Adsorption and Antibacterial Activity of Silver-Dispersed Carbon Aerogels

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ABSTRACT: Silver-dispersed carbon aerogels (Ag/CAs) were obtained by the direct immersion of organic aerogels in aqueous $AgNO_3$ solutions and then carbonization of the resulting material under a nitrogen atmosphere. The adsorption and antibacterial activity of *Escherichia coli* and *Staphylococcus aureus* on Ag/CAs were studied by the measurement of the amount of viable bacteria in suspensions and scanning electron microscopy (SEM) observations. The adsorbed amount of bacteria on samples without silver increased with an increase in the carbonization temperature and contact time. SEM studies showed that the adsorption capacity of Ag/CAs decreased with an increase in the silver content; this was considered to be mainly due to the dissolution behavior of bacteria by silver ions. The antibacterial test showed that 2.5 mg of Ag/CAs with more than 3.6% Ag could inhibit the growth of 10^5 cfu/mL *E. coli* in 10 mL of a Mueller–Hinton broth culture, but in the case of *S. aureus*, 10-mg samples just got the same antibacterial effect. An antibacterial persistency test showed that 25 mg of Ag/CAs with 6.5% Ag could kill 50 mL of 10^5 cfu/mL *E. coli* eight times. These results indicate that Ag/CAs possess strong and long-term antibacterial activity. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 102: 1030–1037, 2006

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INTRODUCTION

Microbial pollution caused by microorganisms has produced various problems in daily life and industry. Porous carbon materials have been widely used in wastewater treatments to remove organic or inorganic pollutants because of their large surface areas and high adsorption capacities. Because carbon materials have excellent affinity to microorganisms, bacteria may adhere to the carbon surface.[1] Silver is well known for its bactericidal effects; therefore, many silver-containing porous carbon materials have been developed, such as silver-containing activated carbons (Ag/ACs) and silver-containing activated carbon fibers (Ag/ACFs).[2–5]

The antibacterial activities of Ag/ACs and Ag/ACFs have been widely pointed out,[5–8] and much attention has been directed toward these as a new technique to purify drinking water. To overcome the shortcoming of their weak washing resistance and prolong their effective term of antibacterial activity in real applications, we have recently developed novel silver-dispersed carbon aerogels (Ag/CAs) in which the silver nanoparticles are uniformly incorporated and fixed in the pore network of the aerogels to provide sustained release of silver ions at an acceptable antimicrobial level.[9]

In previous studies,[10–12] the adsorption capacity of activated carbon was reported to depend much on its porous texture and the chemical properties of its surface. The chemical and textural characteristics of carbon aerogels (CAs) are quite different from those of activated carbons or activated carbon fibers. CAs are prepared from organic aerogels that are formed by the sol–gel polycondensation of resorcinol with formaldehyde in solutions. This kind of novel porous carbon material has many interesting properties, such as low bulk density, high surface area, controllable porosity, and highly crosslinking structures.[13,14] These characteristics must play important roles in the adsorption capacity of CAs on bacteria, even affecting the antibacterial activity of Ag/CAs. On the other hand, little information is available regarding the bacterial adsorption capacity of carbon materials under dispersing silver particles and how they affect the antibacterial activities.

The toxicities of metal ions are considered to be related to the solubility, absorbability, transport distance, chemical reactivity, and so forth.[15] Both the adsorption capacity of CAs on bacteria and the reduction–adsorption property of carbon materials

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toward silver ions[16] influence the antibacterial activity of Ag/CAs. The roles of the carbon microstructure, the silver particles, and their interplay in antibacterial activity are still unclear. However, well-dispersed silver particles in CAs are expected to show marked and long-term antibacterial activity in solutions containing bacteria because of the separate distribution of nanometer-sized silver particles throughout the three-dimensional CAs. The antibacterial activity of Ag/CAs in aqueous solutions is very important for applications in drinking water purification systems.

The World and Health Organization[17] has recommended that any water intended for drinking should contain zero counts of fecal and total coliform in any 100-mL sample. *Escherichia coli* (Gram-positive) is the predominant member of the fecal coliform group, and *Staphylococcus aureus* (*S. aureus*) is the representative bacterium of Gram-negative groups. They are usually chosen as fecal contamination indicators to evaluate the bactericide activity. Thus, *E. coli* and *S. aureus* were chosen as test bacteria for this study. The antibacterial activity of Ag/CAs for *E. coli* and *S. aureus* was studied through the measurement of the changes in the residual amount of bacteria in aqueous solutions with bacteria to be killed. The adsorption properties of CAs and Ag/CAs were studied through the measurement of the unabsorbed amount of bacteria and scanning electron microscopy (SEM) observation. To evaluate the effective life of the Ag/CAs, an antibacterial persistency test was also performed.

EXPERIMENTAL

Preparation and characterization of the samples

The preparation procedure for the organic aerogel by the ambient-pressure and room-temperature drying method is described in detail elsewhere.[9] Ag/CAs were obtained by the direct immersion of organic aerogels in aqueous $AgNO_3$ solutions and then carbonization of the resulting material under a nitrogen atmosphere.[18] Typically, 22.0 g of resorcinol, 33.2 mL of furfural, and 0.8 g of hexamethylenetetramine were dissolved in 220 mL of isopropyl alcohol; this was followed by curing for 7 days at 75°C and drying at the ambient pressure and room temperature. These preformed organic aerogels were immersed in aqueous $AgNO_3$ solutions, shaken at room temperature for 24 h, and then dried at room temperature. The Ag-containing organic aerogels were heated to 300–900°C at a heating rate of 5°C/min and kept at the carbonization temperature for 3 h in flowing N_2 (800 mL/min). The resultant Ag/CAs used in antibacterial and adsorption tests were called Ag/CA-*xx*, where *xx* denotes the test number. The CAs without silver loadings were called CA*xxx*, where *xxx* denotes the carbonization temperature. Another CA named MCA with a higher density was obtained according to the literature.[19] The particle size in all cases was between 10 and 40 mesh.

Nitrogen adsorption and desorption isotherms were taken with an ASAP 2010 surface area analyzer (Micromeritics Corp., Atlanta, GA). The Brunauer–Emmett–Teller surface area (S_{BET}), micropore surface area, micropore volume, and mesopore volume of the samples were analyzed with the Brunauer–Emmett–Teller theory, *t*-plot theory, Horvath–Kawazoe theory, and Barrett–Johner–Halendar theory, respectively. For SEM observation, samples were treated as follows: 0.1-g carbon samples were brought into contact with a 10-mL 10^6 cfu/mL bacterial suspension for 2 h at 37°C and then were taken out, immediately washed with distilled water, fixed with 25% glutaraldehyde (v/v) for 5 min, dehydrated step by step in 30, 50, and 100% acetone solutions, and finally dried in air. The dried bacteria-containing carbon samples were mounted on a sample holder and coated with a Au/Pt alloy. The morphology images of the bacteria-containing carbon samples were observed with a Phillips FEI XL30 environmental scanning electron microscope (Eindhoven, The Netherlands).

Adsorption tests of the bacteria

E. coli ATCC 25922 and *S. aureus* ATCC 25923 were used as test bacteria. These bacterial strains were precultured in a Mueller–Hinton (MH) broth at 37°C for 16 (*E. coli*) or 18 h (*S. aureus*) before the test. The bacterial culture was suspended in sterile phosphate-buffered saline (PBS; pH 7.0) with a final concentration of about 10^3 cfu/mL. Carbon samples (0.1 g) were brought into contact with 50 mL of the aforementioned bacterial suspension and then gently stirred at 37°C for 0.5, 1, 2, 4, and 6 h. At each defined time, a 0.1-mL solution was taken out and spread in a 15-mL MH agar plate and cultured at 37°C for 24 h. Subsequently, the colonies that formed with bacteria were counted, and the residual amount of bacteria, that is, the unabsorbed amount of bacteria on the samples, was calculated.

Antimicrobial test of the bacteria

The antibacterial activity of the Ag/CAs was judged by the measurement of the change in the residual amount of bacteria in the broth culture with the contact time. A defined quantity of the silver-containing materials was brought into contact with 10 mL of MH broth containing about 10^5 cfu/mL *E. coli* or *S. aureus* and then was cultured at 37°C under orbital shaking at 200 rpm for 2, 4, 6, and 24 h. At each defined time, 0.1-mL treated solutions were taken out and diluted with distilled water to a certain volume (to adjust the bacterial concentration of the treated solution and ensure that

the grown bacterial colonies could be counted easily and correctly). The diluted solution was then spread in a 15-mL MH agar plate, and microorganisms were cultivated at 37°C for 24 h. Subsequently, the number of bacterial colonies was counted. Each evaluation was carried out in triplicate, and the values were averaged to give the final data.

Antibacterial persistency test of the samples

Five Ag-dispersed samples obtained at different carbonization temperatures were used in this test. A 50-mL 10^5 cfu/mL *E. coli* bacterial suspension was added to another that contained 25 mg of a sterilized silver-dispersed material in a conical flask. This new suspension was shaken at 37°C for 2 h. Then, 0.1 mL of this suspension solution was moved to an agar plate and cultured for 24 h to detect the residual viable bacteria. After this step, the Ag-dispersed material was separated and sterilized again, and then the previous experiment was repeated until the material had no antibacterial activity.

RESULTS AND DISCUSSION

Characteristics of the samples

The identities, silver contents, and S_{BET} values of the samples used in this study are shown in Table I. S_{BET} of the Ag/CAs decreased with an increase in the silver content but increased with an increase in the carbonization temperature. As reported in our previous publication,[9] silver particles in CAs were dispersed separately throughout the carbon matrix. The distribution and size of the silver particles were influenced by the silver content and carbonization temperature. The silver particles grew during carbonization, and the distributing density of the silver particles increased with an increase in the carbonization temperature.

Adsorption properties of the bacteria on CAs and Ag/CAs

Figure 1(a,b) shows the variations of the residual amounts of *E. coli* and *S. aureus* when they were in contact with the blank CAs at different times. For the adsorption of *E. coli* on various CAs [see Fig. 1(a)], with an increase in the contact time, the residual amount decreased rapidly with increasing carbonization temperature; that is, the residual amount in CA900 was less than that in CA600. The decreasing tendency of the residual amount of *S. aureus* [see Fig. 1(b)] was similar to that of *E. coli*, but the decreasing speed of *E. coli* was quicker than that of *S. aureus*.

The adsorption of bacteria from aqueous solutions on activated carbon was studied previously by Rivera-Utrilla et al.[10] The adsorption capacity of bacteria was reported to be related to the hydrophobicity, the porosity and ash content of the activated carbon, the size and surface charge of the bacteria, and the solution pH. The surface hydrophobicity of carbon is mainly related to the surface oxygen complexes. A decrease in the oxygen content of activated carbon will increase the hydrophobicity and enhance the adsorption process.[12] For the adsorption of bacteria on the blank CAs, the increase in the adsorbed amount of bacteria with increasing carbonization temperature was supposed to be mainly due to the reduction of functional group on the surface of the CAs. The reason that the adsorbed amount for *E. coli* was larger than that for *S. aureus* was supposed to be the difference between the surface structures of *E. coli* and *S. aureus*. The cell surface of *E. coli* was formed with three layers of lipid A, lipopolysaccharide, and peptidoglycan, and the surface of *S. aureus* was formed with one layer of peptidoglycan.[20]

Figure 2(A,B) shows SEM photographs of the CAs and Ag/CAs with 4.0% Ag after the adsorption of *E. coli*, respectively. This kind of CA has a very low density and a three-dimensional network with many

TABLE I
Silver Content, Density, and S_{BET} for CAs and Ag/CAs

Raw material	Sample	Carbonization temperature (°C)	Bulk density (g/cm^3)	S_{BET} (m^2/g)	Ag (wt %)
Blank CAs without silver loading	CA250	250	0.236	105	—
	CA600	600	0.230	589	—
	CA900	900	0.245	678	—
Ag/CAs with different silver contents	Ag/CA-1	900	0.292	652	1.4
	Ag/CA-2	900	0.302	638	3.6
	Ag/CA-3	900	0.349	522	12.5
	Ag/CA-4	900	0.371	484	26.3
Ag/CAs prepared at different carbonization temperatures	Ag/CA-10	900	0.310	613	6.5
	Ag/CA-8	600	0.284	574	4.9
	Ag/CA-7	450	0.303	518	4.0
	Ag/CA-6	300	0.299	106	3.4
	Ag/OA-5[a]	—	0.312	71	3.0

[a] Silver-containing organic aerogel.

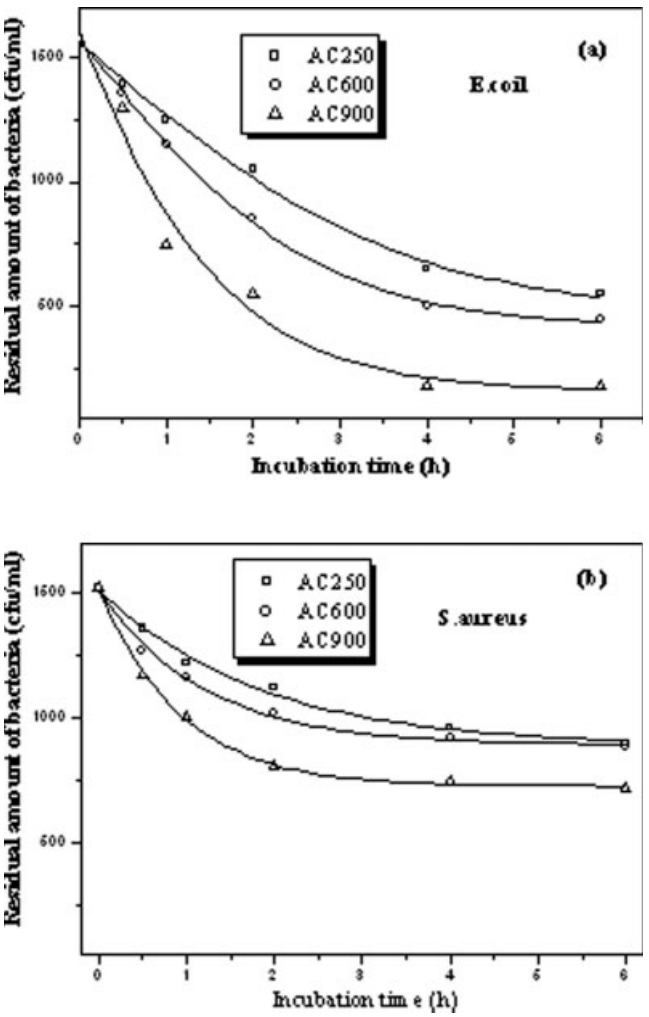

Figure 1 Variations in the residual amounts of (a) *E. coli* and (b) *S. aureus* with the contact time (for blank CAs without Ag, the initial *E. coli* concentration was 1.57×10^3 cfu/mL, and the initial *S. aureus* concentration was 1.52×10^3 cfu/mL).

micropores on the surface of carbon nanoparticles and macropores formed by the stacking of carbon particles. As demonstrated by the SEM photographs [Fig. 2(A,B)], *E. coli*, which has a bacilliform shape with a size of 2 μm$\times$4 μm, is retained on the carbon matrix. In addition, the bodies of *E. coli* bore into the macropores and interweave a netlike distribution. A comparison of Figure 2(A,B) vividly shows that the amount of bacteria adsorbed on the Ag/CAs was less than that on the blank CAs. The decreasing feature of *S. aureus* was similar to that of *E. coli* [see Fig. 2(C,D)]. Spherical *S. aureus* with a size of 600–800 nm looks very similar to the carbon particles in SEM. Nevertheless, the particles of *S. aureus* are large and gray, so they still can be distinguished. In fact, the results from SEM observations with different silver loadings indicated that the adsorbed amount of *E. coli* or *S. aureus* decreased with the increase in the silver content.

The decrease in the adsorption capacity of *E. coli* on Ag/ACFs with an increase in the silver content can be explained by the change in S_{BET} of carbons,[21] which decreases with an increase in the silver content. In our experiments, however, S_{BET} had a weak influence on *E. coli* adsorption. To elucidate the reason for the decreasing trend of *E. coli* adsorption with an increase in the silver content, another kind of CA with a high density, a surface area similar to that of CA900, and many mesopores (see MCA in Table II) was used to adsorb bacteria for comparison in this study. The bacteria were viable *E. coli* [see Fig. 3(A)], dead *E. coli* killed by sterilization in an autoclave at 121°C for 20 min [see Fig. 3(B)], and dead *E. coli* killed by Ag^+ [see Fig. 3(C)]. Unlike CA900, the pore of MCA was too small to be accessible to *E. coli*, which were just attached to the external surface of MCA. This result can also be seen in Table II. The slightly reduced S_{BET} values and volumes of both the mesopores and micropores resulted from the blocking of pores at which the bacteria were deposited on the surface. The bacteria killed by sterilization kept the bacilliform shape, seeming similar to the *E. coli* in Figure 3(A), whereas the *E. coli* killed by Ag^+ was totally distorted into an irregular shape, even dissolved in solution. Thus, the higher the silver content was for the CAs, the less the whole bacterial body existed in suspension, and the less *E. coli* was adsorbed. Comparing Figure 3(C) and Figure 3(B), we can clearly see that the adsorbed amount of *E. coli* killed by Ag^+ was much less than that of *E. coli* killed by sterilization. It can be deduced from these results that the reduction of adsorbing *E. coli* with the increase in the silver content was mainly due to the dissolution behavior of *E. coli* by silver ions released from Ag/CAs.

Antibacterial properties of the Ag/CAs

Tables III and IV show the antibacterial activities of Ag/CAs against *E. coli* and *S. aureus* suspended in 10 mL of an MH broth medium for different contact times. The Ag/CAs exhibited pronounced stronger antibacterial activity against *E. coli* than against *S. aureus*. When 2.5- or 5-mg samples were brought into contact with 10 mL of a 1.57×10^5 cfu/mL *E. coli* containing MH broth, almost all the bacteria were killed, except for the Ag/CA-1 sample (see Table III). However, 5-mg samples with Ag concentrations greater than 6.5% or 10-mg samples with Ag concentrations greater than 3.6% could inhibit the growth of 10 mL of 1.80×10^5 cfu/mL *S. aureus* or kill them (see Table IV). These results indicate that the antibacterial activity increased with an increasing mass concentration of Ag/CAs in the medium and increased with increasing silver content as well.

Table V compares the antibacterial activities of the Ag/CAs obtained at different pyrolysis temperatures on *E. coli* and *S. aureus*. In the case of the Ag/OA-5

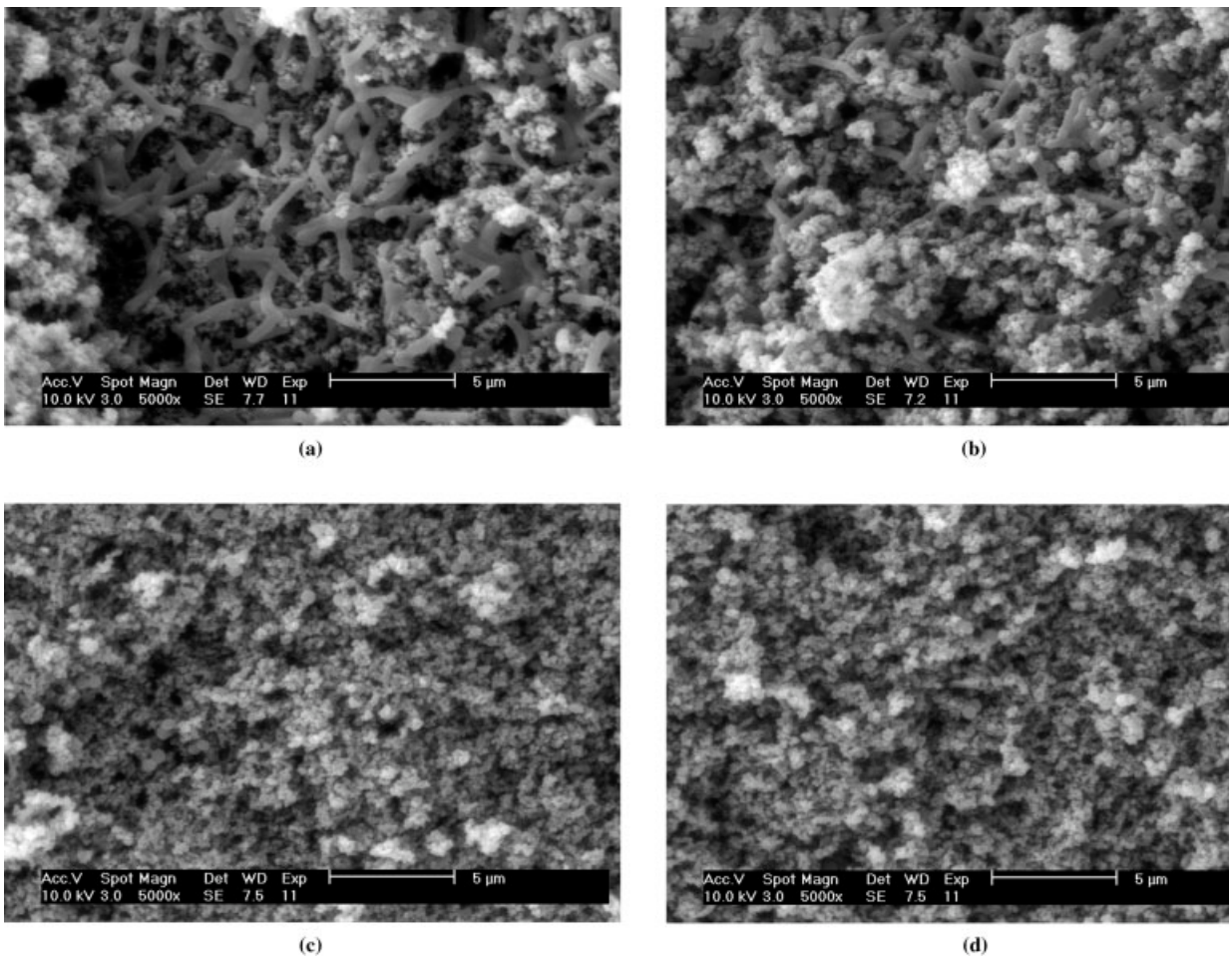

Figure 2 SEM photographs of CA samples that adsorbed *E. coli* and *S. aureus*: (a) CA900 that adsorbed *E. coli*, (b) Ag/CA-2 that adsorbed *E. coli*, (c) CA900 that adsorbed *S. aureus*, and (d) Ag/CA-2 that adsorbed *S. aureus*.

sample on *E. coli* and *S. aureus*, the number of surviving bacteria went to zero at the contact time of 4 h, and its antibacterial activity was stronger than that of Ag/CA-10 (carbonized at 900°C). This can be explained by the high Ag^+ concentration released from the aerogels with the main component of $AgNO_3$. With an increase in the carbonization temperature, a pronounced change was found at a short contact time; that is, the antibacterial activity became stronger and stronger. As the results in Table V demonstrate, the antibacterial activity of all CA samples carbonized at different temperatures for *S. aureus* was weaker than that for *E. coli*.

The mechanism underlying the bactericidal activity of silver-containing compounds remains generally unclear. According to a previous report on the antibacterial properties of ACF/Ag[6–8] and AC/Ag,[5] the following factors may affect the antibacterial activity: (1) the concentration of Ag^+ released from the materials, (2) the ability of microorganisms to be adsorbed on a carbon matrix (the affinity of carbon for the bacteria), (3) the opportunity of bacteria to come into contact with silver, and (4) the reactive oxygen species generated from silver and/or supports.[7,8] The concentration of released Ag^+ is related to the silver content, silver particle size, and S_{BET}

TABLE II
Textual Characteristics of MCA Samples before and after *E. coli* Adsorption

Sample	Density (g/cm^3)	S_{BET} (m^2/g)	S_{mic} (m^2/g)	V_{mic} (cm^3/g)	V_{meso} (cm^3/g)	D_{mic} (nm)
MCA	0.452	623.4	339.1	0.16	1.02	13.4
MCA/*E. coli*	—	589.9	317.1	0.15	1.01	13.2

S_{mic} = micropore area; V_{mic} = micropore volume; V_{meso} = Barrett–Johner–Halendar desorption cumulative pore volume of pores between 1.7 and 300 nm in diameter; D_{mic} = micropore diameter.

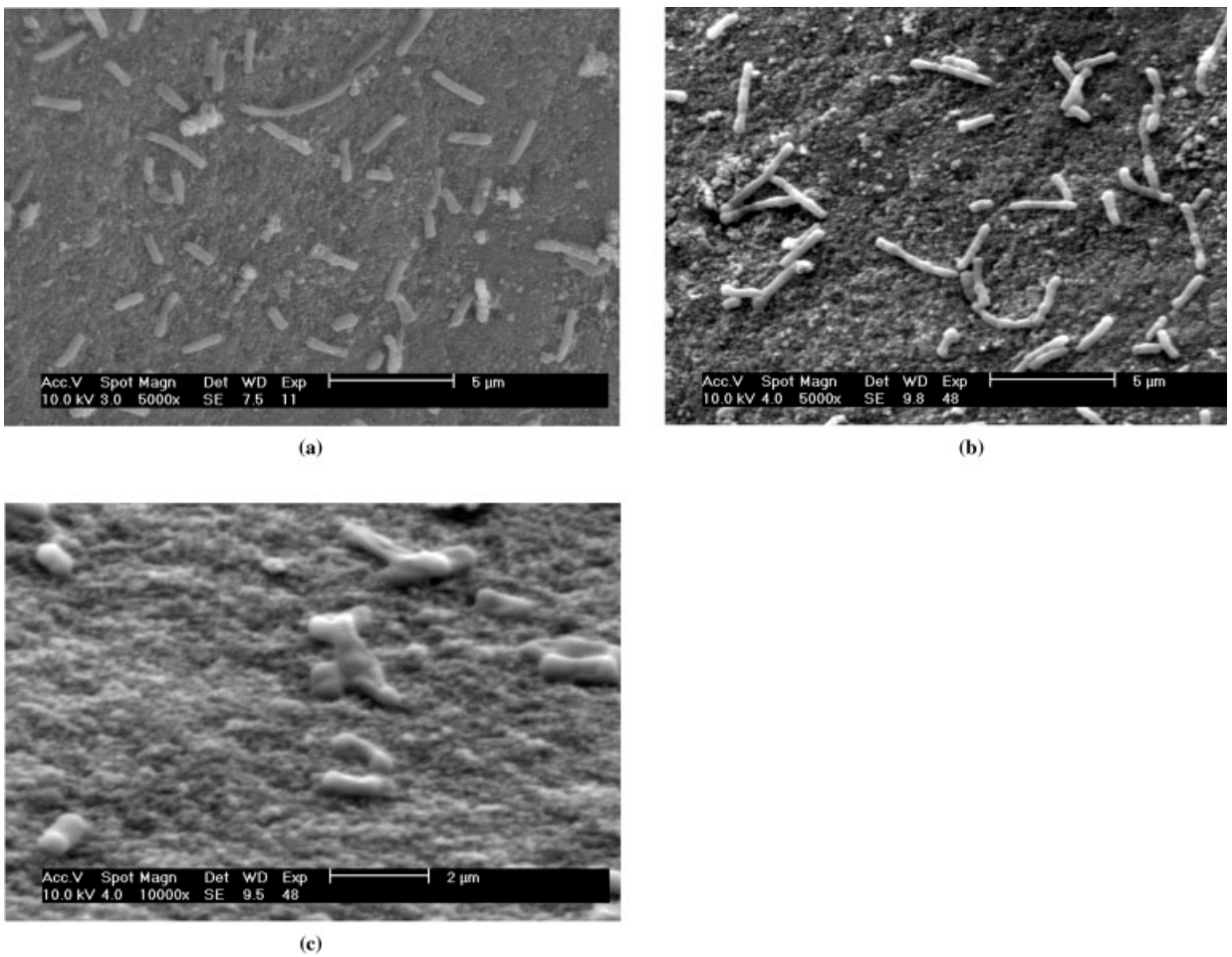

Figure 3 SEM photographs of *E. coli* adsorbed by MCA: (a) adsorption of viable *E. coli*, (b) adsorption of *E. coli* killed by sterilization in an autoclave at 121°C for 20 min before the experiment, and (c) adsorption of *E. coli* killed by silver ions (100 ppm).

value of the carbon matrix. Lowering the silver content is beneficial for suppressing the release of silver ions, but the antibacterial activity gets weak correspondingly. Previously, it has been reported[5,6] that the antibacterial activity is enhanced by a reduction of the silver particle size. In our study, with an increase in the carbonization temperature, the size of the silver particles slightly increased,[9] and the Ag^+ release level became appreciably lower (details about the Ag^+ release mechanism and data will be reported later). From this point of view, the antibacterial activity should decrease with an increase in the carbonization temperature. On the other hand, a large specific surface area of carbon will enhance the adsorption capacity of Ag^+; this also leads to a decrease in the Ag^+ concentration in solution but naturally increases the Ag^+ concentration around the carbon surface. Meanwhile, the adsorbed amount of bacteria on the

TABLE III
Antibacterial Properties of Samples with Various Silver Loading Levels on *E. coli*

	2.5 mg of *E. coli*[a]				5.0 mg of *E. coli*[a]			
Sample	2 h	4 h	6 h	24 h	2 h	4 h	6 h	24 h
Ag/CA-1	6.75×10^5	—[b]	—[b]	—[b]	4.25×10^5	—[b]	—[b]	—[b]
Ag/CA-2	7.50×10^4	3.50×10^3	150	0	1.86×10^4	20	0	0
Ag/CA-10	1.34×10^4	780	15	0	3.50×10^3	35	10	0
Ag/CA-3	4.70×10^3	265	5	0	2.80×10^3	30	0	0
Ag/CA-4	3.50×10^3	20	0	0	2.50×10^3	0	0	0

The initial concentration of *E. coli* was 1.57×10^5 cfu/mL.
[a] Weight of Ag/CAs.
[b] The bacteria were uncountable.

TABLE IV
Antibacterial Properties of Samples with Various Silver Loading Levels on *S. aureus*

	5.0 mg of *S. aureus*[a]				10.0 mg of *S. aureus*[a]			
Sample	2 h	4 h	6 h	24 h	2 h	4 h	6 h	24 h
Ag/CA-1	1.20×10^6	—[b]	—[b]	—[b]	3.71×10^5	2.30×10^7	—[b]	—[b]
Ag/CA-2	9.40×10^4	2.50×10^5	—[b]	—[b]	2.55×10^4	500	130	0
Ag/CA-10	6.90×10^4	5.10×10^3	1.20×10^3	520	2.20×10^4	200	70	0
Ag/CA-3	5.60×10^4	4.20×10^3	8.62×10^2	60	2.40×10^4	20	0	0
Ag/CA-4	5.40×10^4	3.84×10^3	5.60×10^2	0	4.50×10^3	0	0	0

The initial concentration of *S. aureus* was 1.03×10^5 cfu/mL.
[a] Weight of Ag/CAs.
[b] The bacteria were uncountable.

carbon surface also increases with the increase in the carbonization temperature, as we discussed previously. Thus, the bacteria around or on the surface of carbon samples carbonized at a higher temperature have more chance to be killed by contact with silver. As for factor 4, we have had no direct proof to explain the phenomenon until this study. Further investigation needs to proceed on whether the antibacterial effects of Ag/CAs are linked to the reactive oxygen species.

Silver toxicity is known to proceed from Ag^+ binding with the negatively charged peptidoglycans (containing sulfhydryl groups) on bacterial cells, which destroy the structure of the cell wall and then lead to the dissolution and death of the bacteria.[22] The cell surfaces of Gram-positive species (*E. coli*) contain 3–20 times more peptidoglycans than Gram-negative bacteria (*S. aureus*). Because peptidoglycans are negatively charged, they probably bind some portion of Ag^+ in solution. This explains why the antibacterial activity of samples for *E. coli* was stronger than that for *S. aureus*. Kawahara et al.[23] reported that silver zeolite in water released no detectable amounts of Ag^+, whereas that in PBS released 0.53 μg/mL Ag^+ with 24 h of incubation. Similarly, Ag^+ has a strong affinity to sulfhydryl groups: when the bacteria have more opportunity to bind Ag^+, they might enhance Ag^+ release. Accordingly, the killing rate of bacteria would exceed the growing rate, and so the antibacterial activity would be enhanced. Thus, the antibacterial effects were not exclusively linked to the apparent concentration of Ag^+. The increase in the contact opportunity of silver with the bacteria accelerated the ionization of silver. Therefore, these discussions further explain that the strong antibacterial activity of the samples carbonized at a high temperature may have been mainly due to the increasing contact opportunity of bacteria with silver. However, chlorides, sulfur-containing proteins (microorganisms), and other organic pollutants probably inactivate some silver ions released from Ag/CAs. Thus, further studies should be performed to evaluate the antibacterial activity in real applications.

Antibacterial persistency of the samples

Table VI shows the antibacterial persistency of Ag/CAs obtained at different pyrolysis temperatures on *E. coli*. The antibacterial times were prolonged with an increase in the carbonization temperature. For sample Ag/OA-5, the components of silver included Ag^+ ($AgNO_3$) and Ag^0 (formed in the immersion process). Therefore, it still had antibacterial persistency to some extent. In the case of Ag/CA-10, 25-mg samples could adsorb or kill 50 mL of 10^5 cfu/mL *E. coli* eight times. These results obviously indicate that the Ag/CAs possess strong and long-term antibacterial activity. Thus, this kind of material can be expected to have promising applications in water treatments.

TABLE V
Antibacterial Properties of Ag/CAs at Different Pyrolysis Temperatures on *E. coli*

	E. coli					*S. aureus*				
Sample	Weight (mg)	2 h	4 h	6 h	24 h	Weight (mg)	2 h	4 h	6 h	24 h
Ag/OA-5[a]	12.4	15	0	0	0	24.8	2.20×10^3	0	0	0
Ag/CA-6	10.9	2.15×10^4	250	5	0	21.8	1.01×10^5	5.82×10^5	7.50×10^7	—[b]
Ag/CA-7	9.3	1.45×10^4	29	0	0	18.6	1.50×10^4	510	150	0
Ag/CA-8	7.6	1.35×10^4	15	0	0	15.2	1.47×10^4	350	120	0
Ag/CA-10	5.8	3.51×10^3	0	0	0	11.6	1.70×10^4	100	20	0

The initial concentration of *E. coli* was 1.57×10^5 cfu/mL, and the initial concentration of *S. aureus* was 1.03×10^5 cfu/mL.
[a] Silver-containing organic aerogel.
[b] The bacteria were uncountable.

TABLE VI
Antibacterial Persistency of Ag/CAs Obtained at Different Pyrolysis Temperatures on *E. coli*

Sample	Carbonization temperature (°C)	Surviving number of bacteria at each time									
		1	2	3	4	5	6	7	8	9	10
Ag/OA-5[a]	—	0	0	0	500	Colony	—	—	—	—	—
Ag/CA-6	300	0	0	0	0	0	0	150	Colony	—	—
Ag/CA-7	450	0	0	0	0	0	0	100	450	Colony	—
Ag/CA-8	600	0	0	0	0	0	0	50	560	Colony	—
Ag/CA-10	900	0	0	0	0	0	0	0	0	10	Colony

The sample weight was 25 mg, the *E. coli* concentration was 10^5 cfu/mL, and the contact time was 2 h.
[a] Silver-containing organic aerogel.

CONCLUSIONS

CAs impregnated with well-dispersed and nanometer-sized silver particles were obtained by the direct immersion of organic aerogels prepared by an ambient-pressure drying technique in aqueous $AgNO_3$ solutions and then carbonization. For blank CAs, the adsorbed amount of bacteria increased with an increase in the carbonization temperature and contact time. The adsorption speed of *E. coli* was greater than that of *S. aureus*. Furthermore, *E. coli* was adsorbed to a greater degree than *S. aureus*. As for the Ag/CAs, the adsorbed amount of *E. coli* or *S. aureus* decreased with an increase in the silver content. This was considered to be mainly due to the dissolution behavior of the bacteria by silver ions.

The antibacterial activity of the Ag/CAs increased with an increase in the silver content of the samples and carbonization temperature. The antibacterial activity for *E. coli* was stronger than that for *S. aureus*. The strong antibacterial activity of the samples carbonized at a high temperature was supposed to be due to the increasing contact opportunity of bacteria with silver. The results from antibacterial persistency tests indicated that the Ag/CAs possess strong and long-term antibacterial activity. Thus, this kind of material can be promisingly applied to the field of water treatment.

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