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RESEARCH ARTICLE

Influence of Bismuth Contents on Mechanical and Gamma Ray Attenuation Properties of Silicone Rubber Composite

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Abstract

Silicone rubber has been gained interest throughout the world due to its novel applications such in automotive industry, healthcare supplies and nuclear applications. Therefore, this work deals with the study of bismuth silicone rubber composite as a gamma ray shielding material. The Gamma ray attenuation coefficients of the composite were determined at gamma ray energies emitted from ^{232}Th and ^{60}Co radioactive sources. The detection technique is based on Hyper Pure Germanium detector (HPGe) under good geometry conditions. The total mass attenuation coefficients (μ/ρ) have been estimated based on the measured total linear attenuation coefficients (μ) as a function of bismuth silicone rubber composite concentrations. The results revealed that radiation shielding performance increases with increasing bismuth additive in silicone rubber. Theoretical mass attenuation coefficients were calculated using WinXCom program (version 3.1). A good correlation was observed between the experimental and theoretical mass attenuation coefficients. The dependence of the mechanical properties for silicone rubber filled with bismuth compound at different concentration have been studied and discussed.

INTRODUCTION

A variety of materials can be used for radiation shielding for nuclear radiation [1-2]. For shield designs, gamma ray was one of the main types of nuclear radiation, which have to be considered. High effective atomic number can be more efficiently attenuate gamma rays [3- 4].

Recently, there was a continuous demand for improved polymers for use as shielding materials [5-6]. Shielding structures could be realized by using absorbing materials such as polymeric composites with suitable filler. These materials must have specific requests first of all good shielding effectiveness (SE), lightness, good mechanical properties, good processability, and low cost [7-8]. Gamma ray shielding performance could be achieved with composite materials comprising a polymer matrix filled with materials, of high atomic number such as lead, bismuth and barium [9]. Therefore, by increasing the filler content a higher gamma ray shielding efficiency will be obtained [10-11]. Nowadays, silicone rubber is used in a large variety of applications because it has low density, large degree of flexibility, thermal resistance, radiation resistance...etc. [12-13]. Therefore, in this study, an attempted has been devoted to prepare the polymer composite for radiation shielding using silicone rubber as a polymer matrix and bismuth (Bi) which has high effective atomic number as filler with different concentrations. Then, the gamma ray attenuation coefficients and the mechanical properties as a function of gamma ray energy and filler concentrations were investigated.

- **Theoretical aspect**

- **Attenuation measurements**

The linear attenuation coefficient can be calculated according to The Lambert-Beer law which describes attenuation of a monoenergetic beam as follow [14]

$$I = I_o e^{-\mu x} \quad (1)$$

Where I = transmitted gamma radiation intensity, I_o = incident gamma radiation intensity, x = is the thickness of the absorbing medium, μ = is the linear attenuation coefficient.

For photons in an attenuating medium, the mass attenuation coefficient (μ/ρ) is given by [15]

$$\frac{\mu}{\rho} = \ln\left(\frac{I_0}{I}\right)/\rho x \quad (2)$$

Where ρ is the density of the shield material

- **Experimental Procedure**

- **Sample preparation**

Different ratios of bismuth and silicone rubber 20, 40, 60 and 80 phr *(parts per hundred parts of rubber)* were weighed and then mixed on a laboratory two-roll mills (outside diameter 470 mm , working distance 300 mm, speed of slow roll 24 rpm and fraction ratio of 1 : 1.4) in accordance with ASTM D3182-07, the composite were subjected to sheeting on the mill and are cured in an electrically heated hydraulic press at $152^o \pm 1^oC$ and a pressure of about 4MPa. The optimum cure time (Tc_{90}) of the mixes was obtained from a rheometer (Monsanto Oscillating Disc Rheometer, USA) according to ASTM: D2084. The composites were produced with dimensions 4 cm x 4 cm.

For mechanical tests the composites were mixed with other rubber ingredients (stearic acid 2 phr, zinc oxide 5 phr, peroxide 2 phr), to improve its durability along with its mechanical properties.

- **Attenuation measurement**

The gamma ray shielding parameters of the prepared composites were obtained for energy lines, emitted from ^{232}Th and ^{60}Co point sources, using narrow beam geometry. The diagram of the geometry was shown in figure (1). The experimental arrangement consists of Hyper Pure Germanium detector (HPGe) with relative efficiency 30% relative to a 3"× 3" NaI (Ti) detector, active volume 62.3 cm^3 and energy resolution 1.8 keV at 1.33 MeV γ-lines. The detector was coupled through an amplifier to the computer with MCA plug-in card. Because of the sensitivity of HPGe detector, it is usual to shield them from the environment. Therefore, lead shield of thickness 5 cm was used in this study.

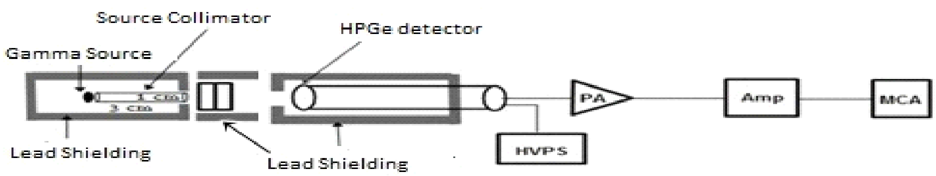


Fig.1 Experimental setup of narrow beam transmission method.

- **Mechanical measurements**

The tensile strength, elongation at break and Young's modulus were determined using a Zwick tensile machine Model 1425 in accordance with ASTM D 412. The hardness was measured using the Shore A Durometer according to ASTM D 2240.

- **Results and discussion**

- **Gamma ray attenuation of bismuth silicone rubber composite**

The linear attenuation coefficient (μ), of the composite was determined experimentally by interposing different layer thicknesses of the testing samples between the gamma ray point source and the detector (HPGe). the energy lines of gamma rays which emitted from ^{232}Th and ^{60}Co radioactive gamma ray sources are shown in figure (2).

The linear attenuation coefficients increase linearly with increasing Bi content, and it is also observed that the linear attenuation coefficient decrease by increasing the energy of gamma rays for all composition under this investigation. The observed behavior of linear attenuation coefficients is attributed to the high atomic number of bismuth which leads to high absorption for gamma rays.

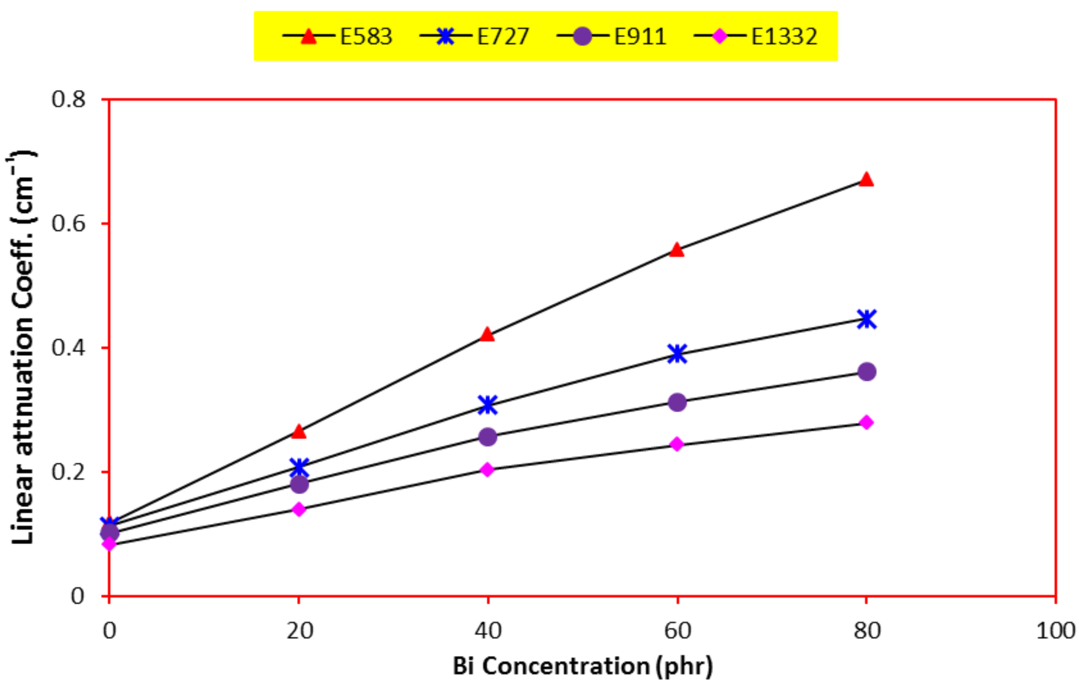
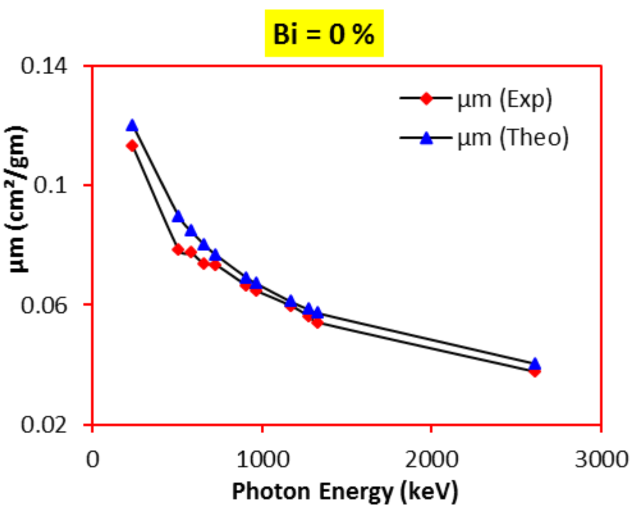
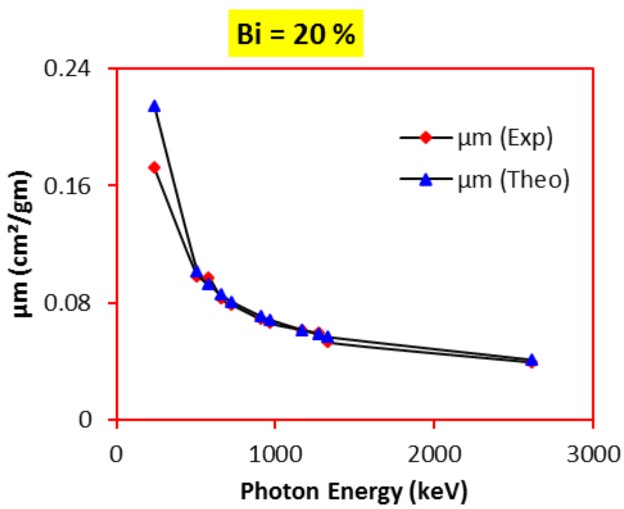
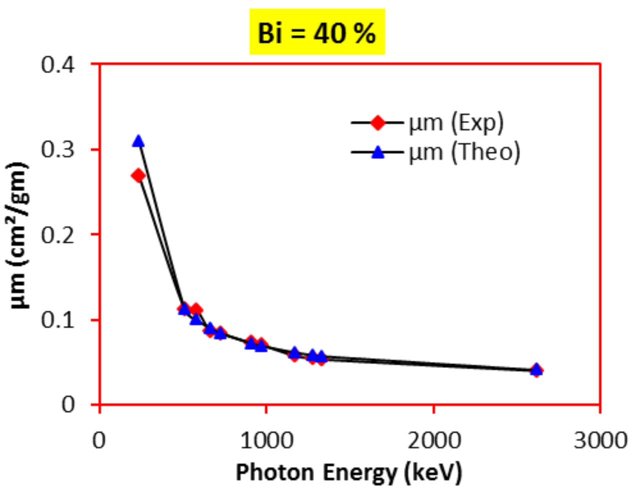


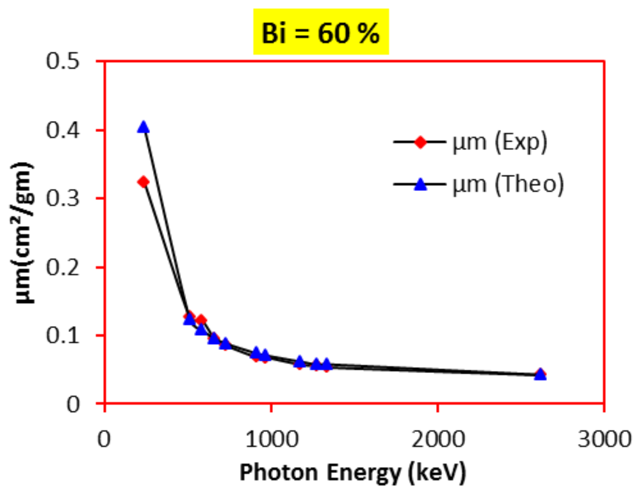
Fig.2 Linear attenuation coefficients of γ-rays emitted from ^{232}Th and ^{60}Co sources at different bismuth concentrations.

The experimental and theoretical mass attenuation coefficients were plotted as a function of gamma ray energies for different bismuth concentration as shown in figure (3). It is observed that the mass attenuation coefficient increases with the weight fraction of bismuth content and inversely proportional to photon energy.


Bi = 0 %
µm (Exp)
µm (Theo)
µm (cm²/gm)
0.14
0.1
0.06
0.02
0
1000
2000
3000
Photon Energy (keV)


Bi = 20 %
µm (Exp)
µm (Theo)
µm (cm²/gm)
0.24
0.16
0.08
0
0
1000
2000
3000
Photon Energy (keV)


Bi = 40 %
µm (Exp)
µm (Theo)
µm (cm²/gm)
0.4
0.3
0.2
0.1
0
0
1000
2000
3000
Photon Energy (keV)


Bi = 60 %
µm (Exp)
µm (Theo)
µm(cm²/gm)
0.5
0.4
0.3
0.2
0.1
0
0
1000
2000
3000
Photon Energy (keV)

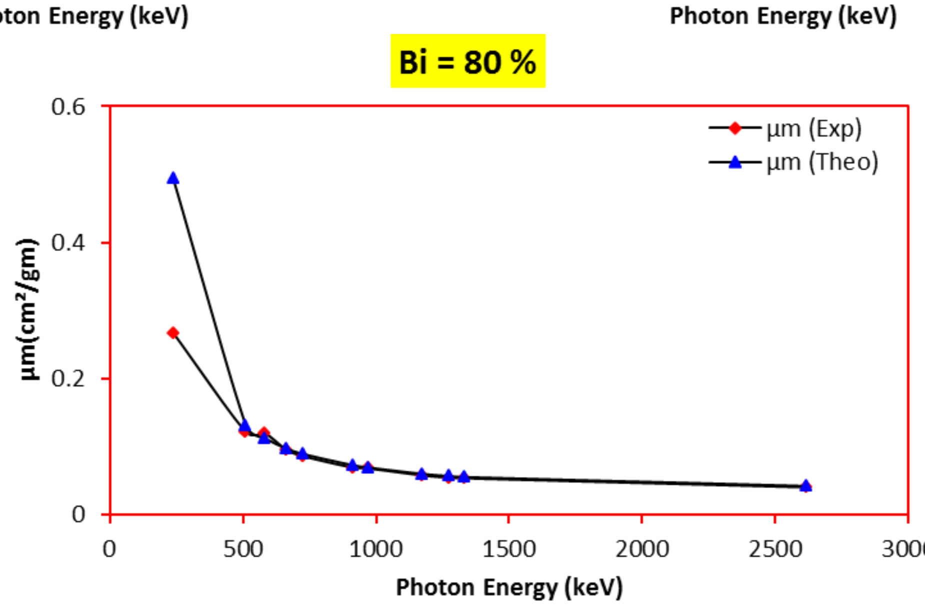

Bi = 80 %
µm (Exp)
µm (Theo)
µm(cm²/gm)
0.6
0.4
0.2
0
0
500
1000
1500
2000
2500
3000
Photon Energy (keV)

Fig. 3 Mass attenuation coefficients of the composite samples as a function of gamma ray energies

The calculated values of half value layers are listed in table (1). The half value layers decreases with the bismuth concentration increase, indicating an improvement of the attenuation properties for the investigated silicone rubber samples and this attributed to the increase in the density of the sample and the high value of mass attenuation coefficients.

Table 1: Half value layer (HVL) for silicone rubber composites at different gamma ray energies

Gamma ray energies keV	HVL(cm) Bi=0 (phr)	Bi=20 (phr)	Bi=40 (phr)	Bi=60 (phr)	Bi=80 (phr)	$\left(\frac{HVL_{0\,phr} - HVL_{80\,phr}}{HVL_{0\,phr}}\right) * 100$
583.19	5.890	2.720	1.647	1.242	1.116	81.050
727	6.205	3.347	2.182	1.777	1.550	75.017
911.2	6.856	3.840	2.504	2.221	1.918	72.025
1332.49	8.412	4.976	3.416	2.845	2.490	70.402

- **Mechanical testing of the composite**

Figure (4) shows the variation of the Hardness Shore A, of silicone rubber with different bismuth concentration. It is observed that the addition of the bismuth content shows an increase in hardness, may be attributed to as more filler (Bi) is incorporated in the rubber matrix, the plasticity of the rubber chain is reduced resulting in more rigid composites.

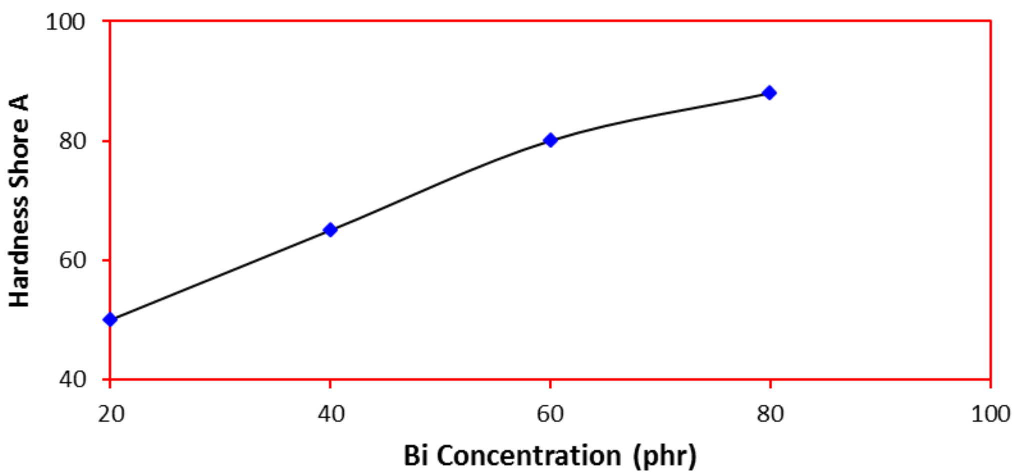


Fig. 4 The variation of Hardness shore A with the filler content X (phr), for Silicone rubber filled with bismuth compound

Figure (5) shows the variation of the elongation at break, tensile strength and young modulus of silicone rubber with different bismuth concentration.

It is clear from the figure that an increase in the filler loading results in significant increase in the tensile strength, elongation at break, and Young's modulus which indicates the reinforcement effect of the filler until the maximum is attained at filler content 60 phr . Further increase of the filler loading leads to decrease the tensile strength, elongation at break, and Young's modulus. This can be due to the ability of bismuth filler to form aggregates. Therefore for small amounts of the filler loadings, good rubber-filler interactions will be occur as a result of good dispersions of the fillers into the matrix.

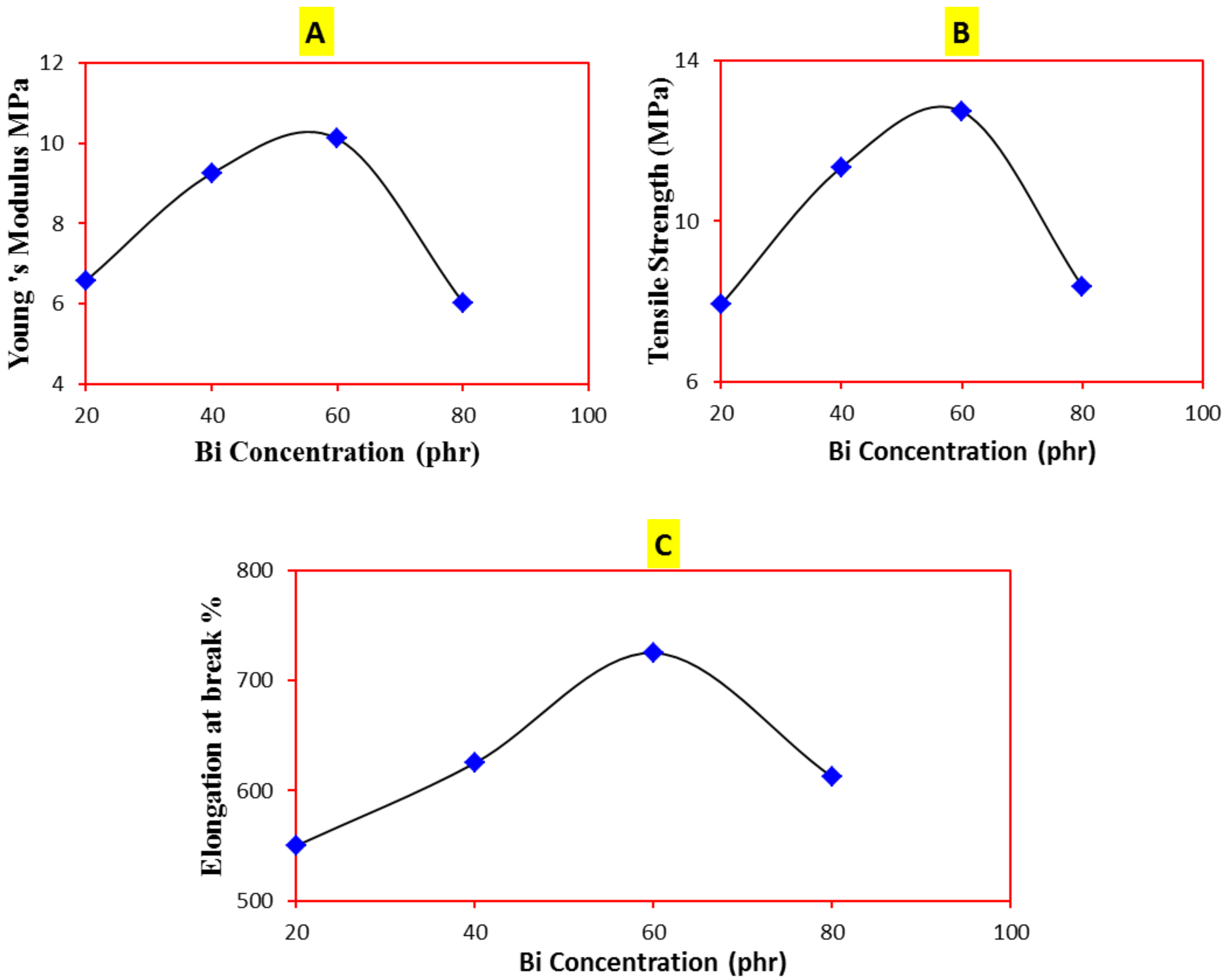


Fig.5 The variation of (A) Young's modulus E (MPa) (B) Tensile strength (MPa), and (C) Elongation at break,% with the filler content X (phr), for Silicone rubber filled with bismuth compoun

- ## Conclusion

In the present work gamma ray attenuation coefficients of silicone rubber filled with bismuth content at different concentrations were investigated. The linear attenuation coefficient and the mass attenuation coefficient increases by the increase of bismuth filler content in the prepared composites.

The mechanical properties of the composites increase by increasing bismuth content. The optimum loaded silicone rubber with bismuth filler content for tensile strength, elongation at break and young modulus is 60 phr while at higher concentration these properties decreased due to the agglomeration of bismuth in silicone rubber. The present study shows that the bismuth silicone rubber can attenuate gamma ray and has a significant improvement in its mechanical properties and can replace lead that has high toxicity.

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