



**Preparation and Characterization of Epoxy/ Poly
(Methyl Methacrylate) (PMMA) Blend System with
Carbon Based Conductive Fillers.**

055088

by

nb
FTA418.9
CGP577
2016

**PHUA JIN LUEN
(1340410911)**

A thesis submitted in fulfilment of the requirement for the degree of Doctor
of Philosophy in Materials Engineering

**School of Materials Engineering
UNIVERSITI MALAYSIA PERLIS**

2016

ACKNOWLEDGEMENT

First and foremost, I would like to express my sincerest gratitude to my supervisor, Dr. Teh Pei Leng, for the continuous support of my Ph.D. study and related research, for her patience, motivation, and immense knowledge while allowing me the room to explore in my way. Her willingness to give her time so generously has been very much appreciated. I would like to extend my very great appreciation to my co-supervisor, Assoc. Prof. Dr. Supri A. Ghani and the rest of my thesis committee, Dr. Yeoh Cheow Keat and Dr. Rozyanty Bt. Rahman, for their valuable and constructive suggestions during planning and development of this research work.

My grateful heart goes to our dean, Dr. Khairel Rafezi and the School of Materials Engineering, for providing an excellent research environment and well-functioned equipment. I would like to offer my heartfelt to Mr. Azmi Bin Kamardin for his guidance and knowledge sharing during my data collection processes. My sincere thanks to all the technicians of the School of Materials Engineering: Mr. Norzaidi Bin Zainol, Mr. Mohd Nasir Bin Haji Ibrahim, Mr. Ku Hasrin Bin Ku Abdul Rahman, Mr. Mohamad Safwan Bin Isa, Mr. Mohammed Faisal Rusli, Mr. Ahamd Hadzrul Bin Iqwan Jalaludin, Mr. Chek Idrus Bin Omar, Mr. Azmi Bin Aziz and Mr. Rosmawadi Bin Othman, for their helpful and patience attitudes in aiding me running my Laboratories works.

For this dissertation, I would like to thank my discussion group: Mohamad Nur Fuadi, Devi Shantini, Saw Lip Teng, Teo Siew Cheng, Lim Joon Hoong and much more, for their time, stimulating and insightful comments. I gratefully acknowledge the funding sources that made my Ph.D. work possible. Under the Malaysia Ministry of Higher Education, I was awarded MyBrain 15 Sponsorship Programme (MyPhD). Without their

valuable support, it would be not possible to conduct this research. Lastly, I would like to thank my family for all their love and encouragement. For my parents who raised me and helped me in all my pursuits and to my sisters and brother for supporting me spiritually throughout this research and my life in general. Thank you.

Phua Jin Luen

Universiti Malaysia Perlis

June 2016

©This item is protected by original copyright

TABLE OF CONTENTS

	PAGE
ACKNOWLEDGEMENT	i
DECLARATION OF THESIS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	xi
LIST OF FIGURES	xiii
LIST OF ABBREVIATIONS	xx
LIST OF SYMBOLS	xxiii
ABSTRAK	xxv
ABSTRACT	xxvi
CHAPTER 1 INTRODUCTION	1
1.1. Introduction	1
1.2. Problem Statement	6
1.3. Objectives	10
CHAPTER 2 LITERATURE REVIEW	12
2.1. Polymers	12
2.2. Polymer Blends	13
2.2.1. Homologous Polymer Blend	14
2.2.2. Miscible Polymer Blend	14

2.2.3.	Immiscible Polymer Blend	15
2.2.4.	Compatible Polymer Blend	15
2.2.5.	Polymer Alloys/ Compatibilized Polymer Blends	16
2.3.	Phase Separation	16
2.3.1.	Identifying The Phase Separation	16
2.3.2.	Compatibilization	17
2.4.	Preparation of Polymer Blend	18
2.4.1.	Melt Extrusion	18
2.4.2.	High Shear Processing	18
2.4.3.	Reactive Blending	18
2.5.	Morphology Formation & Development	19
2.5.1.	Properties	19
2.6.	Additives or Fillers	22
2.6.1.	Distribution & Dispersion	24
2.7.	Conductive Polymer	25
2.7.1.	Intrinsically Conductive Polymer/ Conjugated Polymer	26
2.7.2.	Filled Conductive Polymer Composites	27
2.8.	Conduction Mechanism	28
2.8.1.	Percolation Threshold	30
2.8.2.	Influence of Immiscible Polymer Blends Towards The Percolation Threshold	30
2.9.	Epoxy Resin	32
2.10.	Epoxy Hardener	35
2.11.	Poly (Methyl Methacrylate) (PMMA)	40
2.12.	Carbon Black (CB)	43
2.13.	Graphene Nanoplatelets (GNPs)	48

CHAPTER 3 RESEARCH METHODOLOGY	54
3.1. Material	54
3.1.1. Epoxy Resin and Epoxy Hardener	54
3.1.2. Poly (Methyl Methacrylate)	55
3.1.3. Carbon Black	55
3.1.4. Graphene Nanoplatelets	56
3.1.5. Methylene Chloride	56
3.1.6. Nitric Acid	57
3.2. Samples Preparation	57
3.2.1. Volume Fraction	57
3.2.2. Dispersion of Filler	57
3.2.3. Single Matrix	58
3.2.4. Dual Matrixes	59
3.2.5. Surface Modification	62
3.3. Testing and Characterization	64
3.3.1. Density	64
3.3.2. Fourier Transform Infrared Spectroscopy (FTIR)	64
3.3.3. Flexural Testing	64
3.3.4. Fracture Toughness	65
3.3.5. Bulk Electrical Resistivity and Conductivity	66
3.3.6. Thermogravimetric Analysis (TGA)	67
3.3.7. Thermal Expansion Coefficient (CTE)	67
3.3.8. Scanning Electron Microscopy (SEM)	68
3.4. Flow Chart of Experiment	68

CHAPTER 4 RESULTS & DISCUSSION	70
4.1. Effect of Carbon Black (CB) on The Properties of Epoxy/PMMA System.	70
4.1.1. Effect of CB Filler Loading on Single Matrix Epoxy Composites.	70
4.1.1.1. Density	70
4.1.1.2. Flexural Properties	71
4.1.1.3. Fracture Toughness	76
4.1.1.4. Electrical Bulk Resistivity & Conductivity	77
4.1.1.5. Thermal Stability	79
4.1.1.6. Thermal Expansion Coefficient	80
4.1.1.7. Summary	81
4.1.2. Effect of PMMA Content (vol.%) on The Properties of Dual Matrixes Epoxy/PMMA System Using Solvent Dissolution (SD) and Direct Mixing (DM) Methods.	83
4.1.2.1. Density	83
4.1.2.2. Flexural Properties	85
4.1.2.3. Fracture Toughness Properties	96
4.1.2.4. Electrical Bulk Conductivity	98
4.1.2.5. Thermal Stability	102
4.1.2.6. Thermal Expansion Coefficient	109
4.1.2.7. Summary	111
4.1.3. Effect of CB Filler Loading (vol.%) on The Properties of Dual Matrixes Epoxy/PMMA Blend System Using Solvent Dissolution (SD) and Direct Mixing (DM) Methods.	113
4.1.3.1. Density	113
4.1.3.2. Flexural Properties	114
4.1.3.3. Fracture Toughness Properties	118
4.1.3.4. Electrical Bulk Conductivity	119
4.1.3.5. Thermal Stability	121

4.1.3.6.	Thermal Expansion Coefficient	124
4.1.3.7.	Summary	125
4.1.4.	Effect of Surface Modification on CB Filled Single and Dual Matrixes System.	127
4.1.4.1.	Fourier Transform Infrared Spectroscopy (FTIR)	127
4.1.4.2.	Thermal Stability for Surface Modified CB	131
4.1.4.3.	Density	132
4.1.4.4.	Flexural Properties	133
4.1.4.5.	Fracture Toughness Properties	138
4.1.4.6.	Electrical Bulk Resistivity & Conductivity	140
4.1.4.7.	Thermal Stability	142
4.1.4.8.	Thermal Expansion Coefficient	146
4.1.4.9.	Summary	147
4.2.	Effect of Graphene Nanoplatelet (GNP) on The Properties of Epoxy/PMMA Dual Matrixes System Using Direct Mixing (DM) Method.	149
4.2.1.	Effect of GNP Filler Loading on Single Matrix System.	149
4.2.1.1.	Density Properties	149
4.2.1.2.	Flexural Properties	150
4.2.1.3.	Fracture Toughness Properties	154
4.2.1.4.	Electrical Bulk Resistivity & Conductivity	155
4.2.1.5.	Thermal Stability	157
4.2.1.6.	Thermal Expansion Coefficient	159
4.2.1.7.	Summary	160
4.2.2.	Effect of PMMA Content (vol.%) on The Properties of GNP Filled Dual Matrixes Epoxy/PMMA System Using Direct Mixing Method.	161
4.2.2.1.	Density	161
4.2.2.2.	Flexural Properties	162

4.2.2.3.	Fracture Toughness Properties	164
4.2.2.4.	Electrical Bulk Resistivity & Conductivity	165
4.2.2.5.	Thermal Stability	166
4.2.2.6.	Thermal Expansion Coefficient	168
4.2.2.7.	Summary	170
4.2.3.	Effect of GNP Filler Loading (vol.%) on The Properties of Dual Matrixes Epoxy/PMMA System Using Direct Mixing Method.	171
4.2.3.1.	Density Properties	171
4.2.3.2.	Flexural Properties	172
4.2.3.3.	Fracture Toughness Properties	174
4.2.3.4.	Electrical Bulk Conductivity	175
4.2.3.5.	Thermal Stability	176
4.2.3.6.	Thermal Expansion Coefficient	178
4.2.3.7.	Summary	180
4.2.4.	Effect of Surface Modification on GNP Filled Single and Dual Matrixes System.	181
4.2.4.1.	Fourier Transform Infrared Spectroscopy (FTIR)	181
4.2.4.2.	Thermal Stability	184
4.2.4.3.	Density	185
4.2.4.4.	Flexural Properties	186
4.2.4.5.	Fracture Toughness	190
4.2.4.6.	Electrical Bulk Conductivity	193
4.2.4.7.	Thermal Stability	194
4.2.4.8.	Thermal Expansion Coefficient	198
4.2.4.9.	Summary	199
4.3.	Summary and Comparison Study Between CB and GNP Filled Single and Dual Matrixes System.	201

CHAPTER 5 CONCLUSION & RECOMMENDATION	206
5.1. Summary	206
5.2. Recommendation for Study	208
REFERENCES	210
APPENDIX – A	228
APPENDIX – B	229
APPENDIX – C	230
APPENDIX – D	231
APPENDIX – E	232
APPENDIX – F	233
APPENDIX – G	234
LIST OF PUBLICATION	235
LIST OF CONFERENCES ATTENDED	236

LIST OF TABLES

No.		PAGE
2.1	Conductivity and other properties of common conjugated conducting polymers.	27
3.1	Typical properties of DER 331, epoxy resin	54
3.2	Typical properties of clear-grade, epoxy hardener.	54
3.3	Typical properties of IF 850, poly (methyl methacrylate)	55
3.4	Typical properties of Conductex® K Ultra, carbon black	55
3.5	Typical properties of 0540DX, graphene nanoplatelets.	56
3.6	Typical properties of analytic grade, methylene chloride.	56
3.7	Typical properties of nitric acid (65%).	57
3.8	Filler loading of carbon black and graphene nanoplatelets in single matrix epoxy system.	59
3.9	PMMA content in dual matrixes epoxy/PMMA system.	59
3.10	Summarize of surface modification methods.	63
3.11	SEN-T sample dimension	66
4.1	The $T_{5\%}$, $T_{50\%}$, D_{slope} and T_{DMax} of CB filled single matrix epoxy system.	80
4.2	Summarise of CB filled single matrix epoxy system.	82
4.3	Solubility parameter of epoxy, PMMA and methylene chloride.	100
4.4	The $T_{5\%}$, $T_{50\%}$, D_{slope} and T_{DMax} of unfilled dual matrixes epoxy/PMMA system via (a) SD and (b) DM methods with different of PMMA content.	106
4.5	The $T_{5\%}$, $T_{50\%}$, D_{slope} and T_{DMax} of 15 vol.% CB filled dual matrixes epoxy/PMMA system via (a) SD and (b) DM methods with different of PMMA content.	109
4.6	Summarise of CB filled single and dual matrixes epoxy/PMMA system, the effect of PMMA content.	112
4.7	The $T_{5\%}$, $T_{50\%}$, D_{slope} and T_{DMax} of dual matrixes system via SD and DM method with different of CB filler loading.	124

4.8	Summary of CB filled single and dual matrixes epoxy system, the effect of CB loading.	126
4.9	Characteristic band of modified CB powders.	128
4.10	The $T_{5\%}$, $T_{50\%}$, D_{slope} and T_{DMax} of unmodified and modified CB filled single and dual matrixes system.	142
4.11	Summary of modified CB filled single matrix system.	148
4.12	Summary of modified CB filled dual matrixes system.	148
4.13	The $T_{5\%}$, $T_{50\%}$, D_{slope} and T_{DMax} of GNP filled single matrix epoxy system.	158
4.14	Summarise of GNP filled single matrix epoxy system.	160
4.15	The $T_{5\%}$, $T_{50\%}$, D_{slope} and T_{DMax} of unfilled and filled dual matrixes system with different of PMMA content.	168
4.16	Summarise of GNP filled single and dual matrixes system, the effect of PMMA content.	170
4.17	The onset degradation temperature at 5 and 50% weight loss of single and dual matrixes system, with different of GNP filler loading.	178
4.18	Summarise of GNP filled single and dual matrixes system, effect of GNP loading	180
4.19	Characteristic band of modified GNP.	182
4.20	The $T_{5\%}$, $T_{50\%}$, D_{slope} and T_{DMax} of unmodified and modified GNP filled single and dual matrixes system.	198
4.21	Summary of unmodified and modified GNP filled single matrix system.	200
4.22	Summary of unmodified and modified GNP filled dual matrixes system.	200
4.23	Summarise of CB and GNP filled single matrix system.	201
4.24	Summarise of CB and GNP filled dual matrixes system.	204
A.1	Surface area (BET) of modified CB powders.	228
A.2	Surface area (BET) of modified GNP powders.	228

LIST OF FIGURES

No.		PAGE
1.1	Schematic diagram of conductive particles dispersed in a polymer matrix at different particle volume content.	2
1.2	Typical filler geometries and its respective surface area-to-volume ratios.	5
2.1	Examples of various types of mixing (Peacock & Calhoun, 2006), (a) poor distribution and poor dispersion, (b) good distribution and poor dispersion, (c) poor distribution and good dispersion and (d) good distribution and good dispersion.	25
2.2	Conductivity range of conducting polymers and conductive polymer composites.	25
2.3	Conduction mechanism versus filler loading.	29
2.4	Chemical structure of the epoxy group.	33
2.5	Formation of DGEBA epoxy resin.	33
2.6	Epoxy/ amine reactions.	37
2.7	Chemical structure of polyamide.	39
2.8	Comparison of some amine curative classes, A, adduct-type curative; MB, Mannich base-type curative.	40
2.9	Polymerization process for PMMA.	41
2.10	Different grades of carbon black, prepared via different production.	45
2.11	Relationship between structure and surface area of carbon black.	46
2.12	High resolution TEM images of primary particles for (a) ENSACO® 250G and (b) acetylene black.	47
2.13	Graphene, the building block of all graphitic forms, can be wrapped to form the 0D buckyballs, rolled to form the 1D nanotubes, and stacked to form the 3D graphite.	51
2.14	The “Scotch tape” method for producing single layer graphene.	51
3.1	Particle size distribution of PMMA powder.	61
3.2	SEM micrograph of PMMA powder.	61

3.3	Heating profile of fillers in the furnace.	63
3.4	Geometry of SEN-T sample for fracture toughness.	66
3.5	Flow chart of the experiment.	69
4.1	Density of CB filled single matrix epoxy system at different CB filler loading.	71
4.2	Flexural strength of CB filled single matrix epoxy system at different CB filler loading.	72
4.3	Flexural modulus of CB filled single matrix epoxy system at different CB filler loading.	73
4.4	SEM micrographs of (a) unfilled, (b) 5 vol.% and (c) 15 vol.% CB filled single matrix epoxy system.	75
4.5	Fracture toughness of CB filled single matrix epoxy system at different CB filler loading.	76
4.6	Electrical bulk resistivity and conductivity of CB filled single matrix epoxy system at different CB filler loading.	78
4.7	TGA thermograms of CB filled single matrix epoxy system.	79
4.8	CTE of CB filled single matrix epoxy system with different CB filler loading.	81
4.9	Density of unfilled and 15 vol.% CB filled dual matrixes epoxy/PMMA system via SD and DM with different of PMMA content.	83
4.10	Flexural strength of unfilled and 15 vol.% filled dual matrixes epoxy/PMMA system via SD and DM with different of PMMA content.	86
4.11	Unfilled dual matrixes epoxy/PMMA system via SD method at (a) 10, (b) 40 vol.% PMMA content and (c) 40 vol.% PMMA after solvent extraction.	88
4.12	Filled dual matrixes epoxy/PMMA system via SD method at (a) 10, (b) 40 vol.% PMMA content and (c) 40 vol.% PMMA after solvent extraction.	90
4.13	SEM micrograph of unfilled dual matrixes epoxy/PMMA system at 10 vol.% PMMA content, (a) before and (b) after solvent extraction, and (c) 40 vol.% PMMA content.	93
4.14	SEM micrograph of filled dual matrixes epoxy/PMMA system at (a) 10 and (b) 40 vol.% PMMA content.	94

4.15	Flexural modulus of unfilled and filled dual matrixes epoxy/PMMA system via SD and DM with different of PMMA content.	95
4.16	Fracture toughness of unfilled and filled dual matrixes epoxy/PMMA system via SD and DM with different of PMMA content.	98
4.17	Electrical bulk conductivity of unfilled and 15 vol.% CB filled epoxy/PMMA composites with different of PMMA content.	99
4.18	Percolation threshold of CB in the epoxy matrix (left) and selective localization mechanism (right) of CB in the epoxy matrix (grey region) via incorporation of PMMA powder.	102
4.19	TGA thermograms of both unfilled dual matrixes epoxy/PMMA system via (a) SD and (b) DM methods with different of PMMA content.	104
4.20	DTG curves of both unfilled dual matrixes epoxy/PMMA system via (a) SD and (b) DM methods with different of PMMA content.	105
4.21	TGA thermograms of both filled dual matrixes epoxy/PMMA system via (a) SD and (b) DM methods with different of PMMA content.	107
4.22	DTG curves of both filled dual matrixes epoxy/PMMA system via (a) SD and (b) DM methods with different of PMMA content.	108
4.23	CTE of unfilled and filled dual matrixes epoxy/PMMA system with different of PMMA content.	110
4.24	Density of single and dual matrixes system via SD and DM methods with different of CB filler loading.	113
4.25	Flexural strength of single and dual matrixes system via SD and DM methods with different of CB filler loading.	114
4.26	SEM micrograph of dual matrixes system via SD method, at (a) 10 and (b) 20 vol.% CB filler loading.	116
4.27	Flexural modulus of single and dual matrixes system via SD and DM methods with different of CB filler loading.	118
4.28	Fracture toughness of single and dual matrixes system via SD and DM methods with different of CB filler loading.	119
4.29	Electrical bulk conductivity of single and dual matrixes system via SD and DM methods with different of CB filler loading.	120

4.30	TGA thermograms of dual matrixes system via (a) SD and (b) DM methods with different of CB filler loading.	122
4.31	DTG curves of dual matrixes system via SD and DM methods with different of CB filler loading.	123
4.32	CTE of single and dual matrixes system via SD and DM methods with different of CB filler loading.	125
4.33	FTIR spectrum of modified CB powders, (a) unmodified CB, (b) CB-N, (c) CB-E and (d) CB-O.	129
4.34	Concentric crystallite model, before oxidation (left) and after oxidation (right)	129
4.35	Schematic diagram for the surface modification methods on CB.	130
4.36	TGA thermograms of modified CB powders.	132
4.37	Density of unmodified and modified CB filled single and dual matrixes system.	133
4.38	Flexural strength of unmodified and modified CB filled single and dual matrixes system.	134
4.39	SEM micrographs of unmodified and modified CB filled single matrix system.	136
4.40	Flexural modulus of unmodified and modified CB filled single and dual matrixes system.	137
4.41	Schematic diagram of the crosslink reaction between carboxylic-functionalized CB with amine based epoxy hardener.	138
4.42	Fracture toughness of unmodified and modified CB filled single and dual matrixes system.	139
4.43	Electrical bulk conductivity of unmodified and modified CB filled single and dual matrixes system.	141
4.44	Schematic of stack graphitic layers, where solid lines represent the graphitic layers, L2 is the real diameter, L1 is the defect-free portion, N is the number of layers in the stack and γ is the tilt angle. l_a and l_c are the lengths parallel and perpendicular to the layer.	142
4.45	TGA thermograms of unmodified and modified CB filled single and dual matrixes system.	143
4.46	DTG curves of unmodified and modified CB filled single and dual matrixes system.	144

4.47	CTE of unmodified and modified CB filled single and dual matrixes system.	146
4.48	Density of GNP filled single matrix epoxy system at different GNP filler loading.	150
4.49	Flexural strength of GNP filled single matrix epoxy system at different GNP loading.	151
4.50	Flexural modulus of GNP filled single matrix epoxy system at different GNP loading.	151
4.51	SEM micrographs of (a) 0.4, (b) 1 and (c) 5 vol.% GNP filled single matrix epoxy system.	153
4.52	Fracture toughness of GNP filled single matrix epoxy system at different GNP filler loading.	155
4.53	Electrical bulk resistivity and conductivity of GNP filled single matrix epoxy system at different GNP filler loading.	156
4.54	TGA thermograms of GNP filled single matrix epoxy system.	157
4.55	DTG curves of GNP filled single matrix epoxy system.	158
4.56	CTE of GNP filled single matrix epoxy system.	160
4.57	Density of unfilled and filled dual matrixes system with different of PMMA content.	161
4.58	Flexural strength of unfilled and filled dual matrixes system with different of PMMA content.	162
4.59	Flexural modulus of unfilled and filled dual matrixes system with different of PMMA content.	163
4.60	Fracture toughness of unfilled and filled dual matrixes system with different of PMMA content.	164
4.61	Electrical bulk resistivity and conductivity of unfilled and filled dual matrixes system with different of PMMA content.	165
4.62	TGA thermograms of filled dual matrixes system with different of PMMA content.	167
4.63	DTG curves of filled dual matrixes system with different of PMMA content.	167
4.64	CTE of unfilled and filled dual matrixes system with different of PMMA content.	169

4.65	Density of single and dual matrixes system with different of GNP filler loading.	171
4.66	Flexural strength of single and dual matrixes system with different of GNP filler loading.	172
4.67	Flexural modulus of single and dual matrixes system with different of GNP filler loading.	173
4.68	Fracture toughness of single and dual matrixes system with different of GNP filler loading.	174
4.69	Electrical bulk conductivity of single and dual matrixes system with different of GNP filler loading.	175
4.70	TGA thermograms of dual matrixes system with different of GNP filler loading.	177
4.71	DTG curves of dual matrixes system with different of GNP filler loading.	177
4.72	CTE of single and dual matrixes system with different of GNP filler loading.	179
4.73	FTIR spectrum of unmodified and modified GNP.	182
4.74	Schematic diagram for the surface modification methods on GNP.	183
4.75	TGA thermograms of unmodified and modified GNP powder.	184
4.76	Density of unmodified and modified GNP filled single and dual matrixes system.	185
4.77	Flexural strength of unmodified and modified GNP filled single and dual matrixes system.	187
4.78	SEM micrographs of single matrix system (a) unmodified GNP, (b) GNP-N, (c) GNP-E and (d) GNP-O.	188
4.79	Flexural modulus of unmodified and modified GNP filled single and dual matrixes system.	190
4.80	Fracture toughness of unmodified and modified GNP filled single and dual matrixes system.	191
4.81	Schematic diagram of the crosslink reaction between carboxylic-functionalized GNP with amine based epoxy hardener	192

4.82	SEM micrographs of the fracture surface of single matrix system on (a) GNP-N, (b) GNP-E and (c) GNP-O.	193
4.83	Electrical bulk conductivity of unmodified and modified GNP filled single and dual matrixes system.	194
4.84	TGA thermograms of unmodified and modified GNP filled single and dual matrixes system.	196
4.85	DTG curves of unmodified and modified GNP filled single and dual matrixes system	197
4.86	CTE of unmodified and modified GNP filled single and dual matrixes system.	199

©This item is protected by original copyright

LIST OF ABBREVIATIONS

0D	Zero dimensional
1D	One dimensional
2D	Two dimensional
3D	Three dimensional
ABS	Acrylonitrile-butadiene-styrene copolymer
Ag	Silver
ASTM	American Society for Testing and Materials
BET	Brunauer–Emmett–Teller Theory
CB	Carbon black
CNTs	Carbon nanotubes
CPC	Conductive polymer composites
CTE	Thermal expansion coefficient
DETA	Diethylene triamine
DM	Direct mixing
EVA	Ethylene vinyl acetate
FTIR	Fourier transform infrared spectroscopy
GIC	Graphite intercalation compound
GNP	Graphene nanoplatelet
GO	Graphene oxides
HAF	High abrasion furnace black
HIPS	High-impact polystyrene
HNO ₃	Nitric acid
HPB	Homologous polymer blend
I.U.P.A.C.	International Union of Pure and Applied Chemistry
ICP	Intrinsically conductive polymer

KBr	Potassium bromide
K _{IC}	Fracture toughness
LDPE	Low density polyethylene
MAH	Maleic anhydride
MMA	Methyl methacrylates
MWD	Molecular weight distribution
MWNTs	Multi-walled nanotubes
MXDA	Meta-Xylenediamine
N-AEP	N- Aminoethylpiperazine
NH ₂	Amino group
Ni	Nickel
PA	Polyacetylene
PA6	Polyamide 6
PAni	Polyaniline
PBT	Poly (butylene terephthalate)
PC	Polycarbonate
PEDOT	Poly (3,4-ethylenedioxythiophene)
PMMA	Poly (methyl methacrylate)
PP	Polypropylene
PPy	Polypyrrole
PS	Polystyrene
PTh	Polythiophene
PUR	Polyurethane
RPM	Rotor speed per minutes
r-GO	Reduced graphene oxide
SAN	Styrene acrylonitrile resin
SD	Solvent dissolution

SiC	Silicon carbide
SRF	Semi-reinforcing furnace black
SWNTs	Single-walled nanotubes
TEPA	Tetraethylenepentamine
TETA	Triethylene tetramine
Tg	Glass transition temperature
TGA	Thermogravimetric analysis
TiB ₂	Titanium Diboride
UV	Ultraviolet
ZnO	Zinc oxide

©This item is protected by original copyright

LIST OF SYMBOLS

ΔG_m	Gibbs free energy of mixing
ΔH_m	Enthalpy of mixing
μm	micrometre
A	Cross-sectional area
a	Total notch length
b	Width of beam
B	Thickness of the sample
cm	centimetre
d	Depth of beam tested
dL/dT	Change of length of the sample per unit change in temperature
$f\left(\frac{a}{w}\right)$	Geometry correction factor
F _{max}	Maximum force in the force-deflection trace
GPa	Giga pascal
L	Support span
L	Length of the sample
m	Slope of the tangent to the initial straight-line portion of the load deflection curve (N/mm)
M _f	Mass of filler
M _m	Mass of matrix
mm	millimetre
MPa	Mega pascal
nm	nanometre
P	Load at given point on the load-deflection curve (N)
R	Resistance
t	Thickness

TPa	Tera pascal
V_f	Volume fraction of filler
Vol.%	Volume percentage
W	Width of the sample
W_f	Weight fraction of filler
W_m	Weight fractions of matrix
Wt.%	Weight percentage
ρ_c	Density of composites
ρ_f	Density of filler
ρ_m	Density of matrix
$\Omega.cm$	electrical resistivity
$\Omega^{-1}.cm^{-1}$	electrical conductivity
ω_F	quadratic function of the wave factor

©This item is protected by original copyright