*Materials Science-Poland, Vol. 25, No. 4, 2007*

# Study on absorption and mechanical properties of rubber sheet absorbers

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Based on the impedance matching principle and electromagnetic wave propagating law, double-layer absorbers with impedance-matching structure were designed both theoretically and experimentally. Microwave absorbers were prepared by mixing a commercially available rubber with magnetic micropowder (MMP) and/or dielectric materials. The first layer, made up of MMP has large permeability and magnetic loss, while the second layer (matching layer), comprised of MMP and/or dielectric material, has frequency dispersion with the parameters of permittivity and permeability to match the incidence free space over a wide frequency range. Experiments showed that the matching layer plays a key role in the absorption. Electromagnetic parameters and thickness need to be controlled precisely to achieve high absorption. It was reasoned out that with increasing electromagnetic performance of matching layer, matching thickness will decrease. Tests showed that the reflectivity was below –10 dB for samples 1 and 2, and below –8 dB for samples 3–6 in the frequency range of 8–18 GHz. Finally, mechanical characteristics were also investigated with tensile strength above 10 MPa, indicating that the materials may find practical use in the engineering of microwave absorbers.

Key words: *double-layer absorber; impedance matching; reflectivity; tensile strength; MMP*

## 1. Introduction

The development of microwave absorber continues to attract much attention because of the increasing environmental pollution from wireless telecommunication systems and high-frequency circuit devices and the essential part of a stealth defense system for all military platforms because it can transform undesired electromagnetic waves into heat [1, 2]. An effective electromagnetic wave absorber must fulfil the following requirements [3]:

- maximum absorption of electromagnetic waves with minimum reflection,
- dissipation of incident wave energy changes into heat.

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Distribution of energy density in a sheet absorber with a termination metal is illustrated in Fig. 1 [4]. In the vicinity of the termination metal, electric field energy density ($W_e$) decreases while magnetic field energy density ($W_m$) increases. Therefore, an effective double-layer absorber can be designed by arranging strong magnetic loss materials as the first layer and electric loss (larger thickness) or both electric and magnetic loss materials (smaller thickness) as the second layer.

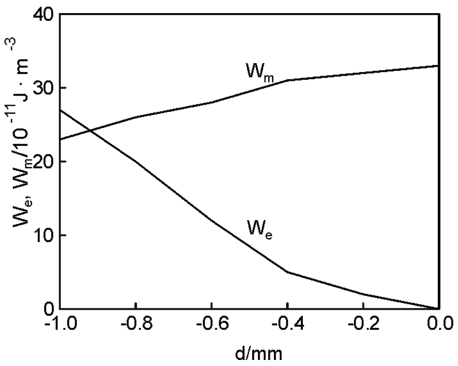


Fig. 1. Distribution of energy density in absorbing materials

Perini and Cohen [5] developed a Powell method to design radar-absorbing materials (RAM) consisting of several dielectric layers. The absorption of RF energy was mostly done in the last layer, and the others were used to match the wave impedance of the RAM to that of the incidence medium. A two-layer absorber composed of the mixture of iron particles and rubber as the inner layer, and of barium hexaferrite powder and rubber as the outer layer, has better attenuation properties compared with the one-layer structure. The reflection of the incident wave can be reduced with increasing matching of the impedance of the outer layer and of free air, while the inner layer can ensure that the microwave power may be mostly exhausted [6]. Meshram et al. reported a two-layer absorber which can provide higher absorption of the order of –9 dB from 8.7 to 10.2 GHz as compared to a single-layer microwave absorber [7].

Since microwave permeabilities of known magnetic materials do not exceed several units above GHz frequency, other approaches to broaden bandwidth of radar absorbers attract great attention. Conventional methods of creating broad-band wave absorbers employ multilayer absorbing structures with impedance-graded composites [8, 9] or the parameters (permittivity and permeability) with frequency dispersion [9, 10]. In this paper, both thicknesses and surface densities of samples (samples 1–6) were gradually reduced, with the reflectivity below –8 dB over the frequency range of 8–18 GHz, to develop light-weight, thin-layer, broad-band, strong-absorption two-layer absorbers.

## 2. Two-layer structure

The computed reflectivity of a single layer absorber comprising 85 wt. % of magnetic micropowder (MMP) is shown in Fig. 2. The absorption of energy at high frequencies decreases with increasing layer thickness. It is probable that the absorber does not match a free space in the high frequency region because the dielectric parameter ($\varepsilon_r''$, $\varepsilon_r''$) has no frequency dispersion, as shown in Fig. 3a.

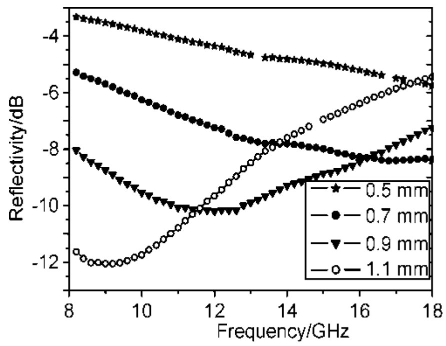


Fig. 2. Reflectivity versus frequency for various thickness rubber composites with 85 wt. % MMP

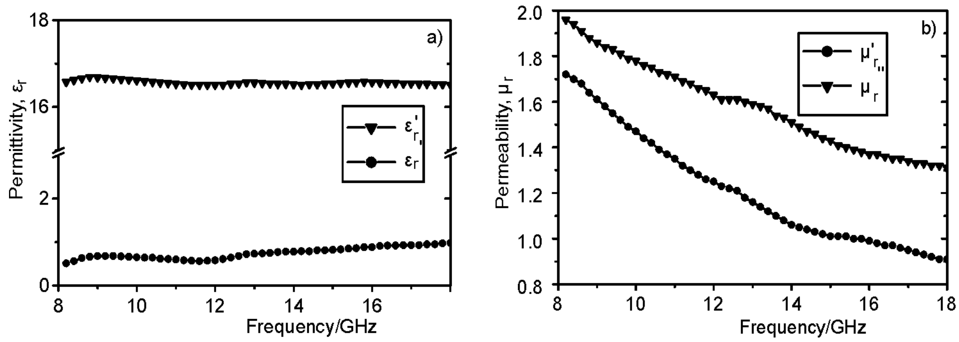


Fig. 3. Relative permittivity (a) and relative permeability (b) as functions of frequency for the rubber composites with 85 wt. % MMP

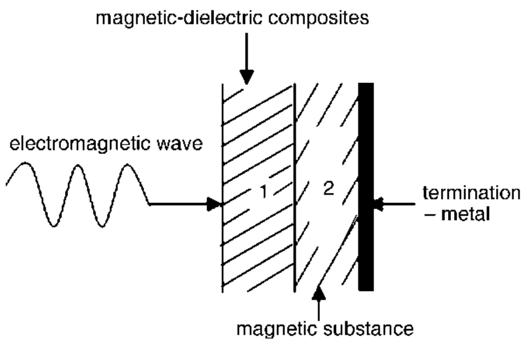


Fig. 4. Structure of a two-layer wave absorber

Table 1. Constitutions and matching thicknesses of the samples[a]

| No. | Second layer | Thickness [mm] | First layer | Thickness [mm] |
|---|---|---|---|---|
| 1 | 10% carbon fibre | 1.5 | 85% MMP | 0.8 |
| 2 | 20% $TiO_2$ | | | |
| 3 | 10% carbon fibre, 1.6% graphite | 1.1 | | |
| 4 | 20% $TiO_2$, 2.3% graphite | | | |
| 5 | 10% carbon fibre, 38%MMP, 5% graphite | 0.6 | | 0.6 |
| 6 | 20%$TiO_2$, 30%MMP, 2.9% graphite | | | |

[a]Matching thickness corresponding to the optimum performance (⩽ –8 dB) in a broad frequency range

The structure of a double-layer absorber with a metal substrate is shown in Fig. 4. The first layer is composed of the rubber composites with 85 wt. % MMP (Table 1) which maintains a higher permeability (particularly imaginary part of the permeability), leading to a larger magnetic loss. The second layer comprises composites of magnetic and/or dielectric materials which induces frequency dispersion and dielectric losses caused by dipole rotation effects (known as Debye relaxation) and others [11].

The return loss coefficient of the two-layer absorber in Fig. 4 is given [12] by

$$R = 20\lg\left|\frac{z_{in} - z_0}{z_{in} + z_0}\right| \tag{1}$$

$$Z_{in} = \frac{z_1 \tanh(\gamma_1 d_1) + z_2 \tanh(\gamma_2 d_2)}{1 + \frac{z_1}{z_2}\tanh(\gamma_1 d_1)\tanh(\gamma_2 d_2)} \tag{2}$$

where $z_{in}$ is the input impedance measured from the surface of the absorber to the termination; $z_0$ is the characteristic impedance of vacuum; $z_1$, $\gamma_1$, $d_1$ and $z_2$, $\gamma_2$, $d_2$ are the characteristic impedances, propagation constants and thicknesses of the first (1) and second (2) layers, respectively. They are given by

$$\gamma_i = j2\pi f\sqrt{\mu_i \varepsilon_i}, \qquad i = 1, 2 \tag{3}$$

$$z_i = \sqrt{\frac{\mu_i}{\varepsilon_i}}, \qquad i = 1, 2 \tag{4}$$

where $z_0 = \mu_0/\varepsilon_0$ equals 377 Ω.

## 3. Preparation of samples and testing methods

MMP was prepared from a compound consisting of fine particles of FeCo and rare earth by ballmill techniques. Carbon fibre, $TiO_2$, and graphite were purchased in the market. The adhesive matrix is known as hydrogenation acrylonitrile-butadiene rubber (HNBR) and comes from Japan. The materials were blended with HNBR in various proportions in a roll mill, as shown in Table 1. Test specimens were obtained in different sizes: toroidal shape (outer diameter of 7.00 mm, inner diameter of 3.04 mm, and thickness of 3.0–5.0 mm) to test electromagnetic parameters and rectangular shape (180×180×(0.6–2.3) $mm^3$) for reflectivity measurements.

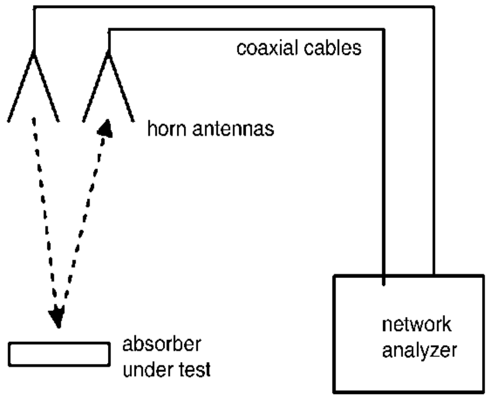


Fig. 5. Schematic diagram of the experiment system

The schematic diagram of the measurement set-up, as a free space measurement system, is shown in Fig. 5, such that two horn antennas and absorber under test are set in an anechoic chamber. The measurements are made with a network analyzer system which consists of a HP8510B network analyzer, an HP83622A synthesized sweeper and an HP8515A S-parameter test set. The antennas are positioned 2 m from samples and set almost normal to their surfaces. The permeability ($\mu$) and permittivity ($\varepsilon$) of the samples are obtained from the transmission/reflection (T/R) method. The reflectivity is attained by comparing the signal reflected by the sample under test to the signal input.

## 4. Experimental results

### 4.1. Absorption properties

The dependence of reflectivity on frequency for samples 1–6 is shown in Figs. 6–10. The $\varepsilon_r$ and $\mu_r$ spectra of the first layer of the double-layer absorber are shown in Fig. 3.

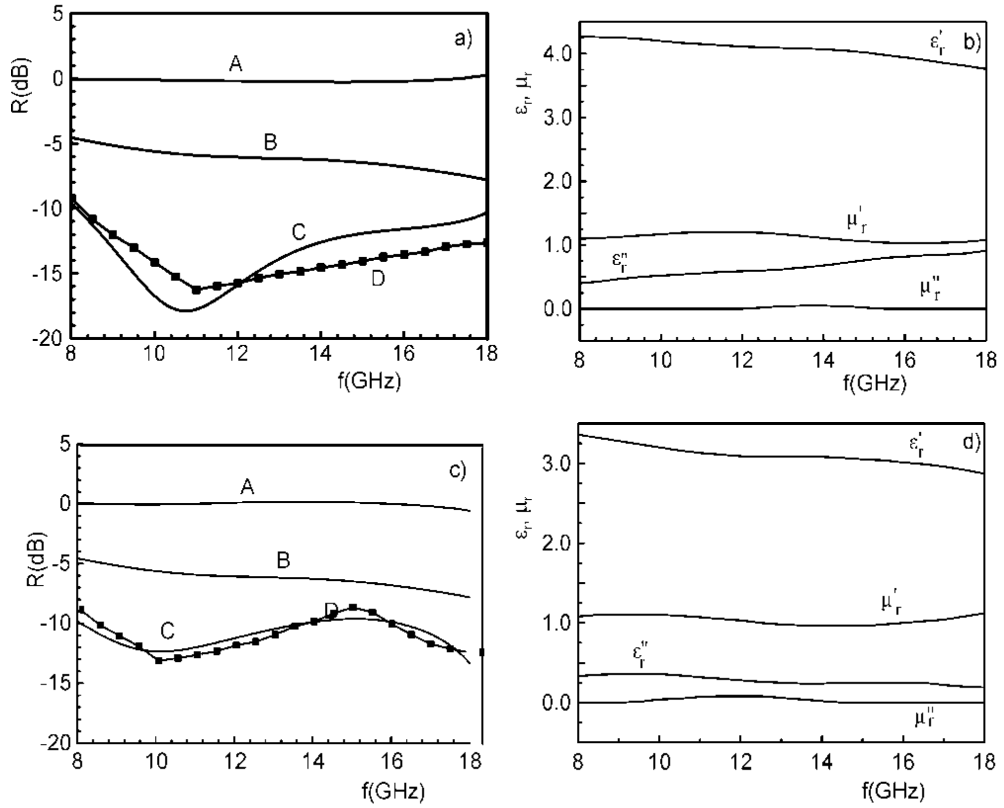


Fig. 6. Reflectivity versus frequency for sample 1 (a), $\varepsilon_r$ and $\mu_r$ spectra of the second layer of sample 1 (b), reflectivity versus frequency for sample 2 (c), $\varepsilon_r$ and $\mu_r$ spectra of the second layer of sample 2 (d); A – reflectivity of the second layer, B – reflectivity of the first layer, C – experimental results, D – theoretical curves

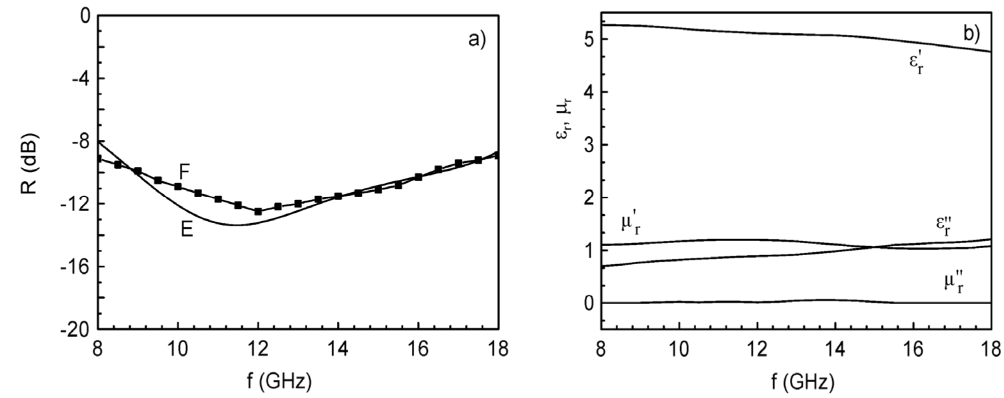


Fig. 7. Reflectivity versus frequency for sample 3 (a): E – experimental results, F – theoretical values, $\varepsilon_r$ and $\mu_r$ spectra of the second layer of sample 3 (b)

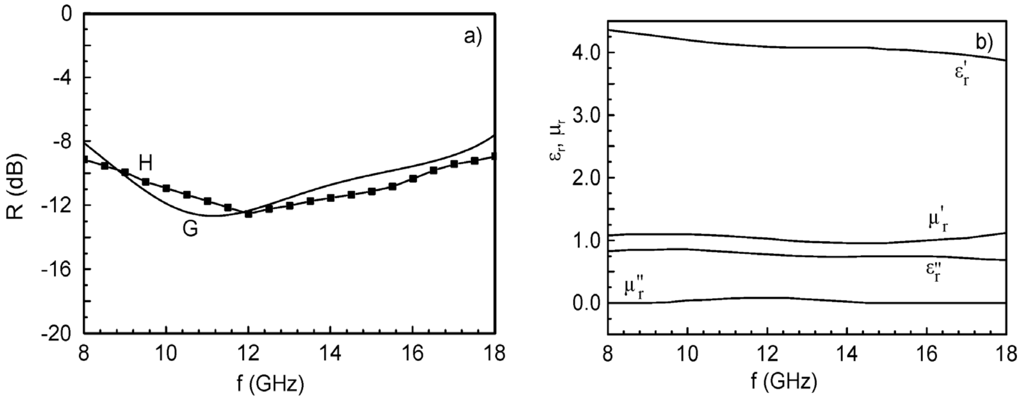


Fig. 8. Reflectivity versus frequency for sample 4 (a): G – experimental results, H – theoretical values, $\varepsilon_r$ and $\mu_r$ spectra of the second layer of sample 4 (b)

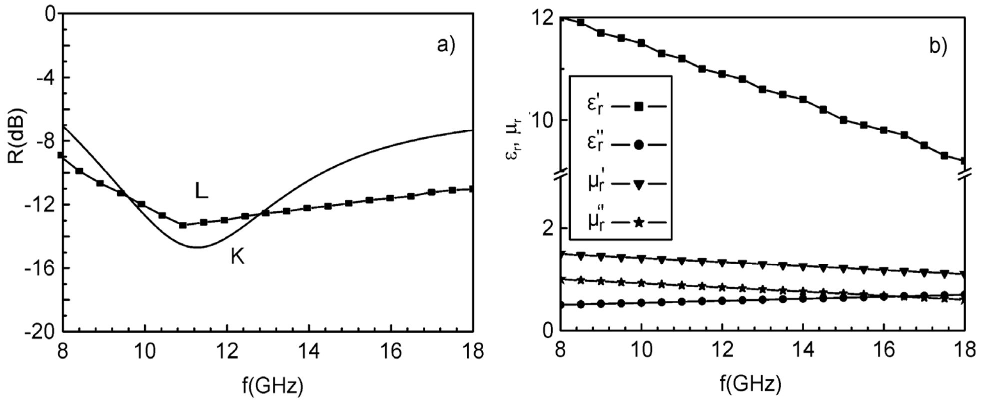


Fig. 9. Reflectivity versus frequency for sample 5 (a): K – experimental results, L – theoretical values, the $\varepsilon_r$ and $\mu_r$ spectra of the second layer of sample 5 (b)

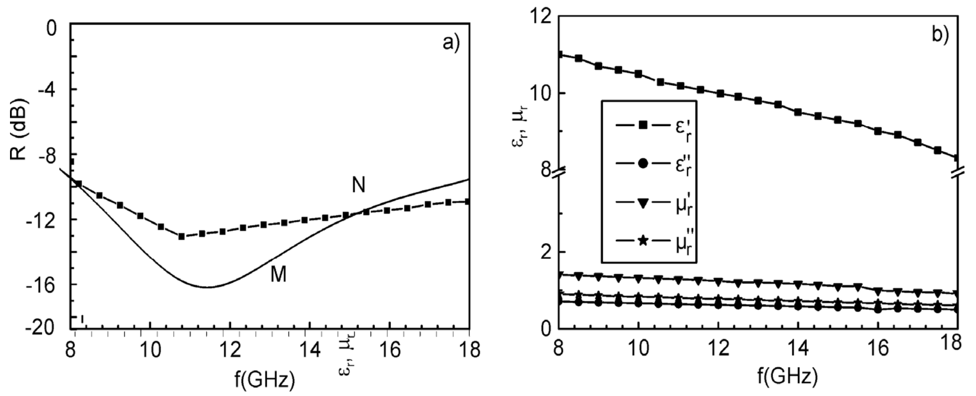


Fig. 10. Reflectivity versus frequency for sample 6 (a): M – experimental results, N – theoretical values, $\varepsilon_r$ and $\mu_r$ spectra of the second layer of sample 6 (b)

Table 2. Matching thickness (mm), surface density ($kg/m^2$) and tensile strength (MPa) of the samples

| Sample No. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Matching thickness | 1.5+0.8 (2.3) | 1.5+0.8 (2.3) | 1.1+0.8 (1.9) | 1.1+0.8 (1.9) | 0.6+0.6 (1.2) | 0.6+0.6 (1.2) |
| Surface density | 4.0 | 4.3 | 3.6 | 3.8 | 3.3 | 3.5 |
| Tensile strength | 12.8 | 10.2 | 13.8 | 11.1 | 11.9 | 10.3 |

As shown in Figs. 6–10, the measured reflectivities agree well with theoretical values. Slight differences in measured and predicted results are likely due to the inability to achieve consistent thickness and practical variations in mixing of various materials. The matching thicknesses and surface densities of samples 1–6 are listed in Table 2.

### 4.2. Mechanical properties

Sample sulfuration was carried out by heating at 165 ºC for 25 min on a QLBD400×400 galvanothermy slab sulfuration machine. Tensile strength was measured in a XL100-pull experiment machine, according to GB/T528-1998 (sample 1, pull velocity – 500 mm/min). The samples were cut into dump-bell (Fig. 11), to test tensile strength after setting for a week. The results are shown in Table 2.

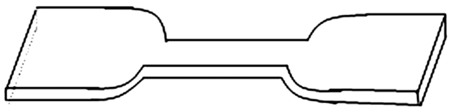

Fig. 11. Structure of the sample to test tensile strength

## 5. Analysis and discussion

Absorption ratio of absorbers is greatly improved by introducing matching layers (the second layer), as shown in Figs. 6a, c. Though the matching layer hardly dissipates electromagnetic wave, attenuation is improved when it laminates the first layer to form a two-layer structure. Therefore, impedance matching plays a key role in absorbing materials. Since both carbon fibre and $TiO_2$ have low permittivities and permeabilities (Figs. 6b, d), the thickness of the second layer must increase to form a matching structure. This corresponds to the fact that, $\varepsilon_1$, $\mu_1$ and $d_1$ being constant, and $\varepsilon_2$ and $\mu_2$ being small, the thickness $d_2$ should increase to realize the matching of $Z_{in}$ to $Z_0$ as evident from Eq. (2).

Conductor network is formed in the matching layer by introducing graphite to samples 3 and 4. Current is converted to heat, and absorption is improved (Figs. 7a, 8a). It is also proved by that the electric permittivities ($\varepsilon'$, $\varepsilon''$) of the matching layer are increased (Figs. 7b, 8b). Meantime, the matching thickness decreases and the surface density is reduced, too. When too much graphite induces a strong reflection, electromagnetic wave cannot transmit into the absorber to wear down.

Matching layers of samples 1–4 are made of dielectric materials, and they dissipate electromagnetic wave mainly by dielectric polarization. In order to reduce thickness and improve absorption, MMP is added to the matching layer to form electromagnetic media (samples 5, 6). As a result, values of the electromagnetic parameters ($\mu'$, $\mu''$, $\varepsilon'$, $\varepsilon''$) increase, the matching thickness decreases, absorption is greatly improved due to magnetic and dielectric loss (Figs. 9, 10).

Considering the electromagnetic parameters of samples 1–6, the parameters of the matching layer are lower than those of the first layer, thus also forming electromagnetic parameters – graded structure from the free space, the second layer to the first layer. Meanwhile, frequency band is broadened because of frequency dispersion; parameters decrease as frequency increases.

Dielectric materials are characterized by low density, high strength and good stability, while MMP has large permeability and magnetic loss. When they are combined to form a double-layer absorber, mechanical and absorption properties are improved. These designs offer less weight and higher absorption in the upper frequency region of 10–18 GHz when compared to commercially available flexible magnetic sheet absorbers, e.g. Emerson and Cuming ECCOSORB® FGM. Tensile strength of sample 3 was the best with the value of 13.8 MPa (Table 2). Tensile strengths of samples 1, 3 and 5 were better than those of samples 2, 4 and 6. This is because carbon fibre can build up the sulfuration absorber strength.

## 6. Conclusion

Impedance matching plays a key role in designing effective electromagnetic wave absorbers. Reflectivity is greatly affected by the electromagnetic parameters and thickness of the matching layer. These parameters need to be controlled precisely to achieve high absorption. In addition, with increasing values of electromagnetic parameters of matching layer, matching thickness will decrease.

In this work, the reflectivities of samples 1, 2 were below –10 dB at the thickness of 2.3 mm and surface density ≤ 4.4 kg/m$^2$; while the reflectivities of samples 3–6 below –8 dB at the thickness ≤ 1.9 mm and surface density ≤ 3.8 kg/m$^2$ over 8–18 GHz. Tensile strengths had the values above 10 MPa for all samples, which may meet requirements for the practical use in engineering of microwave absorbers.

Further research could optimize the absorber by having a host material of more complex permeability. In addition, the detailed absorbing wave characteristics in oblique incidence should be the subject of further study.

**Acknowledgement**

This work was supported by Grant-in-Aid for Scientific Research No.50371029 from the Ministry of Education, Science and Technology of China. The authors would like to thank Professor Xiucheng Zhang for his help with the samples measurement.

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*Received 14 February 2007*
*Revised 27 March 2007*