Photomechanical actuation of polydimethylsiloxane/carbon black nanocomposite

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Materials such as carbon black (CB), carbon nanotube, graphene, etc. have been found to deform on exposure to the light source. Introducing these materials into polymers could convert them to photo-responsive composites. This is demonstrated by the experiment in which polydimethylsiloxane (PDMS) polymer containing CB nanofiller composites is prepared, and its photomechanical actuation from exposure to IR light source is recorded using a laser displacement sensor. The particle size analysis reveals the size of the CB, which is verified by the dynamic light scattering method. The UV–vis–IR spectrophotometer study shows that an increase in the light absorbance capacity of nanocomposites compared to the plain polymer. The PDMS/CB nanocomposite beam exhibited a significant deformation compared to plain PDMS. Deformation of the order of 10–11 mm is observed for a given IR source. The deformation found to have good repeatability but with some thermal hysteresis in cyclic actuation and de-actuation.

1. Introduction: In recent years, significant attention has been paid to photoactive materials that exhibit mechanical actuation driven by photoenergy, as they can directly convert photoenergy into mechanical work that can potentially be applied to micromotors [1], artificial muscles, smart actuators [2–4], micro-robots [5–8] and energy harvesters [9]. Materials based on liquid crystal elastomer films and derivatives of azobenzene have been reported [10–12] that deform/deflect upon illumination of light due to phase transformation (trans to cis) and change in volume [13–15]. One disadvantage of these materials is that they absorb a limited light spectrum, but not for a wide range such as solar light.

The attempts are being made to use polymer composites with fillers providing a wide range of absorption [16, 17]. Carbon black (CB) as a filler material has a wide range of absorption from UV to IR [18, 19], which could lead to a photoactive composite. Also, polydimethylsiloxane (PDMS) is one of the best polymer materials, and there is a lot of research on the properties of PDMS nanocomposites [20, 21], but not for photo-actuator studies.

In this work, a composite of PDMS with a CB nanofillers was prepared. Later, CB powder and nanocomposite specimens are examined for particle size, light absorbance, and morphology analysis. Eventually, the photomechanical deformation of the produced composite beam is studied upon illumination of light.

2. Material and methods: CB of average particle size 200–300 nm from Cabot Corporation and the matrix material PDMS was from Dow Corning (Slygard184). The particle size of the CB was analysed using a particle size analyser of the DLS method (Microtrac solution). The light absorbance of nanocomposite and plain PDMS were carried out using a UV–vis–IR spectrophotometer (Shimadzu-3600 plus). The sample was fitted with a 20 mm path length of the quartz substrate, which was used for light absorbance study. The dispersion and morphology study of the polymer nanocomposite were analysed using a scanning electron microscope (Jeol.Ltd).

The PDMS/CB nanocomposites preparation phases are depicted in Figs. 1*a–j*. In the preliminary phase, part-A (monomer), part-B (curing agent), and CB material are taken into the beaker and weighed appropriately. A curing agent in the proportion 1 to 10 parts of the monomer is added to the mixture and stirred. CB (10 Vol%) is added to the PDMS mixture and stirred thoroughly for a further 15 min. Finally, the mixture is poured into a mould after degassing and allowed to cure for 48 h at room temperature.

The schematic setup for measuring the deflection of the composite beam is shown in Fig. 2*a*. The composite sample is exposed to IR light of intensity 1000 W/m^2 and wavelength 600–800 nm. The deflection of the beam is recorded using a micro epsilon laser displacement sensor, and data is monitored using ILD 1420 data acquisition software.

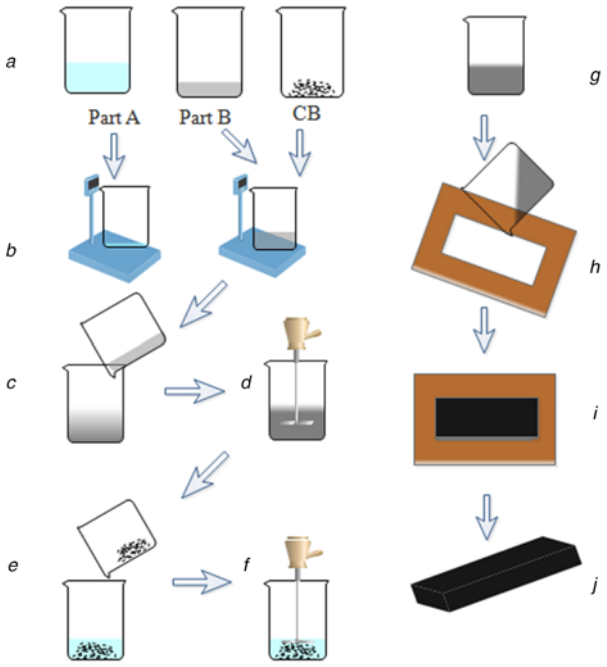


Fig. 1 *Preparation phases of PDMS/CB nanocomposite beam*
a Receiving the material
b Weighing
c Blending of monomer and curing agent
d Stirring
e Adding filler material
f Stirring composite mixture
g Degassing
h Pouring mixture into the mould
i Curing at room temperature
j Final composite sample

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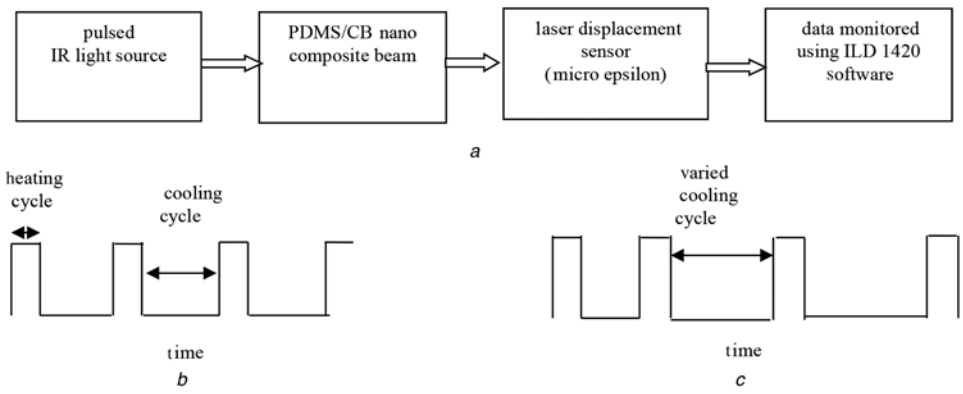


Fig. 2 *Experimental procedure and conditions of photo actuator*
a Schematic diagram of the test setup for measuring actuation of the composite sample
b Fixed cooling
c Varied cooling

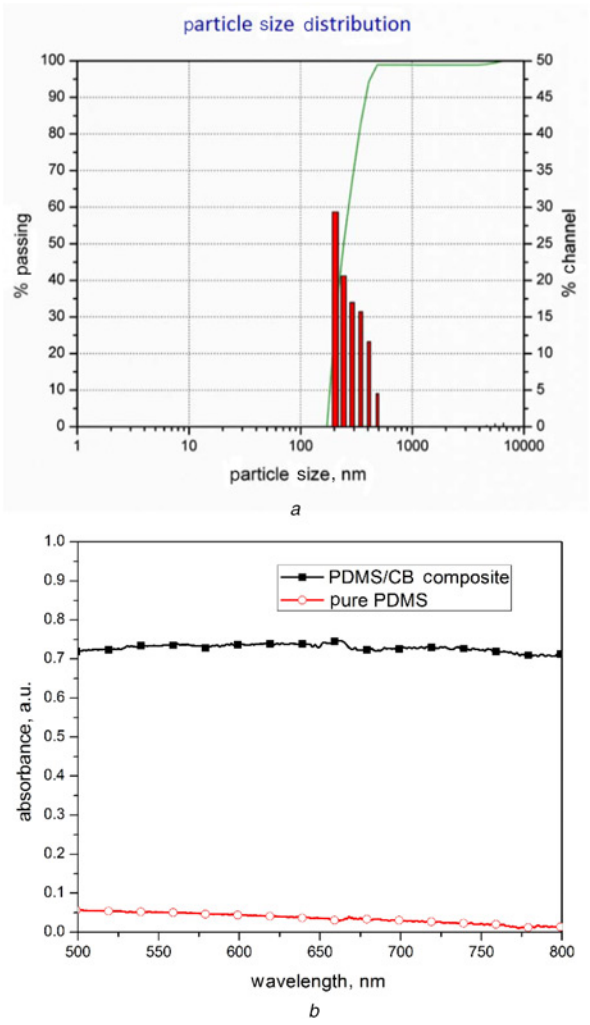


Fig. 3 *Particle and absorbance characterization through*
a Particle size analysis of CB nanoparticle
b UV–vis–IR spectrophotometer of plain PDMS and PDMS/CB nanocomposite

Measurements are taken under two conditions: (i) with fixed 15-s heating and 150-s cooling cycle shown in Fig. 2*b*, and (ii) fixed 15-s heating and varied cooling based on the return of the beam to its original position, as shown in Fig. 2*c*.

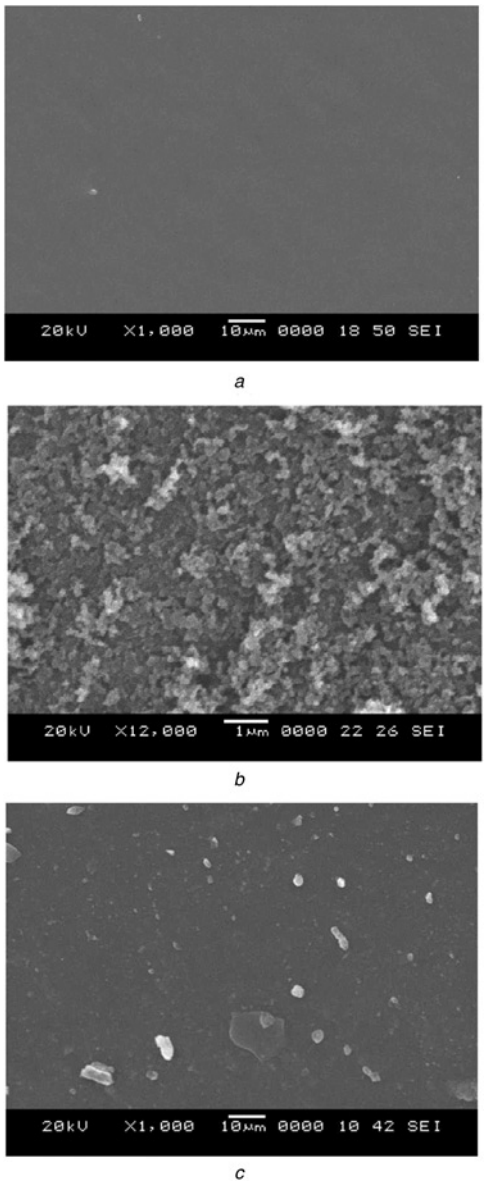


Fig. 4 *SEM image of*
a Prepared pure PDMS
b Pristine CB
c CB nanoparticle filled with PDMS sample

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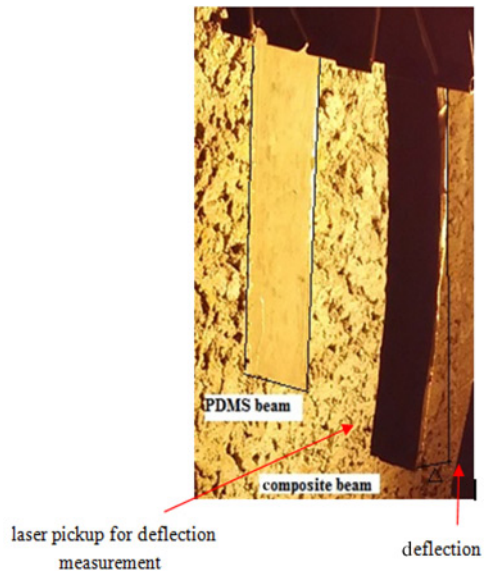


Fig. 5 *Deflection of PDMS/CB nanocomposite beam and plain PDMS sample*

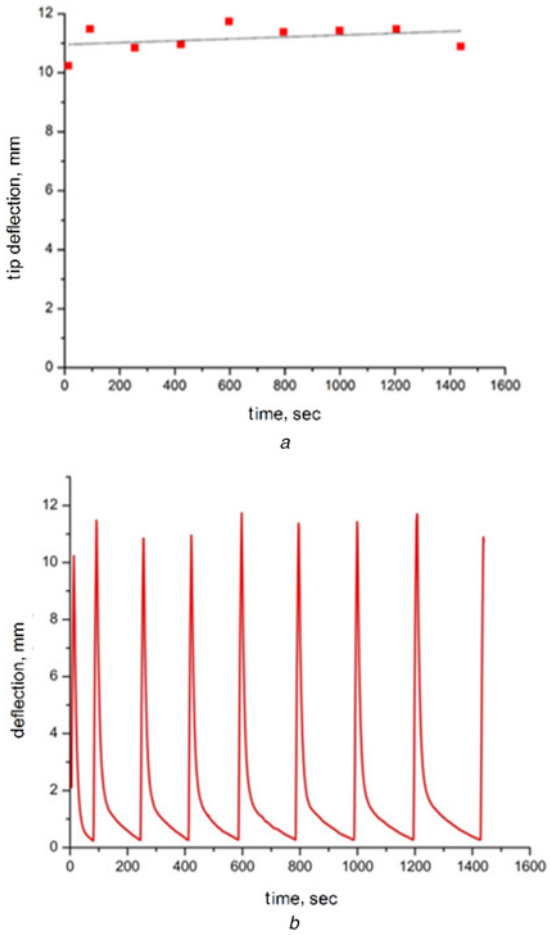


Fig. 6 *Deflection analysis through*
a Tip deflection of the nanocomposite beam
b Deflection of the sample with the different cooling cycle

3. Results and discussion: The particle size of the CB is analysed using a dynamic light scattering (DLS) method. The size of CB particles is found to be ranging from 184 to 416 nm, as shown in Fig. 3*a*.

UV–vis–IR spectrophotometer is one of the main tools to confirm the light absorbance of the nanocomposite sample. The measurement was performed in UV to IR range, and absorbance plotted against the wavelength is shown in Fig. 3*b*. It is shown that the light absorbance value of the PDMS/CB nanocomposite increases to nearly 0.72 a.u., on an average compared to <0.05 a.u. of plain PDMS material. The higher light absorbance thus achieved, results in a rise in temperature of the nanocomposite material facilitating photothermal actuation.

The SEM images of pure PDMS, CB powder, and PDMS/CB nanocomposites are shown in Figs. 4*a–c*, respectively. The morphology of the pure PDMS is homogenous, and there was no presence of other discrepancy phases. The PDMS/CB composite distribution appeared with small agglomeration. In some places, most of the CB particles are randomly dispersed in the polymer.

The photothermal deflection experiment was conducted for both plain PDMS and PDMS/CB nanocomposites. The deflection of the beam was recorded for the composite beam as mentioned above. The beam was observed to deflect when the light is on and regain its original position after the light is cut-off.

The fabricated samples of plain PDMS and PDMS/CB nanocomposites of dimensions 80 mm × 12 mm × 5 mm were exposed to the IR light. No deflection could be observed in pure PDMS, whereas the PDMS/CB composite exhibited a significant deflection, as shown in Fig. 5.

Also, IR radiations are said to be heatwaves, which will certainly cause relaxation in the polymeric matrix. To prevent catastrophic structural failure, nanocomposites used for structural applications are needed to maintain their mechanical integrity for a period of time during and after heat/fire exposure. This is important when it comes to competing with metals. Metals can hold integrity for a long time while the composite cannot hold the structure even for a short period of time when polymer parts (responsible for holding the filler) of the composite softens, degrades, and burns.

The tip deflection of the PDMS/CB nanocomposite beam after every heating cycle was recorded and plotted, as shown in Fig. 6*a*. It could be observed from the plot that there is significant repeatability of the deflection that has been achieved. When the beam deflection is measured with the variable cooling phase, as mentioned in the previous section, a thermal hysteresis could be observed. Also, which manifests an increase in the cooling period can be seen in Fig. 6*b*. The cooling phase gradually increases from 150 to 205 s in a span of three cycles.

4. Conclusion: A photoresponsive composite beam with PDMS and CB nanofiller was prepared. The fabricated PDMS/CB composite confirmed an increase in light absorbance (0.72) by spectrophotometer. The size of the CB powder was measured using the DLS method. The particle size varied in the range of 184–413 nm.

The photothermal test was conducted for plain PDMS and PDMS/CB nanocomposites material. The deflection of the nanocomposite beam was measured using the laser displacement sensor. The composite beam deformation was found to be about 10–11 mm, upon illumination with IR light. The beam recovers its initial position after turning the source off. The PDMS/CB nanocomposite has exhibited good repeatability for deformation value, but also some thermal inertia as mentioned. This work demonstrates the photomechanical effect in the PDMS nanocomposite with CB nanofiller.

The main advantages of photomechanical actuation offer wireless actuation, electromechanical decoupling, electric circuit elimination, thermostat, and an array of device actuation from a single light source. Applications of photoresponsive material are exhibit promising performance in the area of plastic motors, photoswitches, artificial muscle, microgripper, and solar energy harvester.

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