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Multifunctional Gels for Strain Sensing and Radiation Shielding in Space

Lucia LAMBERTINI[1,a], Maria Gabriella SANTONICOLA[2,b] and Susanna LAURENZI[1,c*]

[1]Department of Astronautical Electrical and Energy Engineering, Sapienza University of Rome, Via Salaria 851-881, 00138 Rome, Italy

[2]Department of Chemical Engineering Materials Environment, Sapienza University of Rome, Via del Castro Laurenziano 7, 00161 Rome, Italy

[a]lucia.lambertini@uniroma1.it, [b]mariagabriella.santonicola@uniroma1.it, [c]susanna.laurenzi@uniroma1.it

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Abstract. This work investigates a novel class of multifunctional poly(vinyl alcohol) (PVA) gels incorporating multi-walled carbon nanotubes (MWCNTs) for combined radiation shielding and strain-sensing applications. The proposed PVA/MWCNT gels, crosslinked with boric acid, offer high flexibility, conductivity, and mechanical robustness. MWCNT dispersion was optimized by analyzing sedimentation behavior as a function of sonication temperature and PVA concentration. Experimental characterization, including compression tests (–60 °C to +60 °C) and tensile–impedance coupling, demonstrated excellent electromechanical stability. These findings confirm the suitability of PVA/MWCNT gels for flexible, radiation-resistant SHM sensors in space structures.

Introduction

Flexible, durable, and conductive materials have played a crucial role in the development of Structural Health Monitoring (SHM) systems [1]. Traditionally, they have been employed as strain sensors to track the mechanical deformation of structures under load, enabling the early detection of potential threats to structural integrity [2-4]. In the space sector, SHM techniques are widely used to monitor primary structures such as satellite solar panels and antennas. Strain sensors are typically fabricated by embedding conductive materials, such as carbon nanotubes (CNTs), graphene, metal powders, and conductive polymers, within the matrix of elastomers [5, 6]. This approach enables elastomer-based sensors to achieve significant stretchability while maintaining good electrical conductivity. However, the practical use of elastomers in space applications remains challenging because of their sensitivity to the harsh radiative environment.

In addition to elastomers, conductive gels heve also attracted considerable interest as alternative strain-sensing materials [7]. Due to their high water content, softness, and tissue-like mechanical properties, gels can conform to complex surfaces and detect even subtle deformations. Moreover, their conductivity, which can be further enhanced by incorporating conductive fillers, makes them suitable for flexible and stretchable sensor systems.

Results from the PErsonalized Robotics as SErvice Oriented applications (PERSEO) project have demonstrated that liquid water is highly effective in mitigating radiation damage in space environments [8]. Among the various candidate materials for radiation shielding, gels have gained particular attention in the medical and pharmaceutical fields due to their high water content, which provides superior shielding performance compared to conventional polymers. Being intrinsically rich in hydrogen, an essential element for attenuating ionizing radiation such as neutrons and protons, water-based gels represent a promising solution for multifunctional systems. Therefore,

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incorporating gels into SHM systems could simultaneously enable strain sensing and passive radiation shielding.

In this work, we propose a novel class of multifunctional gels designed for simultaneous radiation shielding and strain sensing applications. The gels are based on a polyvinyl alcohol (PVA) matrix incorporating 0.5, 1.0, and 2.0 wt% multi-walled carbon nanotubes (MWCNTs), which act as conductive fillers to enhance both mechanical robustness and electrical conductivity. Dispersion quality of MWCNTs was optimized by analyzing sedimentation times as function of sonication temperature and PVA concentration. The aqueous PVA–MWCNTs dispersions were then chemically crosslinked with boric acid (BA), aiming to leverage the well-established neutron absorption capabilities of the ^{10}B isotope for shielding applications [9]. To validate their multifunctionality, both experimental and numerical investigations were conducted. Compression tests across the temperature range typical of satellites (–60 °C to +60 °C) were performed using dynamic mechanical analysis, while quasi-static tensile tests coupled with impedance monitoring were used to evaluate electromechanical stability. Finally, radiation transport simulations using the On-Line Tool for the Assessment of Radiation in Space (OLTARIS) tool confirmed the gels' potential as lightweight shielding materials. These findings open new avenues for the development of smart, adaptive materials capable of withstanding extreme environments while providing real-time structural monitoring.

Fabrication of PVA/BA gels

The following materials were obtained from Sigma-Aldrich: poly(vinyl alcohol) (PVA, Mw = 30,000 Da, ρ = 1.3 g/cm³, product no. 8438680100), boric acid (BA, product no. B0394), and ethanol (ρ = 0.790 g/cm³ at 20 °C, product no. 02860-1L). Pristine multi-walled carbon nanotubes (MWCNTs, NC7000 series) supplied by Nanocyl S.A. (Belgium) were used as nanofillers in the gel matrix.

The dispersion of MWCNTs in water was optimized using poly(vinyl alcohol) (PVA) as dispersing agent. 0.03g of MWCNTs were dispersed in ultrapure water (12 mL) containing different PVA concentrations. The suspensions were magnetically stirred and sonicated for 1 hour at 60 °C. The investigated PVA-to-MWCNT weight ratios were 4:1 (denoted as PVA 1 wt%), 12:1 (PVA 3 wt%), 20:1 (PVA 5 wt%), 32:1 (PVA 8 wt%), 40:1 (PVA 10 wt%) and 60:1 (PVA 15 wt%). Sedimentation tests revealed that dispersions below 5 wt% PVA were unstable, while 5 - 15 wt% PVA at 60 °C ensured homogeneous, long-lasting dispersions. Further optimization identified 8 wt% PVA as the optimal concentration, maintaining full stability for at least eight days. After dispersing the MWCNTs in ultrapure water using the optimized PVA concentration, the PVA/BA–MWCNT gels were synthesized by chemical crosslinking. A 30 wt% aqueous PVA–MWCNT solution was prepared by magnetic stirring at 80 °C for 1 hour. Separately, a 10 wt/vol% boric acid (BA) stock solution in ethanol was prepared under the same conditions. Crosslinking was initiated by adding the BA solution to the PVA dispersion to obtain a final BA concentration of 4 wt/vol%. The resulting mixtures were cast into glass molds and conditioned in a climate chamber at 30 °C and 50% relative humidity for 48 hours.

Compressive behavior

Dynamic mechanical analysis (DMA) of PVA/BA–MWCNT gels revealed a strong dependence of viscoelastic behavior on MWCNT concentration (Fig. 1). The pristine gel showed the lowest storage modulus (Fig. 1a), indicating a weak polymer network. Introducing 0.5 wt% MWCNTs significantly increased the modulus, confirming efficient load transfer between polymer chains and dispersed nanotubes. At 1.0 wt%, the modulus plateaued, suggesting a percolation threshold and possible nanotube agglomeration. A minor improvement at 2.0 wt% indicated mechanical saturation. The loss modulus curves (Fig.1 b) displayed distinct glass transition peaks, with higher

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MWCNT content enhancing energy dissipation. This increase reflects stronger polymer – nanotube interfacial interactions and reduced free water within the gel network.

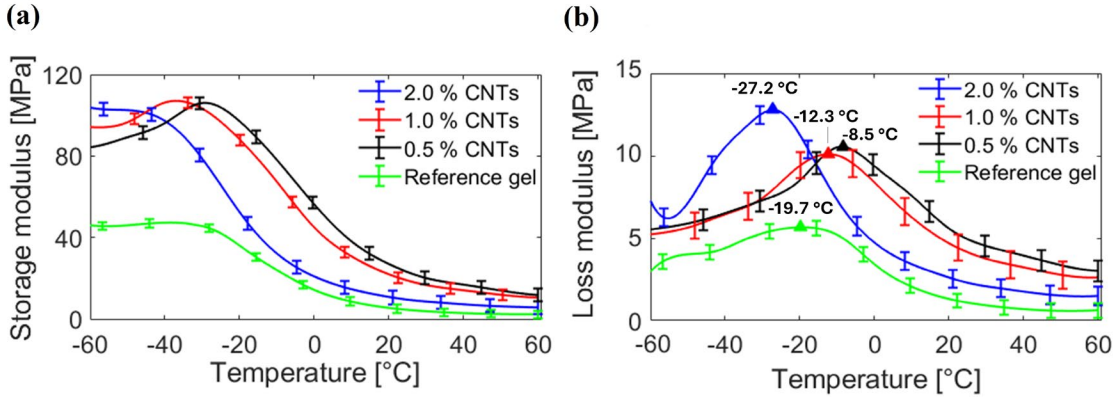


Fig. 1: DMA results of gels: (a) Storage and (b) Loss modulus with varying CNTs content.

SHM behavior through tensile-electrical tests

Tensile tests (ASTM D412-C) on PVA/BA gels with increasing MWCNT content (0–2 wt%) showed significant improvements in mechanical performance (Fig. 2a). The stress–strain curves shifted upward with higher filler content, indicating increased strength, elasticity, and energy absorption. The Young's modulus rose from 6.93 MPa for the reference gel to 18.41 MPa at 2 wt% MWCNTs, representing a threefold increase in stiffness. Additionally, the maximum strain at failure nearly doubled, demonstrating that MWCNT incorporation enhances both rigidity and toughness, allowing the gels to sustain larger deformations before failure.

Surface electrical conductivity measurements during tensile deformation (Fig. 2b) showed a clear increase in conductivity with higher MWCNT content, confirming the formation of interconnected conductive networks within the gels. Conductivity remained stable under strain, indicating good structural integrity of the network. As summarized in Table 11.5, conductivity rose by nearly three orders of magnitude—from 3.3×10^{-8} S/m for the reference gel to 2.4×10^{-5} S/m at 2 wt% MWCNTs.

Electrical conductivity describes how efficiently charge carriers move through a material, while conductance depends on geometry and deformation state. To evaluate the gels' sensing capability, conductance was derived from the real part of the admittance measured at 1 V and 1 kHz. As shown in Fig. 2c, the reference sample (0 wt% MWCNTs) and 0.5 wt% MWCNTs gels exhibited negligible conductance, indicating no percolating network. At higher filler contents, conductance increased markedly, reaching ~3×10^{-3} S for the 2 wt% MWCNT sample. This behavior confirms the formation of conductive pathways once the percolation threshold is achieved. From a Structural Health Monitoring (SHM) perspective, these conductance variations correlate with strain and integrity, providing a sensitive, non-destructive means to detect structural changes.

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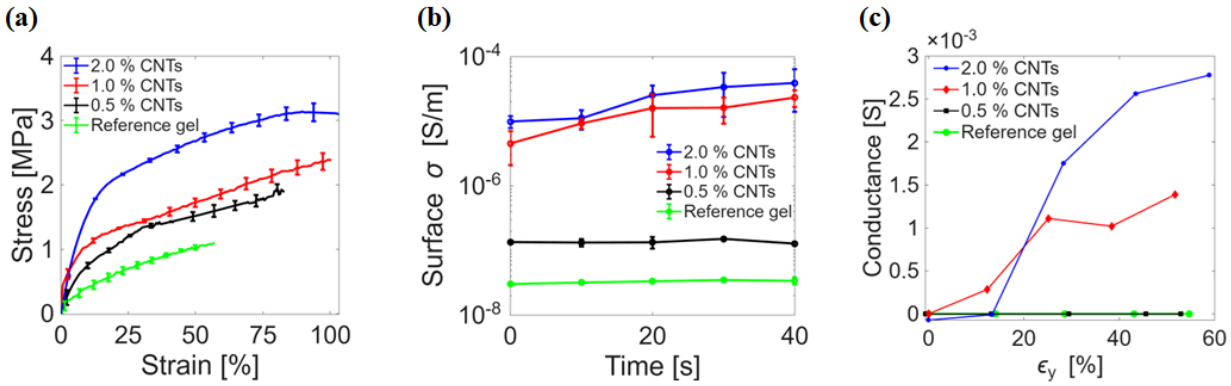


Fig. 2: Tensile-electrical results of PVA/BA-MWCNTs gels: (a) Engineering stress–strain curves of PVA/BA gels containing different weight fractions of MWCNTs (0, 0.5, 1.0, and 2.0 wt%); (b) Surface electrical conductivity (σ) of the gels as a function of time during tensile tests measured at frequency of 1 kHz; (c) Time evolution of the conductance at frequency of 1 kHz.

Numerical simulations

The radioprotective performance of gels was assessed through simulations using NASA's OLTARIS tool, developed at Langley Research Center [10]. In this study, the shielding effectiveness of PVA/BA gels was compared with standard liquid water investigated during PERSEO project. Simulations were carried out for a deep-space environment located at 1 astronomical unit (AU) from Earth, considering exposure to Galactic Cosmic Radiation (GCR) and Solar Particle Events (SPEs). The geometry consisted of a spherical shell with an inner void (radius 150 cm) and an external shielding layer of variable areal depth (0 – 5 g/cm²). This setup enabled a direct comparison between unshielded conditions (0 g/cm²) and progressively thicker protective layers. The Badhwar–O'Neill 2020 (BON2020) model was employed to represent the GCR spectrum, while the NUCFRG3 model was used for heavy-ion fragmentation processes. Historical SPE event of October 1989 was also simulated to evaluate solar proton exposure scenario. Materials of external layers were defined on the "Web Interface" using their density and elemental mass percentages reported in Table 1. Results were computed for the Male Adult voXel (MAX) human phantom modelt o assess radiation effects on human body.

Table 1: Input data for defining materials on OLTARIS tool.

Materials	Density [g/cm^3]	Elemental mass percentages []
PVA/BA (Ref. gel)	1.21	0.3436 C, 0.0931 H, 0.0029 ^{10}B, 0.0118 ^{11}B, 0.5486 O
PVA/BA-0.5 wt% CNTs	1.14	0.3730 C, 0.0909 H, 0.0031 ^{10}B, 0.0124 ^{11}B, 0.5206 O
PVA/BA-1.0 wt% CNTs	1.14	0.3577 C, 0.0912 H, 0.0029 ^{10}B, 0.0115 ^{11}B, 0.5367 O
PVA/BA-2.0 wt% CNTs	1.22	0.3550 C, 0.0903 H, 0.0027 ^{10}B, 0.0108 ^{11}B, 0.5412 O
H_2O (Liquid water)	1.00	0.1111 H, 0.8889 O

Fig. 3 illustrates the behavior of total effective doses equivalent as a function of areal depth for GCR and SPE environments. Results compare liquid water with PVA/BA gels incorporating different concentrations of carbon nanotubes (CNTs). In all cases, the effective dose equivalent decreases as depth increases, and the CNT-reinforced gels demonstrate shielding capabilities comparable to pure PVA/BA and water. These findings suggest that CNT reinforcement can be used to improve electrical and mechanical properties without compromising the radiation protection capability of PVA-based gels.

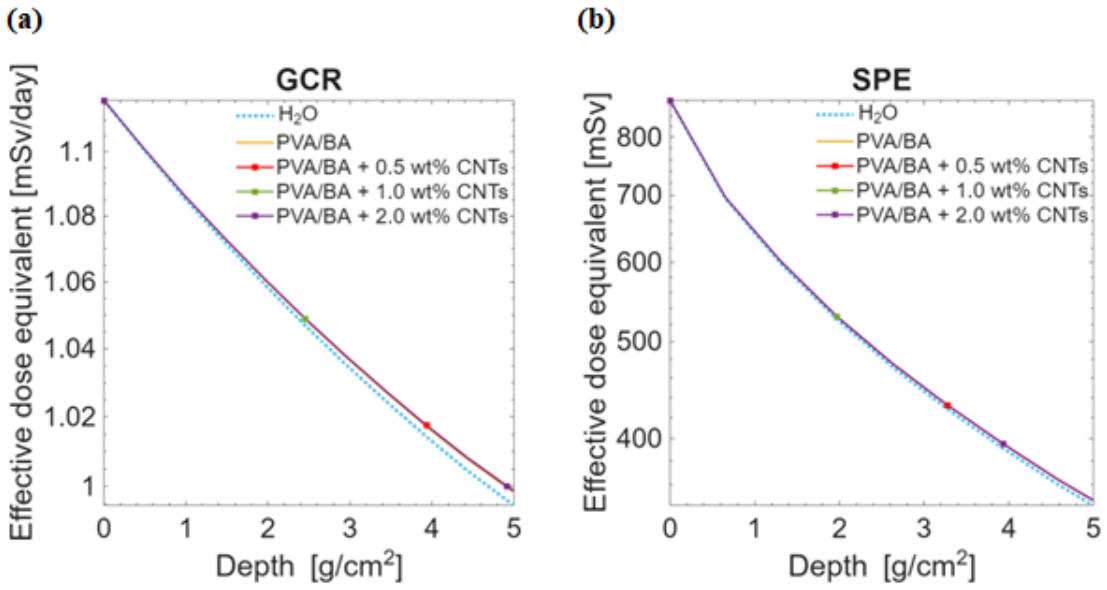


Fig. 3: Total effective dose equivalent as a function of depth for (a) GCR and (b) SPE scenarios.

Conclusions

PVA/BA–MWCNT gels were produced through an optimized nanotube dispersion process in water, ensuring uniform filler distribution within the polymer matrix. The resulting materials exhibited significant improvements in mechanical and electrical properties. DMA results showed that the storage modulus increased notably at 0.5 wt% MWCNTs, marking a mechanical percolation threshold between 0.5 and 1.0 wt%. The glass transition temperature displayed a non-monotonic trend, reflecting the balance between water plasticization and MWCNTs confinement. Electrical analysis revealed frequency-dependent conductivity enhancement, with a sharp rise between 0.5 and 1.0 wt% indicating conductive network formation. Tensile tests confirmed a threefold increase in stiffness (from 6.93 to 18.41 MPa) and nearly doubled strain at failure, while conductivity rose by three orders of magnitude. Overall, these gels combine mechanical strength and high conductivity, demonstrating strong potential for multifunctional sensing and structural health monitoring applications. Finally, numerical simulations confirmed that the incorporation of MWCNTs has a negligible impact on the radiation shielding capability of PVA-based gels, ensuring that the improvements in mechanical and electrical properties are achieved without compromising the protective behavior of pristine PVA/BA gels.

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References

[1] B. Cheng, Y. Li, H. Li, H. Li, S. Yang, P. Li, Y. Shang, An adhesive and self-healable hydrogel with high stretchability and compressibility for human motion detection, Composites Science and Technology, Vol. 213, 108948, 2021. https://doi.org/10.1016/j.compscitech.2021.108948

[2] Y. Park, M. Park, J. Lee, Reduced graphene oxide-based artificial synapse yarns for wearable textile device applications, Advanced Functional Materials, Vol. 28, 1804123, 2018. https://doi.org/10.1002/adfm.201804123

[3] Y. Liu, H. Fan, K. Li, N. Zhao, S. Chen, Y. Ma, X. Ouyang, X. Wang, Strain-isolation bridge structure to improve stretchability of highly sensitive strain sensors, Advanced Materials Technologies, Vol. 4, 1900309, 2019. https://doi.org/10.1002/admt.201900309

[4] M. Khatib, O. Zohar, W. Saliba, S. Srebnik, H. Haick, Highly efficient and water-insensitive self-healing elastomer for wet and underwater electronics, Advanced Functional Materials, Vol. 30, 1910196, 2020. https://doi.org/10.1002/adfm.201910196

[5] Y. Jung, K. K. Jung, D. H. Kim, D. H. Kwak, J. S. Ko, Linearly sensitive and flexible pressure sensor based on porous carbon nanotube/polydimethylsiloxane composite structure, Polymers, Vol. 12, 1499, 2020. https://doi.org/10.3390/polym12071499

[6] K. Kim, N. Jang, S. Ha, J. H. Cho, J. Kim, Highly sensitive and stretchable resistive strain sensors based on microstructured metal nanowire/elastomer composite films, Small, Vol. 14, 1704232, 2018. https://doi.org/10.1002/smll.201704232

[7] Y. Chen, Y. Zhang, A. Mensaha, D. Li, Q. Wang, Q. Wei, A plant-inspired long-lasting adhesive bilayer nanocomposite hydrogel based on redox-active Ag/Tannic acid-Cellulose nanofibers, Carbohydrate Polymers, Vol. 255, 117508, 2021. https://doi.org/10.1016/j.carbpol.2020.117508

[8] G. Baiocco, M. Giraudo, L. Bocchini, S. Barbieri, I. Locantore, E. Brussolo, D. Giacosa, L. Meucci, S. Steffenino, A. Ballario, The PERSEO Experience: A Water-Filled Garment Prototype for Personal Radiation Protection of Astronauts Successfully Tested on Board the International Space Station, Aerotecnica Missili & Spazio, Vol. 99, Pages 111-114, 2020. https://doi.org/10.1007/s42496-020-00048-0

[9] L. Lambertini, G. Coccarelli, E. Toto, M. G. Santonicola, S. Laurenzi, Poly(vinyl alcohol) gels cross-linked by boric acid for radiation protection of astronauts, Acta Astronautica, Vol. 221, Pages 142-154, 2024. https://doi.org/10.1016/j.actaastro.2024.05.020. https://doi.org/10.1016/j.actaastro.2024.05.020

[10] E. Toto, L. Lambertini, S. Laurenzi, M. G. Santonicola, Recent Advances and Challenges in Polymer-Based Materials for Space Radiation Shielding, Polymers, Vol. 16, 382, 2024. https://doi.org/10.3390/polym16030382