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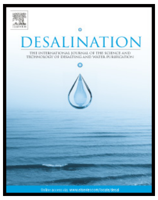

Mechanical properties of water desalination and wastewater treatment membranes

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HIGHLIGHTS

- Experimental techniques to assess the mechanical properties of water treatment membranes are reviewed.
- Mechanical degradation mechanisms of water treatment membranes are discussed.
- Stress-state of the water treatment membranes are analyzed at different scales.
- Advanced mechanical testing methods are proposed to study structure-properties relationship for water treatment membranes.

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ABSTRACT

Applications of membrane technology in water desalination and wastewater treatment have increased significantly in the past few decades due to its many advantages over other water treatment technologies. Water treatment membranes provide high flux and contaminant rejection ability and require good mechanical strength and durability. Thus, assessing the mechanical properties of water treatment membranes is critical not only to their design, but also for studying their failure mechanisms, including the surface damage, mechanical and chemical ageing, delamination and loss of dimensional stability of the membranes. The various experimental techniques to assess the mechanical properties of wastewater treatment and desalination membranes are reviewed. Uniaxial tensile test, bending test, dynamic mechanical analysis, nanoindentation and bursting tests are the most widely used mechanical characterization methods for water treatment membranes. Mechanical degradations induced by fouling, chemical cleaning as well as membrane delamination are then discussed. Moreover, in order to study the membranes mechanical responses under similar loading conditions, the stress-state of the membranes are analyzed and advanced mechanical testing approaches are proposed. Some perspectives are highlighted to study the structure-properties relationship for wastewater treatment and water desalination membranes.

1. Introduction

Although 72% of the earth is covered with water, 97% of that is salty seawater, which is not suitable for domestic and industrial applications. Moreover, 70% of the rest 3% fresh water is locked in ice and not accessible. Nowadays, the growing population results in an increasing demand on the quantity and quality of drinking water, especially in water-stressed countries. In the meantime, some existing groundwater and rivers are gradually polluted and unavailable due to industrialization and urbanization [1]. Therefore, global fresh water shortage is becoming the most serious problem affecting the economic and social development [2]. Attention is focused on the development of more sustainable technological solutions that are able to meet the increasing water consumption of future generations. Seawater desalination and wastewater treatment are the main technologies for producing clean water. Conventional desalination processes are generally based on

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Abbreviations: AFM, atomic force microscopy; AQPz, Aquaporin Z; CFD, computational fluid dynamics; CNF, carbon nanofiber; DG, diethylene glycol; DMPC, 1,2-dimyristoyl-*sn*-glycero-3-phosphocholine; DVB, divinylbenzene; GO, graphene oxide; MBF, multibore hollow fiber; MD, membrane distillation; NF, nanofiltration; PA, polyamide; PAI, poly(amide–imide); PEG, polyethylene glycol; PES, polyethersulfone; PLA, poly(lactic acid); PRO, pressure retarded osmosis; PSF, polysulfone; PVA, poly(vinyl alcohol); PVDF-HFP, polyvinylidenefluoride-*co*-hexafluoropropylene; SAXS, small-angle X-ray scattering; SEM, scanning electron microscope; TFC, thin film composite; VMD, vacuum membrane distillation; ZrDETPMP, zirconium diethylene triamine pentamethylene phosphonic acid; APDSPO, bis(4′-aminopropyldiethoxysilylphenyl) 1,3,4-oxadiazole; CA, cellulose acetate; CMS, chloromethyl styrene; CNT, carbon nanotube; DIC, digital image correlation; DMA, dynamic mechanical analysis; FEP, poly(tetrafluoroethylene-*co*-hexafluoropropylene); hPI, hydrogenated polyisoprene; MBR, membrane bioreactor; MF, microfiltration; NMP, *N*-methyl-2-pyrrolidone; PAA, polyacrylic acid; PAN, polyacrylonitrile; PEI, poly(ethyleneimine); PET, polyethylene terephthalate; PP, polypropylene; PS, polystyrene; PU, polyurethane; PVDF, polyvinylidenefluoride; RO, reverse osmosis; SBF, single-bore hollow fiber membrane; SPES, sulfonated polyethersulfone; UF, ultrafiltration; WAXS, wide-angle X-ray scattering.

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thermal processes consuming substantial amount of energy with large greenhouse gases emission [3]. An environmental-friendly method for water purifying at low cost, with less energy and with less chemicals is therefore more attractive and desirable.

Membrane technology is favored over other approaches for desalination and wastewater purification due to its promising high efficiency, ease of operation, energy and space saving, and the no use of chemicals. Membrane filtration for water treatment has increased significantly in the past few decades with the enhanced membrane quality and decreased membrane costs. This method is a separation process that uses a semipermeable membrane to divide the feed stream into a desirable permeate stream that passes through the membrane walls and a retentate stream containing high concentration of rejected species [4–7].

Most of the reported research that deals with seawater desalination or wastewater treatment membranes focuses on membrane processing [8,9], surface modification [10,11], and antifouling properties [12,13]. More recently, molecular dynamics simulations of the physical and mechanical properties for nanoporous graphene membrane were conducted [14–18]. However, experimental investigations of the mechanical behaviors under complex loading modes with temperature and pressure effects for porous membranes are rarely reported. According to Scopus database, the annual publications on desalination and water treatment membranes has grown from 1050 publications in 2004 to nearly 2500 publications in 2014. On the other hand, the number of annual publications that investigate the mechanical properties of desalination and water treatment membranes, regardless of being increased from 20 publications in 2004 to about 100 publications in 2014, is still represents less than 5% of the annual desalination and water treatment membranes publications.

In addition to high permeate flux, high contaminant rejection, good chemical and fouling resistances, water treatment membranes require good mechanical stability and durability. Membrane processes end users require a suite of techniques to independently assess the properties of the membranes received from the manufacturer before commissioning the process and at different stages during the membrane life (for diagnosing performance). Thus, analysis of the membrane real loading conditions and examining their mechanical properties under similar conditions are very important. Furthermore, understanding the mechanical behaviors of water treatment membranes with underlying deformation mechanisms is critical not only for designing membrane structure, but also for predicting membrane failures including: 1. Complete breakage (which is very rare); 2. Surface damage (impingement by sharp particles); 3. Cracking (due to insufficient flexibility of the membrane, this particularly affects outside feed formats that use air scour in backwash and for inside feed formats, a lack of compression strength will cause the fiber to crack since it cannot withstand the high flow and pressure in backwash); 4. Dimensional stability (can create disengagement in hollow fiber formats of the membrane from the potting tube-sheet if the membrane shrinks, and can create delamination in composite membranes); 5. Aging (mechanical fatigue and chemical attack due to hydrolysis which can be accelerated by high or low pH. Note that both mechanical fatigue and chemical attack can result in mechanical degradation of polymeric membrane by chain scission mechanism. However, cracks induced by mechanical ageing may initiate at the surface or inside the membranes, while cracks induced by chemical attack can only initiate at the membrane surface [19].)

This article reviews the most widely used experimental techniques for characterizing the mechanical behaviors of desalination and wastewater treatment membranes. Moreover, the mechanisms responsible for the mechanical degradations of these membranes are also discussed. In order to study the mechanical responses of membranes under real operating conditions, the stress-state at both lab and commercial scales is discussed. Finally, some advanced mechanical testing methods are proposed with potential real-time monitoring techniques.

Desalination and wastewater treatment membranes can be classified according to their pore size, mechanisms of rejection, driving forces, composition of membranes, geometry and configuration [20]. According to pore size, wastewater treatment and desalination membranes are classified as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) membranes. Among these membranes, RO membranes has much tighter pore structure that can effectively remove a wide range of ions from water, but requires the highest differential pressure (30–60 bar). Because of its very small pore size, RO has low permeate flux and is usually used for seawater desalination [20]. RO is considered the most energy-efficient water treatment technology in chemical and environmental applications and RO desalination is the primary choice for seawater desalination, dominating about 45% of the total global desalination technology [3,21].

According to their material of construction, wastewater treatment and water desalination membranes are classified as inorganic, organic (polymeric), and hybrid membranes. Inorganic membranes are based on either metallic or ceramic materials and they are used for MF and UF membranes. Their high chemical and thermal stability make them suitable for use in corrosive and high temperature environments. However, ceramic membranes have few commercial applications due to their mechanical fragility and relatively high cost and metallic membranes usage is limited to gas separation. Polymers remain the most widely used material for commercial water treatment membranes due to their good separation performance. Polymeric membranes such as polyvinylidene fluoride (PVDF), polyacrylonitrile (PAN), polyethersulfone (PES) and polyamide (PA) are the most used membranes. However, polymeric materials are very susceptible to thermal, chemical and biological degradation [22]. Blending polymers or composite of polymers with inorganic fillers are effective method to provide new and better polymer based membranes to meet the requirements of many practical applications. The blended membranes can posses a range of chemical, physical and mechanical properties, making blending a favorable approach due to its versatility and simplicity. Recently, the use of nanoparticles to enhance the performance of membranes has been successful attempted by incorporating nanofillers into ceramic or polymeric membranes, leading to breakthrough performance related to fouling mitigation, improvement of permeate quality and flux enhancement [23–26].

For membrane configurations, the spiral wound module is the dominant product type for RO application. In spiral wound configuration, flat sheet membranes are usually wrapped around a central collection permeate tube with a sandwich structure. This configuration can reduce concentration polarization, fouling, and particle cake deposition. However, spiral wound configuration is defenseless to biofouling occurrence [27,28]. Moreover, the seals and glue lines are weak points which may result in the loss of module integrity. Hollow fiber membranes are mostly based on PVDF and PES and are usually submerged in a basin or pressurized in housing for UF and RO applications. Hollow fiber membranes for UF applications are arranged in rectangular modules which form a cassette and directly immersed into an aeration basin for membrane bioreactor (MBR). If RO is used in the hollow fiber configuration, numbers of hollow fibers are tightly bundled and bonded at the end housed in a tube. Table 1 summarizes the applications, the materials and the configurations for water treatment membranes. In this table, we also resumed the most used mechanical approaches for investigating the mechanical behavior of the membranes and how these results can be used in the application.

2. Mechanical characterization techniques

The essential requirements for a common mechanical testing are controllable change in the specimen displacement and displacement speed and a mean to accurately measure the corresponding change in required load. The material stress–strain behavior can be obtained from the measured forces and displacements based on the sample cross section area and loading mode [29].

Conventional tests are difficult to directly apply for studying the mechanical properties of membranes because of their small thickness. For

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