ACTIVATED CARBONS OBTAINED FROM SEWAGE SLUDGE BY CHEMICAL ACTIVATION: GAS-PHASE ENVIRONMENTAL APPLICATIONS

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ABSTRACT

The objective of this study was to evaluate the adsorption capacity for toluene and SO₂ of low cost activated carbons prepared from sewage sludge by chemical activation at different impregnation ratios. Samples were characterized by proximate and ultimate analyses, thermogravimetry, infrared spectroscopy and N₂ adsorption. Because of the low carbon content of the raw material, the development of porosity in the activated carbons was mainly of a mesoporous nature, with surface areas lower than 300 m²/g. The study of gas-phase applications for activated carbons from sewage sludge was carried out using both an organic and an inorganic compound in order to screen for possible applications. Toluene adsorption capacity at saturation was around 280 mg/g, which is a good level of performance given the high ash content of the activated carbons. However, dynamic experiments at low toluene concentration presented diffusion problems resulting from low porosity development. SO₂ adsorption capacity is associated with average micropore size, which can be controlled by the impregnation ratio used to prepare the activated carbons.

Keywords: sewage sludge; activated carbon; gas-phase application; SO₂ adsorption; toluene adsorption

1. INTRODUCTION

Sewage sludge is the major byproduct of wastewater treatment plants worldwide. Its disposal is becoming a growing problem given that it is a potential source of heavy metals and of pathogens, which are contained in the wastes. It is estimated that the need for wastewater treatment will increase and, accordingly, the amount of wastes produced in water treatment plants will also increase (Cao et al., 2013; Fonts et al., 2012).

Usual disposal processes are agricultural applications, landfill and incineration. However, because of limits set by stringent environmental regulations, there is a need to seek other environmental friendly applications. Turning sewage sludge into an activated carbon has received considerable attention (Rozada et al., 2005) owing to its environmental sustainability and its potentially low cost (Stüber et al., 2011). According to the review by Smith et al. (2009) different methodologies have been developed for the production of sewage sludge-based activated carbon, and research is continuing into applications for the removal of pollutants such as dyes, metals and phenols. However, little effort has been devoted to their gas-phase application, such as in toluene and sulphur dioxide adsorption.

The rapid development of chemical, pharmaceutical and other processing industries, and the ever-increasing number of motor vehicles on the world's roads, together with emissions from the combustion of fossil fuels in power plants and similar industrial processes, are resulting in the release of large amounts of hazardous gases and vapours into the atmosphere, which in turn is placing considerable pressure on the availability of clean air. These effluents contain small amounts of a large number of volatile organic compounds (VOCs). These flue gases also contain small amounts of sulphur and nitrogen oxides, the most important of these being SO_2 and NO . These gases combine with VOCs to produce smog and sometimes also produce acid or smog clouds. These occurrences have led to more stringent regulations for pollution control (Bansal and Goyal, 2005).

Numerous studies have established that sewage sludge-based activated carbon shows great promise as feedstock for the production of adsorbents (Smith et al., 2009). However, the properties of the final product and its response to different pollutants are different, depending on the nature of the sewage sludge (Gasco et al., 2005), the nature of the activating agent and the conditions of carbonization and activation processes. Most research has been focused on aqueous adsorption (Gu et al., 2013), such as dye removal (Rozada et al., 2003; Li et al., 2011), metal ion uptake (Otero et al., 2009), copper adsorption (Wang et al., 2011), mercury removal from water (Zhang et al., 2005), adsorption of benzene and toluene from aqueous solutions (Wibowo et al., 2007) and adsorption of 4-chlorophenol (Mansalvo et al., 2011). Some authors (Wen et al., 2011) have studied the adsorption of gaseous formaldehyde, while others have studied the removal of odorous VOCs (Anfruns et al., 2011). However, no further studies were accomplished concerning gaseous adsorption on sewage sludge-based activated carbon.

In this context, this work focuses on the performance of low cost activated carbon prepared from sewage sludge by chemical activation at different impregnation ratios in gas phase applications, through the study of SO₂ and toluene adsorption at low concentration.

2. MATERIALS AND METHODS

2.1. Activated carbon preparation

Sewage sludge (SS) used was collected from drying beds of an urban treatment plant in Mascara, Algeria, where wastewater undergoes biological treatment by means of an activated sludge process. The SS was first dried at 105°C, then crushed and sieved to a uniform size. The fraction with a particle size of 0.5-1 mm was chosen to prepare the activated carbons. Chemical activation with (ortho)-phosphoric acid was carried out using the impregnation method followed by one-step carbonization-activation in N₂ atmosphere. A portion of SS was mixed with a certain amount of

H₃PO₄ (85%wt concentration) and stirred for 2 hours at room temperature. Five impregnation ratios were chosen R1:0.75, R1:1, R1:1.25, R1:1.5 and R1:2 (dry sewage sludge: H₃PO₄, wt/wt). H₃PO₄ was chosen owing to the ease of the post activation extraction process and its relatively low activation temperature (Wang et al., 2011). On completion of the impregnation step, the mixture became a brown adhesive-like solid.

The impregnated samples were pyrolysed in a quartz reactor under a nitrogen atmosphere, with a heating rate of 10°C/min up to 600°C. This temperature was maintained for 1 hour. The materials were then cooled down to room temperature.

The activated carbons obtained were washed using a Soxhlet apparatus for a period of 48 hours until the pH was around 6-7. The products were subsequently dried in a vacuum furnace at 105°C for 4 hours.

The activated carbons obtained were labelled as SSPT600R0.75 (R1:0.75), SSPT600R1 (R1:1), SSPT600R1.25 (R1:1.25), SSPT600R1.5 (R1:1.5) and SSPT600R2 (R1:2).

2.2. Characterization

Samples were characterized by proximate analysis, ultimate analysis, thermogravimetry (TGA), infrared spectroscopy (FTIR) and N₂ adsorption.

Proximate analysis of samples was carried out according to standards ISO-589-1981 for moisture content, ISO-1171-1976 for ash content and ISO-562-1974 for volatile content. Ultimate analysis was carried out in a Termo Flash 1112 microanalysis apparatus to determine C, H, N and S contents. Oxygen content was obtained by difference.

Thermogravimetric analysis of the mixture SS + H₃PO₄ (1:1, after mixing for 2 hours at room temperature) was performed in a thermobalance from TA Instruments. Approximately 20 mg of the mixture was placed in a Pt crucible and heated by 20°C/min up to 850°C under inert atmosphere.

Infrared spectra of the activated carbons were obtained in a Bruker Tensor 27 apparatus. A small amount of finely ground sample was placed directly on the equipment. The spectra were normalized and the baseline was corrected with the software provided with the apparatus.

Textural characterization was performed by N₂ adsorption-desorption at -196°C. Isotherms were obtained in an ASAP 2020 apparatus from Micromeritics. Prior to the analysis, samples were outgassed at 200°C up to a vacuum of 10⁻⁵ mm Hg. The volume of adsorbed nitrogen was measured from a relative pressure of 10⁻⁷ up to 0.995. Surface area was determined by BET method (Brunauer et al., 1938) applied to the adsorption branch of the isotherm. Pore volume corresponding to micropores was calculated using the Dubinin-Radushkevich (DR) equation applied to the adsorption branch of the N₂ isotherm (Dubinin., 1989). Pore volume corresponding to mesopores was calculated with the Barret-Joyner-Halenda (BJH) equation applied to the desorption branch of the N₂ isotherm (Barret et al., 1951). The total pore volume was taken from the measure of adsorbed nitrogen at a relative pressure of 0.95. The average micropore diameter was obtained using the Horvath-Kawazoe (HK) method (Horvath and Kawazoe., 1983).

2.3. Adsorption experiments

(Insert figure.1 here)

The toluene adsorption isotherms were obtained using a gravimetric analyser from VTI Corporation (Miami, USA). This apparatus is fully computer controlled and measures adsorption and desorption on a gravimetric microbalance. The sample temperature (25°C) was constantly monitored throughout the duration of the experiments and the variation was found to be 0.5°C. A pressure transducer in the range of 0-100 mm Hg (accurate to ±0.12%) was used to monitor the vapour pressure in the system. Approximately 100 mg of an activated carbon sample was placed in a stainless steel mesh bucket and was outgassed in situ at 150°C under vacuum up to constant weight. Pressure steps in the range of p/p₀ values 0-0.95 were used to obtain the isotherms. After

equilibrium was reached, the organic vapour pressure was increased to the next set pressure value, and the subsequent uptake was measured until equilibrium was re-established.

The breakthrough curves for toluene and sulphur dioxide were obtained in a homemade experimental system used for dynamic mode. A diagram of the experimental installation is given in Figure 1. It consisted of a fixed-bed adsorber with an internal diameter of 1 cm coupled to a mass spectrometer (MS) from Pfeiffer. Toluene and sulphur dioxide vapours were obtained from cylinders containing either toluene/Ar or sulphur dioxide/Ar to obtain a concentration of 500 ppmv in the gas. The flow rate was 30 ml/min and the adsorption temperature was 25°C. Samples were used without previous degasification. Before starting an experiment, the gas stream bypassed the adsorber bed in order to allow either the toluene or sulphur dioxide concentration to be measured.

3. RESULTS AND DISCUSSION

(Insert table.1 here)

Table 1 shows the elemental and proximate analysis results corresponding to the SS and activated carbons. The SS contained about 50 % ash and presented a carbon content of about 25%. However, after activation, the ultimate analysis showed that the obtained activated carbons contained more carbon, and showed a decrease in other elements (N, H and S) comparing with the dried SS, however their percent weight values differ from one to another activated carbon. SSPT600R1.5 presents the lowest N, H wt % values. While SSPT600R1.25 presents the lowest S wt % value with SSPT600R1.5. Furthermore the amount of oxygen decreases with 1-2% wt when the activation ratio increases; however the SSPT600R2 presents the lowest value 58.86% oxygen. The average amount value of oxygen without SSPT600R2 is 65.4%. This high oxygen percentage was mainly due to the high organic part of the precursor. In addition, the phosphoric acid impregnated the carbon with oxygen, on the one hand, but oxygen was also released with volatile matter, on the other. This combined oxygen has often been found to be the source of the property by which a carbon becomes useful and effective for some applications (Bansal and Goyal., 2005).

(Insert figure.2 here)

Thermogravimetric analysis provides a prior knowledge of initial and final temperatures of thermal degradation of SS (Cao et al., 2013). As shown in Figure 2, pyrolysis of SS consisted of four stages. The first loss phase on the DTG curve corresponded to moisture release. A double peak could be observed in the second stage: the first shoulder could be identified with biodegradable materials, undigested organics and dead bacteria, together with the emissions of semivolatile compounds; the second shoulder could be associated with the evolution of organic polymers, which need higher temperatures to devolatilize. The third stage could be assigned to cellulosic material reaction (Calvo et al., 2004). Last peak could be attributed to the decomposition of inorganic materials. The residue percentage was about 57%. Although the ash content of dried SS was about 51%, it may be concluded that the amount of final residue depends on the organic materials in sludge as well as the amount of inorganic materials. The final temperature for pyrolysis was selected as 600°C based on the profiles obtained from thermogravimetric analysis.

The chemical characteristics of activated carbon are largely determined by surface chemical heterogeneity, which is related to the presence of heteroatoms in the structure of the activated carbons. Oxygen, nitrogen, hydrogen, sulphur and phosphorus, and the delocalized electrons of the carbon structure determine the acidic or basic character of the activated carbon surface. FTIR spectroscopy is one of the most versatile and powerful analytical methods used as a qualitative technique for the evaluation of the chemical structure of carbon materials (Shafeeyan et al., 2010).

(Insert figure.3 here)

The FTIR spectra of the raw SS and the activated carbon samples SST600R1, SST600R1.5 and SST600R2 are shown in Figure 3. The spectrum for the SS exhibited C-O stretching absorption at around 1000 cm^{-1} present in ethers (Grube et al., 2006; Shen et al., 2008) and in polysaccharide or polysaccharide-like substances (Mahapatra et al., 2012). Another band was observed at 1412 cm^{-1} assigned to carbonates or carboxyl-carbonates (Shen et al., 2008). Aromatic -C-C stretching could be noticed at around 1600 cm^{-1} , with this band also being assigned to quinones (Mahapatra et al.,

2012). The band observed at 2921 cm^{-1} attributed to --C-H stretching may have been due to the presence of aldehydes (Mahapatra et al., 2012). A wide band at about 3300 cm^{-1} could be assigned to the --O-H of alcohols (Shen et al., 2008), or could also be assigned to the N-H stretching due to the presence of proteins responsible for the presence of nitrogen (Cao et al., 2013). The FTIR spectra of SSPT600R1, SSPT600R1.5 exhibited similar profiles, whereas, low bands intensity was noticed in the case of SSPT600R2 profile. Comparing their FTIR spectra with that of the raw SS, there was seen to be a clear change in the intensity of the bands, as noticed at around 1600 cm^{-1} , when other band had just disappeared, confirming the decomposition of organic components. Moreover, the activated carbons samples showed a new band at around 1057 cm^{-1} assigned to the O-H of alcohol. Furthermore, it seems that the increase in the impregnation ratio did not affect the type of surface groups on the activated carbons prepared. The activated carbons presented an acidic surface owing to the presence of carboxylic groups that rendered the carbon surface hydrophilic and polar in character, which in turn was able to improve the adsorption properties toward polar gases.

(Insert figure.4 here)

Figure 4 shows the N_2 adsorption isotherms of the activated carbons and Table 2 summarizes the porosity characterization of the samples.

All the N_2 adsorption/desorption isotherms of the activated carbons (Figure 4) were type IV, according to BBDT classification, with a rounded knee at low pressure corresponding to multilayer physical adsorption, and with type H1 hysteresis loops according to IUPAC classification (Sing et al., 1985), typical of mesoporous materials. However, all the samples showed a steep nitrogen uptake at very low relative pressures, which corresponded to the presence of some microporosity. It would seem from the nitrogen adsorption results that all the samples were largely mesoporous, with some micropores. An increase in the amount of H_3PO_4 (increasing of impregnation ratio over 1:1.5) led to a decrease in surface area and microporosity, while mesoporosity increased, as can be seen in Table 2. This could be attributed to the pore-widening that occurred with the increase in the impregnation ratio (Guo et al., 2007; Passe-Coutrin, 2008).

On the other hand, the similar sharp increase for the N₂ uptake ($P/P_0=0.9-1$) for the samples and the appearance of the hysteresis loop at ($P/P_0=0.4-1$) indicated capillary condensation taking place on mesoporous surfaces (Lithoxoos et al., 2010). This could be indicative of a particle clearance hole on the sample which might have affected the gas adsorption-desorption process.

(Insert table.2 here)

From Table 2, it can be seen that sample SSPT600R1.5 developed the maximum BET surface area of 296 m²/g. However, an increase in the impregnation ratio over 1.5 gave rise to a decrease in microporosity, indicating the collapse of the pore wall due to an excess of carbon material loss.

(Insert figure.5 here)

Figure 5 shows the toluene adsorption isotherms for activated carbons. As can be deduced, medium adsorption capacities of around 25 wt% could be obtained with some carbons. Toluene isotherms are type I according to the BDDT classification. In general, carbons obtained at higher impregnation ratios exhibit higher toluene adsorption capacities than those obtained at lower impregnation ratios. By applying the Langmuir model to the toluene isotherms, the limiting value for vapour adsorption (W_m) and constant value K could be obtained. These values are shown in Table 3, as well as the regression coefficient R^2 . Good correlation was obtained despite the presence of mesoporosity, which limited the validity of Langmuir model. However, the fit on the low pressure region was limited when there was continuous adsorption at high relative pressures. K values could be associated with the increased microporosity in a series of carbons, and this development of the microporosity could be related to the degree of activated carbon burn-off.

(Insert table.3 here)

As can be seen from Table 3, values as high as 284 mg toluene/g sample were obtained. However, a low concentration of toluene in gas stream is typical in real gas-phase applications, so, the adsorption at low relative pressures is of great importance.

(Insert figure.6 here)

Figure 6 shows toluene breakthrough curves for the activated carbons. None of them were steep enough to rule out some diffusional problems; this could have been due to poor microporosity development. The integration of the breakthrough curves gave the amount of toluene adsorbed.

(Insert table.4 here)

Table 4 reports the corresponding breakthrough time, saturation time and the amount of toluene adsorbed at saturation. It should be noted that a longer breakthrough time indicates better dynamic adsorption capacity (Zhang et al., 2012), which is corroborated by the maximum adsorption capacity for toluene adsorbed by SSPT600R1.5 (15.6 mg/g). Moreover, as seen in Figure 6, the breakthrough curve of SSPT600R1.5 was noticeably different after breakthrough time compared with breakthrough curves obtained for the other samples, with a big gap as the adsorption moved into saturation. In this range, the breakthrough curve increased, while the slope decreased slightly 50 minutes after the breakthrough time. The slope then increased again for a short time and finally decreased until saturation point, with an s-shape curve. Axial diffusion resistance and axial dispersion were responsible for decreasing the breakthrough curve. Axial diffusion may have been accelerated with smaller particles and axial dispersion may have been slowed with the more compact bed.

Microporosity seems to have been responsible for the difference in the breakthrough time as well as for the amount of toluene adsorbed by the activated carbons. These results are in agreement with previous results found in the literature that conclude that the volume of micropores is an important parameter for VOC adsorption (Zhang et al., 2012). Furthermore, at low pressure the adsorption for VOCs was fairly good in micropores compared with mesopores because of the interaction between the attractive forces of the pore walls and the adsorbents; that could be the reason for the breakthrough time being much longer for the sample with a high proportion of micropores (Zhang et al., 2012).

However, the rest of the samples adsorbed a lower amount of toluene as a result of lower activation, whereas SSPT600R2 showed low adsorption capacity for toluene in dynamic mode because of its

low microporosity. During the preparation of this sample, a very sticky mixture was obtained when it was mixed with H_3PO_4 , which made mixing difficult; so a poor contact between the sewage sludge and the acid was expected. This problem could also have caused difficulties to the flow of inert gas during the pyrolysis step. Moreover, the micropores could have been blocked as a consequence of this (Zhang et al., 2012) or of pore wall collapse (Izquierdo et al., 2011), which would have had negative effects on toluene adsorption.

(Insert table.5 here)

Furthermore, and in order to compare adsorption of toluene in both static and dynamic mode, the uptake for toluene in static mode was calculated by means of the Langmuir model at a relative pressure corresponding to 500 ppmv ($P/P_0=1.3 \times 10^{-2}$) which was the initial concentration in dynamic adsorption. The amounts adsorbed in both cases are presented in Table 5, which reveals that the adsorbed amounts values were quite different. For SSPT600R1.5, for example, the retained amount was 43.4 mg/g at 500 ppmv in static adsorption and about 16 mg/g in dynamic adsorption. Equilibrium was difficult to reach in dynamic mode (De Yuso et al., 2013). The mesoporous nature of these obtained activated carbons may also have played an important role in the large difference between static adsorption uptake and dynamic adsorption uptake values.

(Insert figure.7 here)

(Insert table.6 here)

Figure 7 gives the SO_2 breakthrough curves for samples SSPT600R1, SSPT600R1.5 and SSPT600R2. Samples SSPT600R1 and SSPT600R1.5 showed higher breakthrough times than sample SSPT600R2, which exhibited a less steep breakthrough curve. The amount of SO_2 adsorbed was calculated from the integration of the breakthrough curves and these values are given in Table 6. In the case of SO_2 adsorption, experimental evidence exists of the need for a pore size distribution centred at 0.7 nm (Raymundo et al., 2000). According to these researchers, SO_2 uptake is analysed considering the SO_2 oxidation to SO_3 as a new variable that is strongly affected by pore size distribution. An optimum pore size exists (*i.e.* pore size of about 0.7 nm) in which the oxidation

of SO₂ to SO₃ is favoured. Pore width enlargement decreases the conversion of SO₂ to SO₃ and, thus, the total amount of SO₂ retained by the carbon sample. In the present case, the average micropore size obtained by the HK method was higher than that optimum value. However, sample SSPT600R1.5 had the nearest average pore size to this optimum value and adsorbed around 19.76 mg/g, higher than the amount of SO₂ adsorbed by the other samples.

4. CONCLUSIONS

Activated carbons were obtained from sewage sludge by chemical activation with phosphoric acid. The surface area of the activated carbons was under 300 m²/g. The activated carbons obtained were mainly mesoporous. The impregnation ratio influenced not only the surface area but also the porosity developed, increasing mesoporosity as the impregnation ratio increased up to pore collapse, causing a decrease in micropores. The surface chemistry was similar for all samples studied.

The study of gas-phase applications of activated carbons from sewage sludge was carried out using an organic and an inorganic compound in order to screen for possible applications. Toluene adsorption capacity was around 280 mg/g, which is a good level of performance, taking into account the high ash content of the activated carbons. However, dynamic experiments at low toluene concentration showed diffusional problems owing to low porosity development. SO₂ adsorption capacity was associated with average micropore size, which could be controlled by the impregnation ratio used to prepare the activated carbons.

These results show that activated carbons from sewage sludge are promising low cost adsorbents for gas-phase application. More research should be done in order to optimize preparation, which will improve adsorption characteristics for a specific use.

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Figure 1 (page 6)

Figure 2 (page 8)

Figure 3 (page 8)

Figure 4 (page 9)

Figure 5 (page 10)

Figure 6 (page 10)

Figure 7 (page 12)

FIGURE CAPTIONS

Fig.1. Experimental installation. (Page 6)

Fig.2. DTG of sewage sludge. (Page 8)

Fig.3. FTIR spectra of sewage sludge and activated carbon samples. (Page 8)

Fig.4. N₂ adsorption - desorption isotherms of activated carbons. (Page 9)

Fig. 5. Toluene adsorption isotherms of activated carbons. (Page 10)

Fig.6. Toluene breakthrough curves for activated carbons (operation conditions: temperature 25°C; initial toluene concentration 500 ppm; total flow 30 ml/min). (Page 10)

Fig.7. Breakthrough curves for SO₂ adsorption on samples of activated carbons. (Page 12)

Table 1. Characterization of the starting sewage sludge and activated carbons. (page 7)

Samples	Proximate Analysis				Ultimate Analysis				
	wt %				wt %				
	Humidity	Ash	Volatile	Fixed C	C	H	N	S	O ^a
SS as received	6.98	47.51	42.66	2.85	24.45	3.33	3.25	0.53	68.44
Dried SS	0.00	51.08	45.86	3.06	26.28	2.74	3.49	0.57	66.92
SSPT600R0.75					28.11	1.85	2.03	0.33	67.86
SSPT600R1					29.03	1.45	2.36	0.28	66.88
SSPT600R1.25					32.16	1.42	2.12	0.15	64.15
SSPT600R1.5					34.04	1.02	2.02	0.18	62.74
SSPT600R2					36.64	1.96	2.24	0.30	58.86

% H includes the H of water (humidity). ^a Oxygen content obtained by difference.

Table 2. Textural properties of the activated carbons. (page 10)

Samples	$S_{\text{BET}}^{\text{a}}$ m^2/g	$V_{\text{micro}}^{\text{b}}$ cm^3/g	V_{p}^{c} cm^3/g	$V_{\text{meso}}^{\text{d}}$ cm^3/g	d_{p}^{e} nm
SSPT600R0.75	240	0.089	0.585	0.577	0.95
SSPT600R1	259	0.097	0.633	0.585	0.95
SSPT600R1.25	278	0.116	0.613	0.565	0.91
SSPT600R1.5	296	0.113	0.951	0.575	0.88
SSPT600R2	230	0.077	0.812	0.857	1.12

^a BET surface area

^b volume of micropores, DR method

^c volume of pores at $p/p_0=0.95$

^d volume of mesopores, BJH method

^e average pore diameter, HK method

Table 3. Langmuir isotherm parameters for toluene on obtained activated carbons. (page 10)

Samples	W_m mmol/g	W_m mg/g	K cm^3/g	R^2
SSPT600R0.75	2.43	224	0.44	0.98
SSPT600R1	2.44	226	0.47	0.98
SSPT600R1.25	2.71	250	0.51	0.99
SSPT600R1.5	2.94	271	0.50	0.99
SSPT600R2	3.08	284	0.50	0.98

Table 4. Amount of toluene adsorbed and breakthrough time in dynamic experiments for activated carbons. (page 11)

Samples	Breakthrough time min	Saturation time	
		at	Q_{dyn}
		$C/C_0=0.9$ min	mg/g
SSPT600R0.75	26	60.65	10.72
SSPT600R1	24	84.44	12.21
SSPT600R1.25	30	72.85	11.96
SSPT600R1.5	33	96.78	15.58
SSPT600R2	25	59.23	10.24

Table 5. Comparison between static and dynamic adsorption of toluene. (page 12)

Samples	Static ($P/P_0 = 0.9$)	Static ($P/P_0 = 1.3 \times 10^{-2}$)	Dynamic ($C_0 = 500$ ppm)
	W_m	W	Q_{dyn}
	mg/g	mg/g	mg/g
SSPT600R0.75	223.92	32.15	10.72
SSPT600R1	224.84	34.53	12.21
SSPT600R1.25	249.72	41.01	11.96
SSPT6001.5	270.92	43.44	15.58
SSPT600R2	283.82	46.06	10.24

Table 6. SO₂ adsorbed amount by activated carbons. (page 12)

Samples	Breakthrough time	Q _{dyn}
	min	mg/g
SSPT600R1	65	11.89
SSPT600R1.5	83	19.76
SSPT600R2	16	9.58