91.3
429.9	190.3	24.1	166.3	87.4
3154.2	263.8	39.4	224.4	85.1
13080.8	318.4	68.2	250.2	78.6

IR7W
As-Received
pH 7

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
10.4	119.0	73.4	45.6	38.3
115.5	201.5	121.0	80.5	40.0
2715.6	282.1	149.9	132.2	46.9
12194.4	362.6	211.7	150.9	41.6

IR9W
As-Received
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
20.0	91.1	77.0	14.1	15.5
62.8	161.1	112.9	48.3	30.0
979.7	248.6	133.9	114.8	46.2
6333.3	335.7	152.3	183.5	54.7

IR9A
Acid-Washed
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
2.2	94.9	69.6	25.3	26.6
32.0	173.2	109.3	63.9	36.9
1169.5	271.6	130.4	141.2	52.0
7017.1	315.0	125.3	189.7	60.2
20806.1	351.9	120.2	231.7	65.8

CG6 Carbon

IC2W
As-Received
pH 2

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
211.5	131.4	19.3	112.1	85.3
366.3	149.5	18.3	131.2	87.7
1101.5	195.3	22.2	173.0	88.6
1902.2	211.2	19.4	191.8	90.8
4410.0	258.5	31.5	227.0	87.8
6566.9	280.9	50.0	230.9	82.2
14891.2	309.1	25.1	284.0	91.9
22170.8	332.4	54.9	277.5	83.5

IC9W
As-Received
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
87.5	103.8	60.5	43.4	41.8
394.9	174.7	88.2	86.5	49.5
2018.5	247.2	94.0	153.2	62.0
7759.1	332.7	125.5	207.3	62.3

Regeneration of Ambersorb Resins

I729W
As-Received
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
11.2	95.9	37.5	58.5	60.9
167.6	166.5	59.6	106.9	64.2
1366.0	263.4	80.9	182.5	69.3
6529.7	335.3	96.7	238.6	71.2
18334.1	368.2	95.9	272.4	74.0

I759W
As-Received
pH 9

Ce ppm	Total Composite	Irrevers Composite	Revers Composite	Percent Reversible
20.4	129.2	47.1	82.1	63.5
279.1	223.8	89.6	134.2	60.0
2292.8	317.7	111.8	205.9	64.8
8793.2	347.6	121.0	226.6	65.2
21576.3	348.0	119.0	229.0	65.8

Water Uptake Measurements
 21-Jun-96
 Equilibration with water saturated with NaOH

Sample	Bottom	Bottom + Carbon	Carbon	Top	Total Mo
1	9.5649	10.5577	0.9928	14.9075	25.4652
2	8.0739	9.045	0.9711	14.6685	23.7135
3	8.9949	10.0451	1.0502	13.8083	23.8534
4	8.366	9.3287	0.9627	15.2871	24.6158
5	7.8143	8.7848	0.9705	15.3875	24.1723
6	8.8454	9.8448	0.9994	13.6085	23.4533
7	9.4886	10.5099	1.0213	13.83	24.3399
8	9.8448	10.8276	0.9828	14.6493	25.4769
9	8.6915	9.5908	0.8993	13.9301	23.5209
10	8.3646	9.3631	0.9985	13.657	23.0201
11	7.9268	8.8944	0.9676	15.0654	23.9598
12	8.7177	9.71	0.9923	14.1139	23.8239

Sample	After Vapor Uptake		Mf K-Acetate	ug/m2 K-Acetate	Kd ug/m2-RH	R-Square	95% CI	NaOH	
	Mf LiCl	ug/m2 LiCl						Uptake ueq/m2	
1	25.4673	2.03	25.4710	5.60	23	0.969	8.5	0.14	F AW
2	23.7144	0.88	23.7154	1.85	8	0.999	0.6	0.00	F AW H1
3	23.8556	2.16	23.8634	9.84	39	0.885	29.9	0.60	F AW H1 OX 2/50
4	24.6204	4.59	24.6308	14.97	61	0.942	31.6	0.94	F AW H1 OX 2/70
5	24.181	8.69	24.2034	31.08	126	0.926	74.6	1.71	F AW H1 OX 9/70
6	23.4538	0.49	23.4568	3.40	13	0.824	13.2	0.26	F AW H1 OX 2/70 H6
7	24.3416	1.56	24.3469	6.43	26	0.901	18.0	0.55	F AW H1 OX 9/70 H6
8									W AW
9	23.5291	7.01	23.5372	13.94	62	1.000	0.2	0.31	W AW H1
10	23.0257	4.41	23.0365	12.91	54	0.960	22.4	0.76	W AW H1 OX 2/50
11	23.971	8.94	23.9871	21.79	93	0.987	21.6	1.14	W AW H1 OX 2/70
12	23.8296	5.21	23.8378	12.70	54	0.987	12.6	0.27	RO AW

Kd Value Summary

	LiCl ug/m2-RH	K-Acetate ug/m2-RH	Kd ug/m2-RH	ug/m2 K-Acetate	NaOH Uptake ueq/m2
1 F AW		17.93	49.52	23.46	5.60
2 F AW H1		7.77	16.41	8.15	1.85
3 F AW H1 OX 2/50		19.15	87.05	38.76	9.84
4 F AW H1 OX 2/70		40.62	132.46	61.29	14.97
5 F AW H1 OX 9/70		76.95	275.06	125.77	31.08
6 F AW H1 OX 2/70 H6		4.30	30.12	12.94	3.40
7 F AW H1 OX 9/70 H6		13.82	56.90	25.60	6.43
10 W AW H1 OX 2/50		39.02	114.27	53.67	12.91
11 W AW H1 OX 2/70		79.10	192.81	93.23	21.79
9 W AW H1		62.07	123.38	61.97	13.94
12 RO AW		46.09	112.39	54.34	12.70

Save This Data Sheet!
It Contains Important Information About This Product.

Ambersorb® Carbonaceous Adsorbents

Catalog Numbers

Ambersorb 563: 1-0430 Ambersorb 575: 1-0433
Ambersorb 564: 1-0431 Ambersorb 348F: 1-0434
Ambersorb 572: 1-0432

Characteristics

Carbonaceous, black spherical beads possessing excellent mechanical strength, high capacity and fast kinetics, make them particularly suited for use in a wide range of large-scale separation applications.

Developed and patented by Rohm and Haas, these adsorbents are produced by pyrolysis of a highly sulfonated styrene-divinylbenzene macroreticular ion-exchange resin having moderate surface area. After pyrolysis, the Ambersorb adsorbents have significant microporosity (<20Å) in addition to mesoporosity (20-500Å) and macroporosity (>500Å).

Features

- Fast Mass Transfer** — of analytes to the micropores results from significant macroporosity and mesoporosity
- Excellent Capacity** — provided by high microporosity and large surface area, combined with a very hydrophobic surface
- Easy regeneration *in situ*** — made possible by the pore structure and hydrophobicity
- Excellent physical integrity** — eliminates concern about dusting and attrition
- Effective adsorption** — under humid conditions and in aqueous media due to the hydrophobic surface properties

Typical Properties of Ambersorb Carbonaceous Adsorbents

Listed below are typical properties for the new family of Ambersorb adsorbents. These properties are typical and should not be considered as specifications.

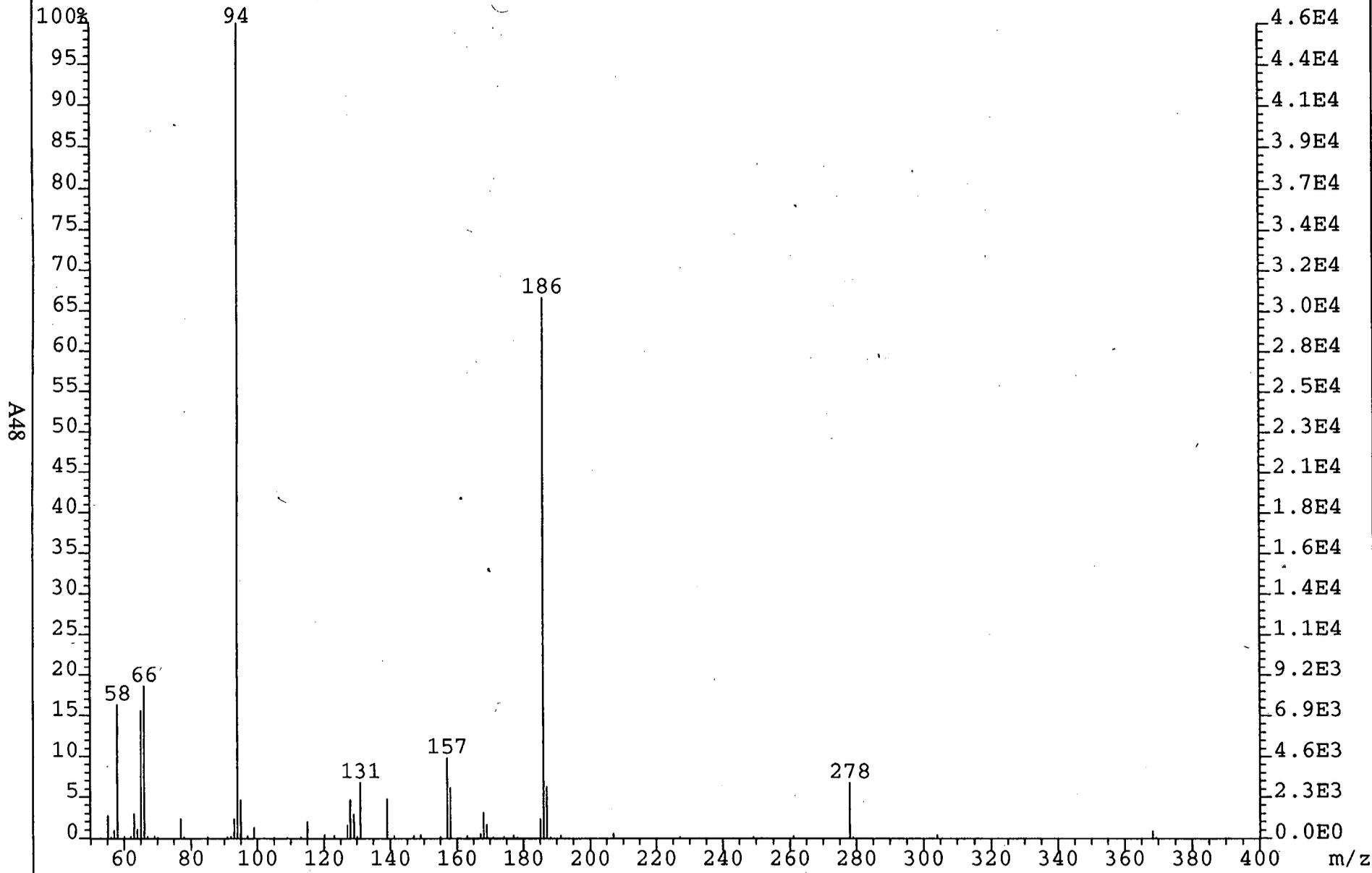
Adsorbent	Hydrophobicity Ranking	Particle Size (Mesh)	Surface Area (m ² /g)	Density (g/cc)	Porosity (ml/g)		
					Micro	Meso	Macro
Ambersorb 563	1♦	20/50	550	0.53	0.23	0.14	0.23
Ambersorb 564	2	20/50	550	0.60	0.24	0.13	0.14
Ambersorb 572	5	20/50	1100	0.49	0.41	0.19	0.24
Ambersorb 575	3	20/50	800	0.55	0.32	0.20	0.20
Ambersorb 348F	4	50/100	750	0.56	0.32	0.12	0.13

♦ Most Hydrophobic

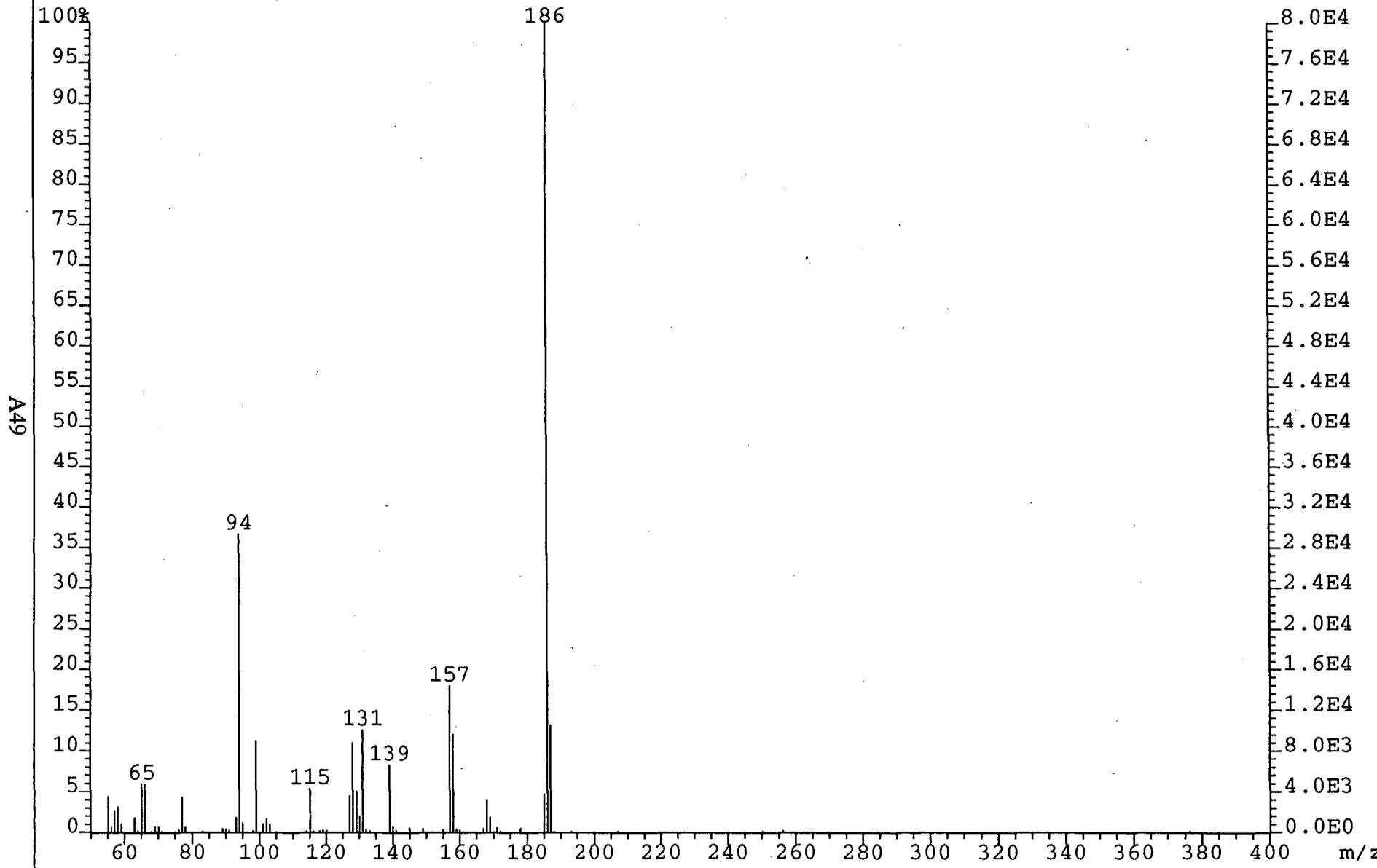
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SUPELCO
Bellefonte, PA

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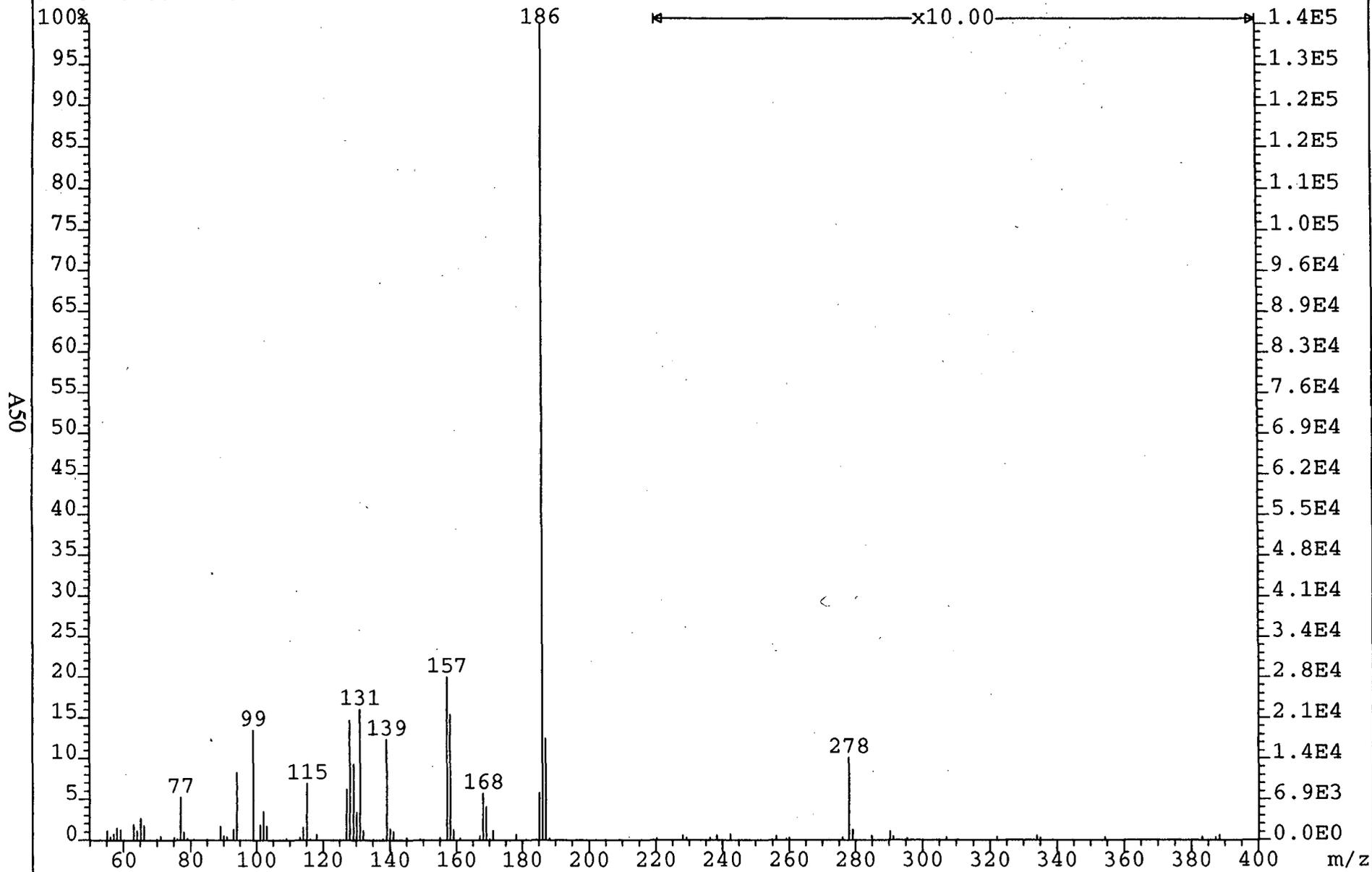
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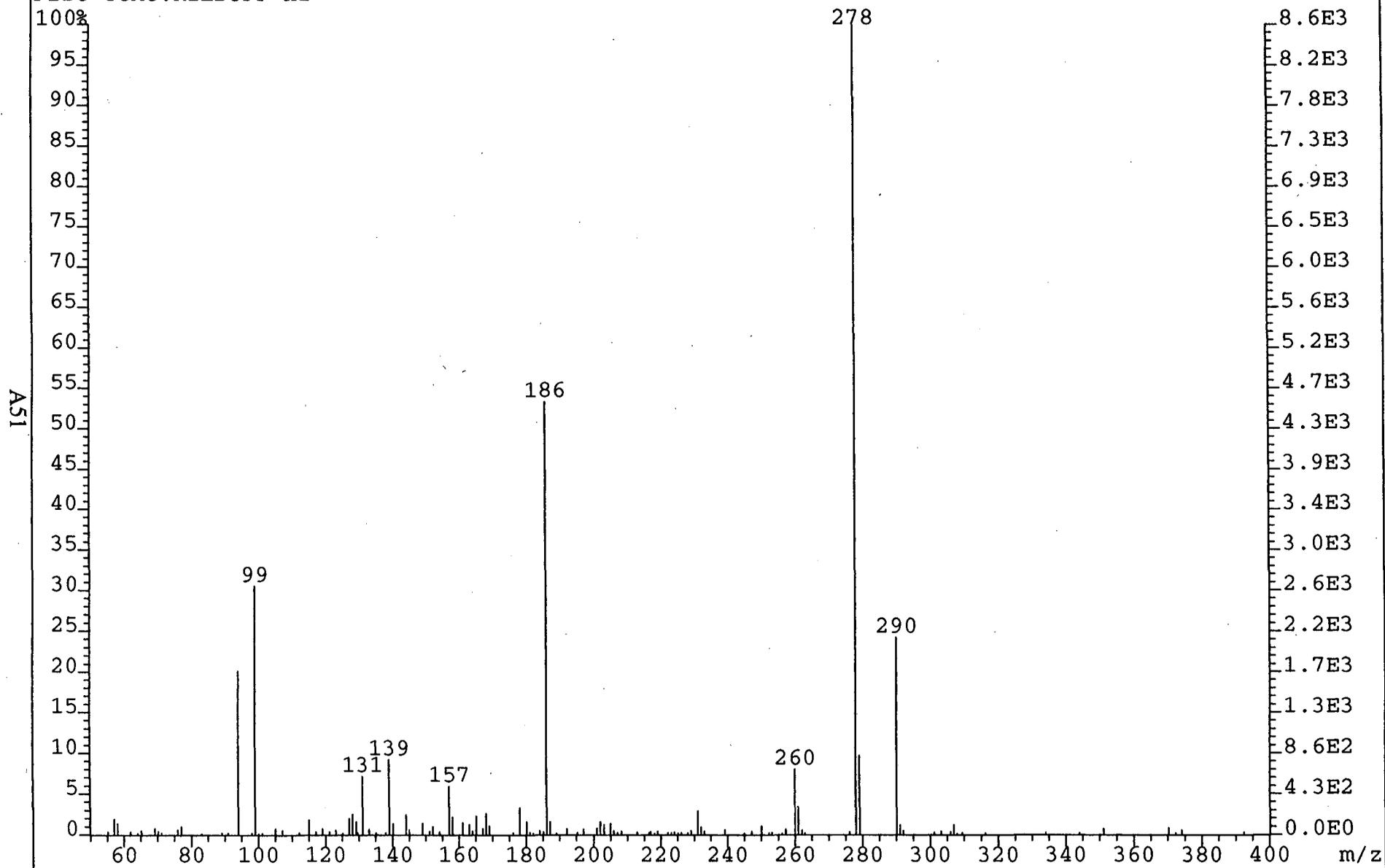
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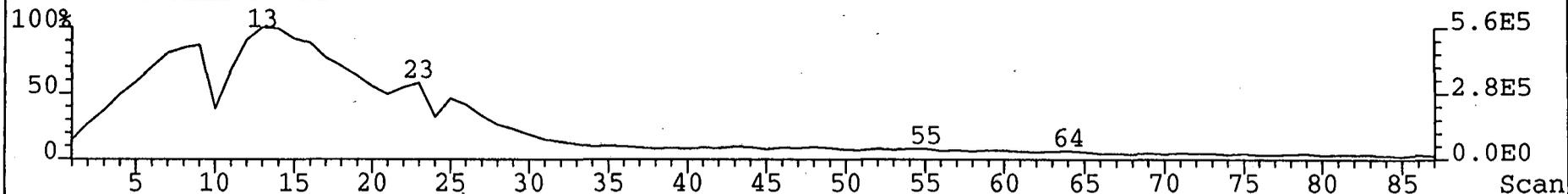
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TIC (+RP) Exp:MAGNET

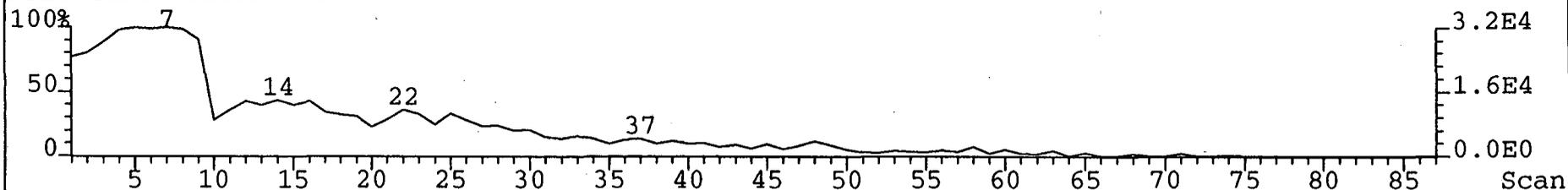
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94 (+RP) Mer Def 0.25 Exp:MAGNET

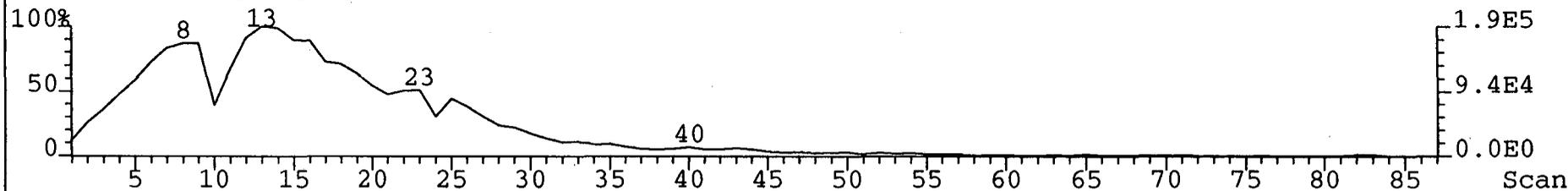
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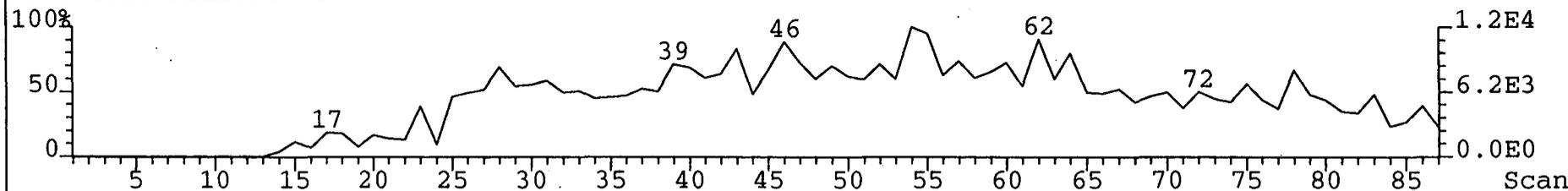
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278 (+RP) Mer Def 0.25 Exp:MAGNET

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