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TIRADENTES, MG

Organised & Edited by

R.J. da Silva

T.H. Panzera

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Dedicatory

To **Prof. Stephen W. Tsai**, that has devoted his career to research in composite materials. One of the most renowned composite engineers, he is known for the Tsai-Hill failure criterion, lamination parameters, the Tsai-Wu failure criterion and strength ratios, the Halpin-Tsai micromechanics model, trace, master ply, omni envelopes and unit circle failure criterion, among others.

Prof. Tsai has thus far published nine books (not including conference series): (1) Introduction to composite materials, (2) Composite Materials: design and applications, (3) Composites design, (4) Structural behaviour of composite materials, (5) Analyses of composite structures, (6) Strength & life of composites, (7) Theory of composites design, (8) Composite Materials Design and Testing, and (9) Design of Composite Laminates.

He is still active as an emeritus professor at Stanford University, and his lifelong talent and mastery in the field have recently led to the development of the Double-Double composite manufacturing and design technique, the theme of his new book launched this year (2022).

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R.J. da Silva: (I) Management of submission and review processes of full manuscripts; (II) Template and editing of full manuscripts; (III) Organisation, compilation, layout and publication of the book. **T.H. Panzera:** (I) Supervision of submission and review processes; (II) Supervision and review of book editing and layout; (III) Resources.

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About the 6th BCCM

The oldest train in operation in Brazil was inaugurated in 1881 by Dom Pedro II and it travels 12 km between *Tiradentes* and *São João del-Rei*.

6th Brazilian Conference on Composite Materials

The 6th BCCM was attended by over 300 participants from 14 countries. More than 100 articles have been published and presented orally, with authors from more than 60 research, teaching and technology institutions. The 6th BCCM was held from 14th to 18th August 2022, in *Tiradentes*, a charming and warm-hearted historical city famous for its gastronomy and architecture. *Tiradentes* was founded in 1718, named after *Joaquim José da Silva Xavier*, the "*Tiradentes*", patron of the Brazilian Republic.

Since its first edition in 2012, the Conference congregates Brazilian and worldwide students, professors, and researchers from academia and industry to promote the recent developments and discuss the challenges in composite materials in Brazil and abroad. The range of topics is comprehensive, including Damage and Fracture; Simulation in Composites; Adaptive Composites; Durability and Ageing; Mechanical and Physicochemical Properties of composites; Nanocomposites; Recycling and reuse of composite materials; Experimental Techniques; Lignocellulosic Composites; Processing and Manufacturing of composites; Health Monitoring in composite structures; Multi-Scale Modelling; Industrial Applications.

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Behind the 6th BCCM

The 6th Brazilian Conference on Composite Materials was co-organised by the Federal University of São João del-Rei (**UFSJ**), the Federal University of Minas Gerais (**UFMG**), and the Centre for Innovation and Technology in Composite Materials (**CIT^{e}C**).

Ranked among Brazil's top Institutions of Higher Education and located a short distance from the state capital city of *Belo Horizonte*, **UFSJ** offers a wide selection of over 50 graduate and undergraduate courses in areas such as Health Sciences, Arts and Humanities, Music, Social Sciences, Engineering and Technology, and Basic Sciences. Courses are taught on six different campuses, three of them located in *São João del-Rei* and the other three in the towns of *Divinópolis*, *Ouro Branco*, and *Sete Lagoas*. The University offers a stimulating environment for academic work, and at the same time, situated as it is in the historical heart of the state of *Minas Gerais*, it gives access to a range of cultural activities and attractions.

Placed in the southeast of Brazil, the most industrialized region of the country, **UFMG**, a free-of-charge public educational institution, is the oldest university in the state of *Minas Gerais*. It was founded in September 7th 1927 by the name of University of Minas Gerais (UMG). Nearly one hundred years later the institution is the national leader when it comes to education, university extension, culture, scientific research and patent generation in several fields of knowledge.

CIT^{e}C is a research group created in 2011 at UFSJ for the development and characterisation of laminate, particulate, hybrid and structural composites consisted of polymer and ceramic matrices for aeronautical, automotive, leisure, civil construction and orthopaedic applications. One of the pillars of the group is the research of sustainable materials through the use of natural fibres and recycled wastes. The group stands out for the use of statistical techniques in the evaluation of composite materials, counting on a significant number of articles published in journals of high impact. National and international collaborators have been contributing to the effective growing of the group. Visiting fellows, MSc and PhD students have been also a great motivation for our research team.

Conference Schedule

Time	Sunday 14th	Monday 15th
07:30		**Register**
08:00		**Opening ceremony**
08:30		**Plenary 1** (Ramesh Talreja)
09:20		**Presentation 1** (Room 1-3)
10:40		Coffee-Break
11:05		**Presentation 2** (Room 1-3)
12:25	**Register**	**Lunch**
14:15	**Short-courses: part I** (Adriano Koga; Sérgio Pezzin)	**Plenary 2** (Steven Tsai)
15:05		**Presentation 3** (Room 1-3)
16:25	Coffee-Break	Coffee-Break
16:50 17:40	**Short-courses: part II** (Adriano Koga; Sérgio Pezzin)	**Presentation 4** (Room 1-3)

Time	Tuesday 16th	Wednesday 17th	Thursday 18th
08:30	**Plenary 3** (Fabrizio Scarpa)	**Plenary 5** (Pedro Camanho)	**Technical Lectures** (Anton Paar; HEXCEL)
09:20	**Presentation 5** (Room 1-3)	**Presentation 7** (Room 1-3)	**Presentation 11** (Room 1-3)
10:40	Coffee-Break	Coffee-Break	**Closing ceremony**
11:05	**Presentation 6** (Room 1-3)	**Presentation 8** (Room 1-3)	
12:25	**Lunch**	**Lunch**	
13:55	**Plenary 4** (Eloi Figueiredo)	**Plenary 6** (Mauricio Donadon)	
14:45	**Short-courses: part I** (Sandro Amico; Flamínio Levy Neto; Gerson Marinucci)	**Presentation 9** (Room 1-3)	
16:05	Coffee-Break	Coffee-Break	
16:30 17:50	**Short-courses: part II** (Sandro Amico; Flamínio Levy Neto; Gerson Marinucci)	**Presentation 10** (Room 1-3)	
20:00		**Dinner**	

Keynote Speakers – Plenaries

Three decades of pattern recognition for structural health monitoring of bridges

Prof. Elói Figueiredo
Lusófona University
Portugal

Mechanical metamaterials and biobased composites: new trends for sustainable high-performance structures

Prof. Fabrizio Scarpa
University Of Bristol
United Kingdom

Strength prediction of composite laminates under uncertainties using theory-guided machine learning

Prof. Pedro Camanho
University of Porto
Portugal

Failure analysis of composite materials towards cost/performance trade-off

Prof. Ramesh Talreja
Texas A&M University
USA

The analytic foundation of double-double: DD concepts & operation

Prof. Stephen Tsai
Stanford University
USA

A decohesive interface element for static and fatigue induce damage predictions in adhesively bonded joints under variable loads and debonding mode ratios

Prof. Mauricio Donadon
Aeronautics Institute of Technology
Brazil

Short Courses

Finite Element Method
(FEM)

Adriano Koga
Altair

Analysis of laminated
composite beams

Prof. Flamínio Levy Neto
University of Brasília

Fundamentals of polymeric
matrix composites

Prof. Gerson Marinucci
Nuclear and Energy
Research Institute

Introduction to
composite manufacturing

Prof. Sandro Amico
Federal University of
Rio Grande do Sul

Self-healing
composites

Prof. Sérgio Pezzin
Santa Catarina State University

Technical Lectures

Characterisation of mechanical properties
in composite materials

Anton Paar

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About published articles

The 6th BCCM featured the publication of 119 articles, and all work presentations were performed orally, distributed in 3 rooms with 11 presentation sessions each. The presenter's name is underlined in the manuscript header.

In this book section, the reader will find a list with all participating institutions (authors' affiliation), a summary with all the titles of published articles, and the schedule for the oral presentations performed at the conference.

Serra de São José, with a maximum altitude of approximately 1300 m, is located between the municipalities of *Tiradentes, São João del-Rei*, *Santa Cruz de Minas*, *Prados* and *Coronel Xavier Chaves*.

Participating institutions
(author's affiliation)

Algeria
- University of Guelma

Austria
- FRACTURE ANALYTICS

Brazil
- Aeronautics Institute of Technology
- Amazonas State University
- Braskem S.A.
- Brazilian Army Technological Center
- Catholic University Centre of Santa Catarina
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- Federal Center for Technological Education of Minas Gerais
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- Federal University of Minas Gerais
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- Federal University of Pernambuco
- Federal University of Rio de Janeiro
- Federal University of Rio Grande do Norte
- Federal University of Rio Grande do Sul
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- Federal University of São Carlos
- Federal University of São João del-Rei
- Federal University of São Paulo
- Federal University of Western Bahia
- Institute for Technological Research
- Muniz & Spada Ltda.
- National Institute of Technology
- National Laboratory for Scientific Computing
- Nuclear and Energy Research Institute
- Petrobras
- Pontifical Catholic University of Rio de Janeiro
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- São Paulo State Technological Colleges
- São Paulo State University
- State University of Campinas
- State University of Londrina
- University of Brasília
- University of Caxias do Sul
- University of São Paulo

Chile
- Pontifical Catholic University of Valparaiso

Cuba
- Santa Clara University
- Technological University of Habana

Germany
- Federal Institute for Materials Research and Testing
- Leibniz Institute of Polymer Research Dresden
- Munich University of Applied Sciences

Italy
- University of Campania Luigi Vanvitelli

Latvia
- Riga Technical University

Portugal
- Lusófona University
- University of Porto

South Korea
- Hanyang University

Spain
- University of Cantabria

Sweden
- KTH Royal Institute of Technology
- Luleå University of Technology
- Research Institutes of Sweden
- University of Borås

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- Radboud University
- Toray Advanced Composites
- University of Twente

United Kingdom
- Glyndwr University
- University of Bristol
- University of Edinburgh
- University of Glasgow
- University of Strathclyd

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Rheology behavior of epoxy/carbon nanoparticles suspension

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Abstract: The use of nanoparticles as additives to obtain different functionalities in resins such as epoxy has recently attracted much attention. In this work, the rheological behavior of suspensions of graphene nanoparticles (GN) and carbon nanotubes (CNT) (0.05-2 wt.%) were investigated. Graphene oxide (GO) and carbon dots (CQD) are also being investigated, being reactive species that could act as compatibilizers. The suspensions were produced by mechanical stirring (30 min) followed by ultrasonication (30 min). The Bagley diagram was constructed with the solubility parameters (δ_i) of the nanofillers, and it was noted that the GO is more compatible with the hardener (TETA), while CNT and CQD with the resin. CNT system showed rheology percolation with a content above 0.2 wt.%, whereas with NG no percolation was observed up to 2 wt.%.

1. Introduction

The use of nanoparticles as additives to obtain different functionalities in resins such as epoxy has recently attracted much attention, for instance, coatings with microbial action using silver nanoparticles [1], adhesives using graphene (GN) [2], conductive materials with carbon nanotubes (CNT) [3], and anti-counterfeiting materials such as carbon quantum dots (CQDs) [4]. Nonetheless, the specific functionalities of the resin involve many steps, such as obtaining a stable suspension so that its properties are little affected during processing.

The low solubility is a significant obstacle for the effective dispersion in liquids and resins of carbonic nanoparticles such as GN. This is related to the van der Waals forces that promote their agglomeration and the number of polar groups in their structure, resulting in hydrogen bonds, yielding stable suspensions [5]. An alternative is to use surfactants to aid in dispersion and reduce re-agglomeration [6]. However, this additive can be a defect former in applications such as structural composites. Other strategies such as the inclusion of surface groups can be employed, but this requires further processing steps and brings difficulties in scaling-up. These observations are also noted for CNT. Besides, the rheological percolation limit for CNT is lower compared to GN.

Nanoparticles such as graphene oxide (GO) and carbon quantum dots (CQDs) have to surround chemical groups with active hydrogen and are very soluble in polar solvents and resins such as epoxy. This is because, in their structure, there are oxygenated and nitrogenated chemical groups with active hydrogen [7]. Thus, these nanoparticles can be used as a compatibilizer and other carbonic particles with lower polarity, such as GN and CNT. However, the rheological properties of the resin and its hardener must be little affected to prevent composite processing difficulties and to guarantee its applicability.

This work investigates the epoxy resin (DGEBA/TETA) flow behavior using different carbonic fillers (GN and CNT), as well as the use of carbonic particles such as GO and CQDs as compatibilizers.

2. Experimental

An epoxy resin (DGBEA) with an average molecular weight of 750 g.mol^{-1} (GPC measurements, THF, and polystyrene standards) with code AR260 was acquired from e-composites (Brazil). The triethylenetetramine (TETA) with code HY951 was purchased from Hustman of Brazil. Graphene nanoplatelets with an average thickness of 5 – 10 nm in varying sizes up to 25 µm under and multi-walled CNT (diameter ~140 nm, length ~7 µm) were purchased from Strem Chemicals, Inc. USA. GO was obtained through the modified Hummers method, according to the literature. CQDs were obtained by microwave-assisted reactions and slow pyrolysis, described in [7-8].

Epoxy and hardener suspensions were prepared using 0–2 wt.% nanoparticles. The nanoparticles were first mechanically stirred separately in the resin and hardener at a speed of 13000 rpm (Ultra-Turrax T 18) for 30 min in an ice bath. After that, they were sonicated for 30 min in a Sonifier® Model W-450D (amplitude: 60%; pulse on/off, 60 s/60 s) cooled with ice bath. The stability of the suspensions was assessed with visual analysis in graduated cylinders for a minimum time of 7 days. The effect of the particles as compatibilizers was evaluated in the sample with 0.2 wt.% in which half of the GN or CNT was replaced by GO or CQDs. Up-and-down flow curves were obtained in an Anton Paar MCR 101 rheometer using 25 mm parallel plate geometry at 25°C for shear rates of 0.1-1000 s^{-1}.

3. Results and Discussions

To evaluate the solubility of nanoparticles and resin, 2D plots of solubility parameters were employed (Bagley plots) (Fig. 1). This methodology assumes that the effects of the dispersion (δ_d) and polar (δ_p) components of the solubility parameter show close similarity, while the effect of the hydrogen-bonding (δ_h) component is from an entirely different nature. Dispersive, polar, and hydrogen contributions were computed using literature data [9-12]. In the Bagley plot with epoxy resin in the circle's center, the solubility of the nanoparticles in the resin system can be evaluated. As can be seen, GO is more miscible with the hardener D_{12} = 9.65 MPa$^{1/2}$ compared to GN, whereas CNT (6.29 MPa$^{1/2}$) and CQDs (6.71 MPa$^{1/2}$) are more miscible with pure resin. GN is the nanoparticle with lower miscibility with both resin and hardener.

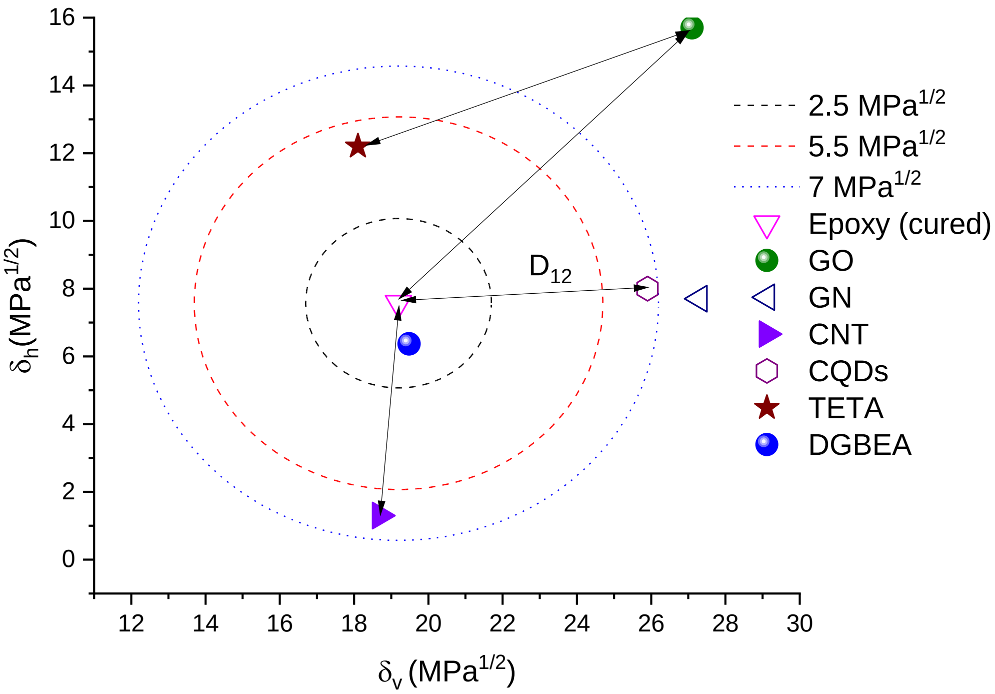

Fig. 1. Bagley plots for epoxy, hardener and nanoparticles. The dotted circles indicate D_{12} equals to 2.5, 5.5 and 7.0 MPa½.

Fig. 2 a-b) show the epoxy resin up-and-down flow curves. No sample showed a significant hysteresis loop. For the system with GN, all suspensions showed a Newtonian behavior, while for those with CNT, the non-Newtonian viscosity behavior depended on the amount of CNT. The Herschel-Bukley model was used and fitted to the systems, with $R^2 > 0.999$. Above 0.2 wt.%, a more significant deviation from the Newtonian behavior is noticed due to the formation of a percolated network, in which the particles significantly increase viscosity of the system. Regarding the TETA/GN and TETA/CNT suspensions, a similar behavior was observed, i.e., a Newtonian behavior with GN and a percolation threshold with 0.2 wt.% of CNT. Addition of CNTs to a Newtonian suspension (resin) increased the apparent shear viscosity at low shear rate and, as the shear rate increased, the viscosity decreased asymptotically to that of the suspension. This type of behavior is known as shear-thinning, and is caused by many factors, such as chemical modification of particles and others. In the current work, it may occur due to a hierarchical structure of aggregated CNT structures [13].

Table 1 shows the fitted rheological data using the Herschel-Bukley model. The τ_0 term is nearly zero, and a rheological behavior of a power-law fluid ($\tau = K\dot{\gamma}^n$) was considered. The systems with GN deviate very little from the Newtonian behavior, as n is very close to 1. In addition, the value of the consistency index, K tends to increase when CQDs and GO are added, which indicates an increase in fluid consistency. A reduction in this parameter for suspensions with CNT is seen, which is similar to what was reported by Ma et al [14] when comparing the rheological behavior of CNT suspensions with and without treatment. This indicates that CQDs can essentially cause the CNT to behave like short fibers that rotate and align under shear flow.

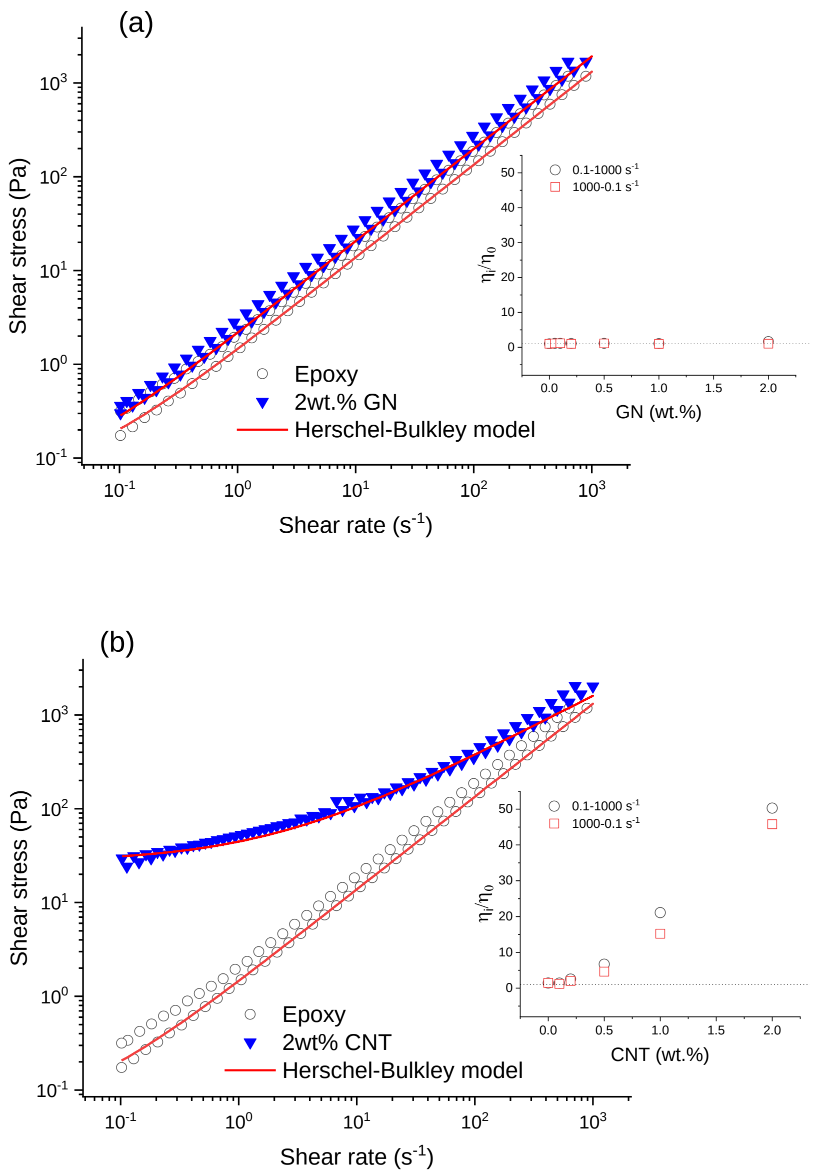

Fig. 2. Up-and-down flow curves of epoxy resin with GN (a) and with CNT (b). Red line represents the Herschel-Bulkey model. Insert refers to the relative viscosity at 10^{-1} s^{-1} as a function of nanoparticle content.

Table 1. Rheological fitted parameters of compatibilized suspensions.

Sample	τ_0 (Pa)	K (Pa.sn)	n	R^2
Epoxy	-	1.368	0.996	0.9999
0.2 GN	-	1.336	0.996	0.9999
0.1 GN + 0.1 CQDs	-	1.414	0.993	0.9999
0.1 GN + 0.1 GO	-	1.656	0.959	0.9991
0.2 CNT	-	2.169	0.929	0.9957
0.1 CNT + 0.1 CQDs	-	1.323	0.992	0.9999

4. Conclusions

Epoxy and TETA suspensions with different carbonic particles were prepared and their rheological behavior was investigated. The solubility parameters contributed to understanding which nanoparticle is more soluble in the resin and the hardener. The system with GN did not present rheological percolation, while for CNT percolation occurred above 0.2 wt.%. This approach showed the possibility of using nanoparticles such as GO and CQDs as GN compatibilizers in epoxy systems due to the presence of specific functional groups (-OH, -COOH and $-NH_2$) in the nanoparticles.

Declaration of Competing Interest

The authors declare no conflict of interest.

Credit author statement

J A. Cruz: Conceptualization; Methodology; Formal Analysis. **L Paim:** Conceptualization; Methodology; Formal Analysis. **R Joffe:** Writing – review. **P Fernberg:** Writing – review. **S Amico:** Supervision; Writing – review. **O Bianchi:** Conceptualization; Writing – original draft; Resources; Supervision

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References

[1] R. Bertani et al. Improving the Antimicrobial and Mechanical Properties of Epoxy Resins via Nanomodification: An Overview. Molecules, 2021. 2617): p. 5426. (https://doi.org/10.3390/molecules26175426)

[2] Z. Wang et al., Graphene nanoplatelets/epoxy composites with excellent shear properties for construction adhesives. Composites Part B: Engineering, 2018. 152: p. 311-315. (https://doi.org/10.1016/j.compositesb.2018.08.113).

[3] M. Mecklenburg et al., On the manufacturing and electrical and mechanical properties of ultra-high wt.% fraction aligned MWCNT and randomly oriented CNT epoxy composites. Carbon, 2015. 91: p. 275-290. (https://doi.org/10.1016/j.carbon.2015.04.085).

[4] U. Lee et al. Carbon dots for epoxy curing: Anti-forgery patterns with long-term luminescent stability. Chemical Engineering Journal, 2021. 405: p. 126988. (https://doi.org/10.1016/j.cej.2020.126988).

[5] H. Gu et al., An overview of multifunctional epoxy nanocomposites. Journal of Materials Chemistry C, 2016. 4(25): p. 5890-5906. (https://doi.org/10.1039/C6TC01210H).

[6] Y. Wan et al., Improved dispersion and interface in the graphene/epoxy composites via a facile surfactant-assisted process. Composites Science and Technology, 2013. 82: p. 60-68. (https://doi.org/10.1016/j.compscitech.2013.04.009).

[7] L. Agnol et al. Green synthesis of Spirulina-based carbon dots for stimulating agricultural plant growth. Sustainable Materials and Technologies, 2021. 30: p. e00347. (https://doi.org/10.1016/j.susmat.2021.e00347)

[8] E. Fonseca et al. Time-dependent properties of epoxy resin with imidazolium ionic liquid. Journal of Applied Polymer Science, 2021. 138(46): p. 51369. (https://doi.org/10.1002/app.51369)

[9] M. Ayán-Varela et al., A quantitative analysis of the dispersion behavior of reduced graphene oxide in solvents. Carbon, 2014. 75: p. 390-400. (https://doi.org/10.1016/j.carbon.2014.04.018).

[10] Y. Hernandez et al. Measurement of Multicomponent Solubility Parameters for Graphene Facilitates Solvent Discovery. Langmuir, 2010. 26(5): p. 3208-3213. (https://doi.org/10.1021/la903188a).

[11] D. Locatelli et al. Tuning the Solubility Parameters of Carbon Nanotubes by Means of Their Adducts with Janus Pyrrole Compounds. Nanomaterials, 2020. 10(6): p. 1176. (https://doi.org/10.3390/nano10061176)

[12] J. C. Zuaznabar-Gardona and A. Fragoso. Determination of the Hansen solubility parameters of carbon nano-onions and prediction of their dispersibility in organic solvents. Journal of Molecular Liquids, 2019. 294: p. 111646. (https://doi.org/10.1016/j.molliq.2019.111646).

[13] A.W.K. Ma. and M.R. Chinesta. The rheology and modeling of chemically treated carbon nanotubes suspensions. Journal of Rheology, 2009. 53(3): p. 547-573. (https://doi.org/10.1122/1.3093105)

[14] A.W.K. Ma. M.R. Mackley, and F. Chinesta, The microstructure and rheology of carbon nanotube suspensions. International Journal of Material Forming, 2008. 1(2): p. 75-81. (https://doi.org/10.1007/s12289-008-0375-7).