
TABLE OF CONTENTS

List of Tables	XVI
List of Figures	XIX
Abbreviations	XXIV
Chapter 1 Introduction	1-35
1.1 Membranes	1
1.1.1 Classification of synthetic membranes	1
1.2 Polyethersulfone (PES)	4
1.3 Methods of modification	5
1.3.1 Surface modification	5
1.3.2 Blending techniques	5
1.3.3 Bulk modification	7
1.4 Membrane fabrication methods	7
1.4.1 Precipitation by controlled evaporation	8
1.4.2 Thermal precipitation	8
1.4.3 Precipitation by solvent evaporation	8
1.4.4 Precipitation from the vapour phase	9
1.4.5 Immersion precipitation	9
1.5 Carbon nanotubes (CNTs)	10
1.5.1 Types of carbon nanotubes	11
1.5.1.1 Single walled carbon nanotubes (SWCNT)	11
1.5.1.2 Double walled carbon nanotubes	12
1.5.1.3 Multiwalled carbon nanotubes	12
1.5.2 Methods for synthesizing Carbon nanotubes	13
1.5.2.1 Arc Discharge method	14
1.5.2.1.1 MWCNT Synthesis	15
1.5.2.1.2 SWCNT Synthesis	15
1.5.2.2 Laser ablation	16
1.5.2.3 Chemical vapour deposition (CVD)	17

	1.5.2.3.1 Plasma enhanced CVD	18
	1.5.2.4 Flame pyrolysis	19
	1.5.3 Applications of CNTs in membrane technology and literature outline	20
1.6	Water	26
1.7	Noxious ions present in surface and ground water	28
	1.7.1 Sources and Health effects	28
	1.7.1.1 Chromium	28
	1.7.1.2 Lead	28
	1.7.1.3 Cadmium	29
	1.7.1.4 Copper	29
	1.7.1.5 Arsenic	29
1.8	Techniques for water purifications	30
	1.8.1 Chlorination	30
	1.8.2 UV Treatment	30
	1.8.3 Chemical precipitation	31
	1.8.4 Ozone treatment	31
	1.8.5 Electro-deposition	31
	1.8.6 Electro dialysis	31
	1.8.7 Xanthate process	32
	1.8.8 Ion exchange resins	32
1.9	Limitations of these processes and advantage of membrane technologies	32
1.10	Pressure driven membrane processes	33
	1.10.1 Microfiltration	33
	1.10.2 Ultrafiltration	34
	1.10.3 Nanofiltration	34
	1.10.4 Reverse osmosis	34
1.11	Literature summary	34

Chapter 2	Scope of Research	36-38
2.1	Scope of the work	36
2.2	Objectives of the study	36
Chapter 3	Experimental route	39-79
3.1	Materials	39
3.2	Purification and functionalization of MWCNT	39
	3.2.1 Surface Cleaning	39
	3.2.2 Oxidation, amide and azide functionalization of MWCNTs	40
	3.2.3 Incorporation of f-MWCNT into polyethersulfone to form mixed matrix membranes	41
3.3	Sulfonation of polyethersulfone	44
	3.3.1 Incorporation of f-MWCNT into sulfonated polyethersulfone to form mixed matrix membranes	45
3.4	Click coupling of Az-MWCNT/PES membrane	47
3.5	Characterization	50
	3.5.1 Characterization of f-MWCNT	50
	3.5.2 Characterization of mixed matrix membranes	50
	3.5.3 Fourier Transform Infrared Spectroscopy (FTIR)	50
	3.5.4 Thermo gravimetric Analysis (TGA)	50
	3.5.5 Field Emission Scanning Electron Microscopy (FESEM)	51
	3.5.6 Atomic Force Microscopy (AFM)	51
	3.5.7 Zeta potential	51
	3.5.8 Contact angle meter	53
	3.5.9 Capillary flow porometry	53
	3.5.10 Small angle neutron scattering (SANS)	54
	3.5.11 Impedance Measurement	54
	3.5.12 X-ray photoelectron spectroscopy (XPS)	55
	3.5.13 Tensile test	55

3.6	Characterization of functionalized MWCNT	55
	3.6.1 FTIR	55
	3.6.2 TGA	57
	3.6.3 Field Emission Scanning Electron Microscopy	58
3.7	Thermal, mechanical and electrical characterization of f-MWCNT/PES mixed matrix membranes	60
	3.7.1 TGA of membranes	60
	3.7.2 Tensile strength	61
	3.7.3 Electrochemical Impedance Analyzer	63
3.8	Characterization of sulfonated polyether sulfone	66
	3.8.1 FTIR	66
	3.8.2 Nuclear magnetic resonance (NMR) spectroscopy	67
	3.8.2.1 H^1 NMR	67
	3.8.2.2 C^{13} NMR	68
	3.8.3 TGA	69
	3.8.4 Viscosity measurement and degree of sulfonation	70
	3.8.5 X-Ray Diffraction	71
3.9	Thermal and mechanical characterization of SPES/ f-MWCNT membranes	72
	3.9.1 TGA	72
	3.9.2 Tensile strength	73
3.10	Surface, thermal and mechanical characterization of click modified PES/Az-MWCNT membranes	75
	3.10.1 X-ray photoelectron spectroscopy (XPS)	75
	3.10.2 TGA of membranes	77
	3.10.3 Tensile strength	78

Chapter 4	Filtration Performance of Membranes	80-121
4.1	Membrane performances	80
4.1.1	Polyether sulfone/f-MWCNT mixed matrix membranes	80
4.1.1.1	Permeation studies of f-MWCNT/PES membranes	80
4.1.1.2	Heavy metal removal studies	85
4.1.1.2.1	Effect of pressure and pH	86
4.1.1.3	Tertiary wastewater treatment	92
4.1.1.3.1	Membranes	93
4.1.1.3.2	Rejection for several water quality parameters	93
4.1.1.4	Fouling studies of PES/f-MWCNT membranes	96
4.1.2	Sulfonated polyethersulfone/f-MWCNT mixed matrix membranes	99
4.1.2.1	Permeation studies of f-MWCNT/SPES membranes	99
4.1.2.2	Heavy metal removal studies of f-MWCNT/SPES membranes	101
4.1.2.3	Tertiary wastewater treatment	106
4.1.2.3.1	Membranes	106
4.1.2.3.2	Rejection for several water quality parameters	106
4.1.2.4	Fouling studies of SPES/f-MWCNT membranes	109
4.1.3	Click reaction modified PES.Az-MWCNT mixed matrix membrane	113
4.1.3.1	Permeation studies of click reaction modified membranes	113
4.1.3.2	Heavy metal removal studies of Click reaction modified PES/Az-MWCNT membrane	115
4.1.3.3	Tertiary wastewater treatment by click reaction modified membranes	117
4.1.3.3.1	Membranes	117

4.1.3.3.2	Rejection for several water quality parameters	117
4.1.3.4	Fouling studies of click reaction modified PES/Az-MWCNT membranes	119
Chapter 5	Results and Discussion	122-154
5.1	Morphological characterization of f-MWCNT/PES mixed matrix membranes	122
5.1.1	Field Emission Scanning electron microscopy	122
5.1.2	Atomic force microscopy	124
5.1.3	Contact angle	127
5.1.4	Zeta potential Measurement	129
5.1.5	Capillary flow porometry	131
5.1.6	Small angle neutron scattering	132
5.2	Characterization of SPES/f-MWCNT membranes	139
5.2.1	FESEM	139
5.2.2	Atomic Force Microscopy (AFM)	140
5.2.3	Contact angle	142
5.2.4	Zeta potential Measurement	143
5.2.5	Small angle neutron scattering	145
5.3	Characterization of click reaction modified PES/Az-MWCNT membranes	148
5.3.1	FESEM	148
5.3.2	AFM	149
5.3.3	Contact angle measurement	150
5.3.4	Zeta potential measurement	151
5.3.5	Small angle neutron scattering	152

Chapter 6	Summary, Conclusions and Future Prospects	155-158
	References	159
	List of Presentations	178
	List of Publications	180
