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Fine-pore aeration diffusers: Accelerated membrane ageing studies

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ABSTRACT

Polymeric membranes are widely used in aeration systems for biological treatment. These membranes may degrade over time and are sensitive to fouling and scaling. Membrane degradation is reflected in a decline in operating performance and higher headloss, resulting in increased energy costs. Mechanical property parameters, such as membrane hardness, Young's modulus, and orifice creep, were used to characterize the performance of membranes over time in operation and to predict their failure. Used diffusers from municipal wastewater treatment plants were collected and tested for efficiency and headloss, and then dissected to facilitate measurements of Young's modulus, hardness, and orifice creep. Higher degree of membrane fouling corresponded consistently with larger orifice creep. A lab-scale membrane ageing simulation was performed with polyurethane and four different ethylene–propylene-diene (EPDM) membrane diffusers by subjecting them to chemical ageing cycles and periodic testing. The results confirmed full-scale plant results and showed the superiority of orifice creep over Young's modulus and hardness in predicting diffuser deterioration.

1. Introduction

Aerobic biological treatment is currently the preferred choice for municipal wastewater treatment plants in developed areas of the world. Aerobic processes, such as the activated sludge process, are energy intensive (Reardon, 1995) and the energy cost can be sizeable (Rosso and Stenstrom, 2005). Due to their energy conservation benefits, fine-pore diffusers have gained widespread acceptance, which has accelerated with recent increases in energy costs. These increases in energy costs created incentives to upgrade treatment plants to even more efficient treatment systems, and first-generation fine-pore diffusers are being replaced with more efficient technologies and configurations. Among these systems, punched polymeric membranes (see Fig. 1) are becoming ubiquitous and are present in a variety of models and densities (i.e., discs, panel sheets, tubes).

Fine-pore diffusers face the inconvenient and inexorable phenomena of fouling and scaling (Boyle and Redmon, 1983). Fouling typically describes coating or plugging of diffuser surfaces or orifice by a biofilm. Scaling refers to the precipitation of inorganic salts (calcium carbonate, calcium sulphate, silica, etc.). In practice, fouling and scaling usually occur together with the formation of bioslimes composed of bacterial flocs, protozoans, and organic and inorganic compounds. Although fouling and scaling mechanisms can be classified (Kim and Boyle, 1993), the fouling rates are at least in part site-specific. In general, most aeration systems show a more rapid decline in performance within the first 24 months after installation or cleaning (Rosso and Stenstrom, 2006), and tend to foul more rapidly near the raw wastewater feed point. In addition to fouling and scaling, polymeric material properties change over time in service: the polymeric membrane may harden, reducing airflow and changing efficiency

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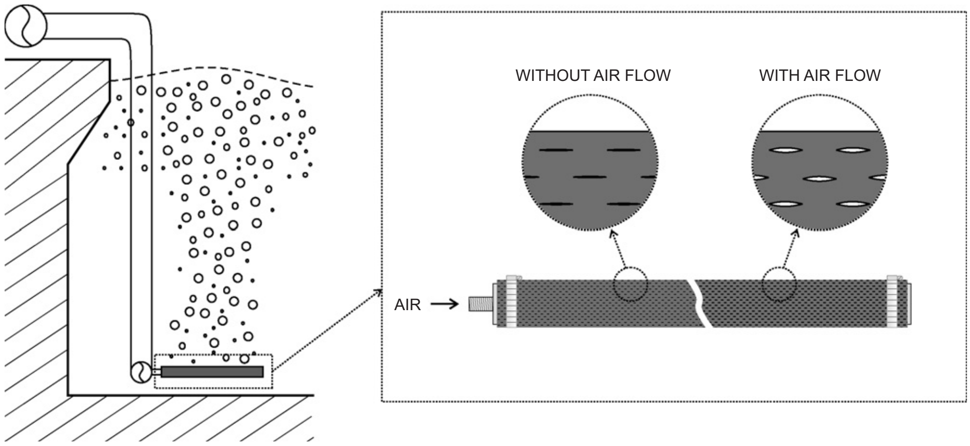

Fig. 1 – Schematic of a fine-pore membrane diffuser in operation. The inset shows details of the membrane orifices with and without air flow.

(Hansen et al., 2004); in other cases, the membrane may soften and expand (Iranpour and Stenstrom, 2001). The reasons for either phenomenon's occurrence are not universally known and are usually attributed to site-specific conditions, such as the nature of the contaminants in wastewater and interactions between bacterial population and membrane components.

At the present time, polymeric membranes for wastewater treatment uses are typically composed of ethylene–propylene-diene-monomer (EPDM), polyurethane, or poly vinyl chloride (PVC). In general, polymeric membranes are not pure in their major component, and contain additives that are blended to enhance mechanical and chemical properties, and to increase polymer processability (e.g., plasticizers). Bacterial activity can be compatible with the chemical nature of these additives, e.g. bacteria may "eat" the plasticizers contained in the polymeric mixture, thus reducing the membrane's ability to flex or stretch (Cheng et al., 2000). In recent years, silicon membranes, which do not require blending with plasticizers or additives, have been proposed as a way of avoiding this problem (Wagner and von Hoessle, 2004).

During its operation, a membrane diffuser experiences a pressure build up on its internal membrane wall. This pressure is needed to overcome the friction through the orifices and the hydrostatic head of the water column above the diffuser. The net headloss across the membrane, i.e. the total discharge pressure minus the hydrostatic headloss, is called dynamic wet pressure, or DWP (US EPA, 1989). Due to membrane properties change with operation, DWP increases over time, thus creating tension that causes permanent membrane stretching (creep) and changes in other properties, such as the tendency to crystallize. The degree of crystallization in a polymer should be kept as low as possible in order to ensure plastic behaviour and limit crack propagation. In a ubiquitous polymer, glass, the increase of degree of crystallization is visible because crystals are optically active (i.e., opaque), while amorphous glass remains transparent.

Current membrane characterization methods, such as DWP build-up, change in membrane hardness, and Young's modulus (described in detail in the following section), are not adequate to quantify membrane deterioration (Kaliman, 2003). Two examples illustrate the problem with existing membrane characterization methods. A large municipal treatment plant using PVC membrane tube diffusers was having problems meeting oxygen transfer at design airflow rates after 3 years of service. Six diffusers were removed from service and evaluated using the Durometer, Young's modulus, and laboratory clean water tests. Durometer measurements of new diffusers were 80 ± 1 Shore A. The Durometer of the used diffusers increased to 85–95, with the highest values being measured from diffusers removed near the effluent end of the aeration tanks. Young's modulus had increased by more than 25%. The oxygen transfer efficiency (OTE, %) of the six used diffusers tested in a laboratory tank decreased by 20% at medium flow rate (85 l/min-tube) and by 5–10% at maximum flow rate (140 l/min-tube) as compared with new diffusers. Airflow from the used diffusers was not uniform. Larger orifices could easily be observed in the used membranes when compared with new membranes. DWP decreased at medium flows by 20% but was nearly the same at the maximum flow rate.

In the second example, polyurethane membranes used at an industrial wastewater treatment plant for 2 years showed excessive pressure drop resulting in blower overloading. Laboratory analyses showed a decrease in Young's modulus of 25%, and increase in DWP by 100%, no significant change in Durometer reading, 14% loss in membrane thickness, and similar OTE but less uniform air distribution. Microscopic examination of the orifices showed enlargement and damage. In both cases, membrane performance became unacceptable, but the Durometer, Young's modulus, and DWP all showed different trends.

Creep deformation offers benefits because it alters orifice size and therefore can be related to changes in OTE. Orifices, in general, can stretch to their maximum diameter at high airflow rate, but at low airflow rate orifices in aged membranes remain overextended, producing larger bubbles than produced by new membranes. This results in larger bubbles with less specific surface area and reduced OTE. The enlarged orifices alters the pressure distribution within the diffuser, which causes uneven production of larger bubbles and is typically observable as irregular distribution of bubbles at the liquid surface (Rosso et al., 2007). Air release along the length or diameter may also be uneven, with the majority of the air being released in one area of the diffuser, which is more observable in tube-style diffusers. At the same time, the enlarged orifices increase the probability of wastewater entering the diffuser, with consequent deleterious effects on the diffuser fouling and on the entire aeration system. It is generally assumed that any change in membrane properties will cause a decrease in overall performance, hence the need for material science studies.

The objective of this paper is to introduce a new testing method, called orifice creep testing, to characterize membrane diffuser degradation. Orifice creep testing, which measures the effects of orifice stretching under stress, is a promising new method since it has a direct, causal relation to changes in OTE. Furthermore, microscopy allows the early detection of membrane changes, which should allow designers and operators to predict aeration system failures.

2. Materials and methods

2.1. *Accelerated membrane ageing*

Two test series were performed. The first used a single polyurethane membrane diffuser cut into 16 dog-bone-shaped specimens (dimensions in Fig. 2), and divided into four groups that were soaked without loads using four different solutions at 80 °C in sealed containers. The four different solutions were deionized water (DI water; CAS No. 7732-18-5), 1% and 2% hexane (i.e., n-hexane; CAS No. 110-54-3), 1% and 2% methanol (CAS No.67-56-1), and 1% and 2% acetic acid (HAC; CAS No. 64-19-7). The concentrated solutions and elevated temperature were designed to accelerate ageing.

The erratic trends in Young's modulus (discussed in detail in the following section) prompted the development of a more precise test, orifice creep testing, to quantify membrane degradation processes. Hardness, as measured by the Durometer (described later), which is presently performed in membrane ageing investigations, was added to the next series of experiments. The second series used four different types of EPDM diffuser membranes, cut into five dog-bone-shaped specimens (dimensions in Fig. 2). Each membrane was produced by a different manufacturer, having different hole-punch patterns and punching technique (slit length and density). In all cases, the membranes were oriented so that the long dimension of the punch was perpendicular to the direction of the strain. One specimen was damaged during the study, and could not be replaced, leaving 19 specimens to be soaked in four different solutions: DI water, 5% hexane, 5% isopropyl alcohol (IPA; CAS No. 67-63-0), and 5% HAC. Each EPDM specimen was labelled to identify manufacturer and type of soaking solution.

Orifice creep can only be measured on diffusers that have been subjected to a static load. In normal diffuser operation, the static load is caused by DWP acting on internal membranes walls. For this experiment, a static load was created by hanging weighted specimens in the soaking solution in graduate cylinders, sealed with parafilm (isopropyl alcohol was substituted for methanol due to its increased boiling point). Lead anchors, weighing approximately 197 g (7 ounces) were used, which closely approximated the Hoop's Stress caused by a DWP value of 4.48 kPa, which for a membrane disc of standard 229 mm (9 in) size correspond to a pressure drop of 400 mm water column (~16 in water column).

After fastening the weights to the specimens, each specimen was placed into a graduate cylinder with the appropriate degrading chemical solution. One unloaded specimen of each brand was placed in a 250 ml sealed glass container filled with DI water at 80 °C and served as control. The entire group of 15 cylinders and four jars were then placed in a hot water bath to maintain the temperature at 80 °C to accelerate the deformation processes. The type 1 EPDM sample specimen with IPA was damaged and was omitted.

Every 2 weeks all specimens were relieved of loads and taken from the cylinders to dry at room temperature. After approximately 24 h, all specimens were tested for Young's modulus, hardness, and orifice creep. These procedures were repeated three times to create 6 weeks of observations.

2.2. *Tensile strength tests*

ASTM D412 (ASTM, 2002) test was used to determine the diffusers' Young's modulus. A small loading frame was constructed using a load cell to measure force and a standard

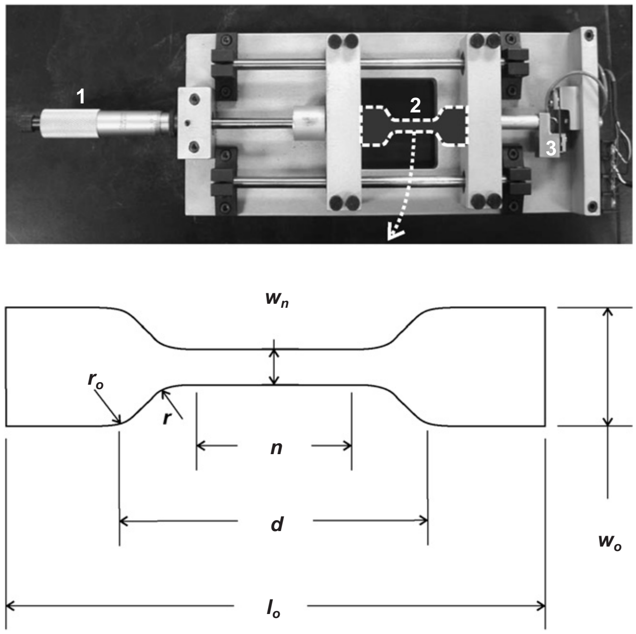

Fig. 2 – Laboratory apparatus for the ASTM D412 standardised test to determine membrane diffusers Young's Modulus. Specimens are cut according to the ASTM D638 standard. Key: 1 = micrometric screw; 2 = membrane specimen; 3 = pressure cell; w_o = overall width, 19 mm; w_n = width of the narrow section, 6 mm; n = length of the narrow section, 33 mm; d = distance between grips, 64 mm; l_o = overall length at no stress, 115 mm; r_o = outer radius, 25 mm; r = fillet radius, 14 mm.

micrometer to create displacement (see Fig. 2). The frame was open in the centre so that it could be placed on a microscope stage for observation. Several measurement repetitions were taken to increase test reproducibility, and the normalized variance was 0.7%. Each membrane diffuser was cut into a dog-bone-shaped specimen. The dimensions of the specimens are in accordance with ASTM D638 type IV (ASTM, 2003), and are reported in Fig. 2. Data from the ASTM D412 test were converted to stresses and strains by using Eqs. (1) and (2):

$$\sigma = \frac{F}{A}, \tag{1}$$

$$\varepsilon = \frac{\delta l}{l}, \tag{2}$$

where σ is the normal stress, ε the strain, F the force, A the cross-sectional area of the specimen, l the initial length of specimen, and δl is the elongation of the specimen. In order to calculate A, it is necessary to measure the membrane thickness z, which was measured using a Mitutoyo model no. 227-101 micrometer. This micrometer is designed to test flexible materials, and has a pressure sensor so that each measurement can be made at the same compression of the specimen.

Young's modulus Y was determined by taking the slope of stress–strain curve shown in Eq. (3):

$$Y = \frac{\Delta\sigma}{\Delta\varepsilon}. \tag{3}$$

Each specimen was stretched by 3.5% during testing. Different elongations may be used and appropriate values will depend on the stress–strain curve behaviour of the material, as well as the application. This value was selected because the specimen remains in the elastic region, which avoids changing membrane properties by over stretching. Owing to this, the stress–strain relationship is essentially linear. This elongation is the same as observed in lab testing of diffusers in a clean water tank, and should be within the range of elongations encountered in field operation of membrane diffusers. At extreme elongations, the relationship departs from linearity, the three materials exhibit different effects, and the strain is irreversible.

2.3. Durometric tests

A Durometer is an instrument used to measure hardness of non-metallic material using a pin that protrudes into the specimen as the instrument is held against the surface of the specimen (ASTM D2240; ASTM, 2005). The procedure requires the measurement to be performed at least 12 mm from the edges, with a minimum thickness of 6 mm. It is not difficult to obtain membrane specimens this large, but membranes are usually less than 6 mm in thickness. Two or more thicknesses of membranes must be used, and the best procedure is to test increasing thicknesses of membranes until the Durometer does not vary with the number of membranes tested. Failure to follow these guidelines may yield in an "apparent" hardness value and four thicknesses were used in these tests. In tests that only seek to determine the change in hardness, an absolute value is not required, and an apparent value can be used (Gent, 1992). The primary use of hardness for diffuser testing is to show changes or trends as an indication of service wear. Membranes usually harden if the membrane loses plasticizer, and soften if the membrane absorbs chemicals from the wastewater. For the experiments described in this paper, each measurement was repeated five times, and the average value was recorded.

2.4. Orifice creep tests

The static load in actual operations is caused by DWP, which begins at a base value caused by pressure loss as the air flows through the diffuser, and generally increases as the diffuser fouls or scales. In rare cases, the DWP may decrease over time, if the orifice size increases and fouling does not occur. Orifice creep testing was introduced to measure the effect of membrane deformation under the load applied by the air pressure. The goal of this test was to determine how much the orifice opening dilated, after the specimens were subjected to static load for defined periods of time.

Orifice opening was determined by microscopic observation. Specimens were placed under an optical stereoscopic microscope (8–120 × enlargements) and the widest distance between the two sides of the orifice was measured. To measure orifice opening at operating pressure, the membranes were placed under stress, equivalent to membrane backpressure of 4.48, 8.97, and 13.4 kPa (i.e., multiples of 400 mm or 16 in. of water column) using the load frame described earlier. The lowest value is the typical DWP for new EPDM membrane diffusers. The equivalent stress is applied by stretching the specimens to the appropriate length, according to Eq. (4), obtained by combining Eqs. (2) and (3):

$$\Delta l = l_o \frac{\Delta\sigma}{Y}, \tag{4}$$

$\Delta\sigma$ is the Hoop's stress caused by DWP acting on the internal membrane wall, and is related to DWP by the following equation (King, 1973):

$$\Delta\sigma = \frac{Pd}{2z}, \tag{5}$$

where P is the DWP, d the diameter of the membrane tube, and z is the thickness of the membrane.

3. Results and discussion

It is generally known that larger orifices produce larger bubbles and reduced OTE. Membrane ageing impacts this phenomenon in two possible ways: a hardened membrane may not stretch, preventing the orifices from expanding, increasing OTE, but at the expense of DWP. The increase in DWP may be so large that the existing blowers may not possess sufficient discharge pressure. Alternatively, if the membrane softens, the orifices may enlarge, reducing OTE and DWP. In this case, the DWP may be so low that poor air distribution occurs across the aeration tank. In cases where membrane hardening creates a hysteresis effect, the orifices may be enlarged at low flow rate and smaller at high flow rate, relative to a new diffuser. The various effects create a complex relation among OTE, airflow rate and DWP. Larger orifices correspond to polymer deformation, which is typically associated with increase in Young's modulus and hardness, and higher propensity for the membrane's mechanical failure.

Fig. 3a shows the result of the normalized Young's modulus versus time for polyurethane membranes (Young's modulus for new membranes = 1.162 Pa). Error bars represent one standard deviation of the four specimens in each soaking solution, and shaded areas are 85% confidence intervals. Polyurethane membranes types 1, 2, and 4 soaked in acetic acid (HAC) generally softened. Membrane types 1 and 2 showed no change in modulus for the other solvents. Fig. 3b shows the set of results for EPDM membranes. By the end of the 6th week most EPDM specimens showed a slightly increasing trend in Young's modulus, although there were some large deviations, such as in type 1 in DI water without loading.

Fig. 4 shows the results of durometric tests on EPDM membranes. Hardness consistently increases for membrane types 1, 3, and 4, but shows erratic behaviour for HAC solutions. This is probably due to incompatibility between the HAC solution and the EPDM membrane compositions. Membrane type 2 has a slight decrease in hardness with ageing. This experiment demonstrates the challenges in testing membranes. The type and amount of fillers and hardeners/softeners of the four EPDMs are different and are proprietary to the specific manufacturer. Custom testing with the specific wastewater, or in the case of industrial treatment with the main constituents of the wastewater, is needed to avoid membrane failures.

In Fig. 5 we graphed the relative ratio of DWP used for new polyurethane and EPDM membranes. Used EPDM membranes have consistently higher DWP, almost independent of airflow rate. This increase in DWP is related to the decrease in membrane elasticity, i.e. higher Young's modulus values in Fig. 3b. Different behaviour is shown by used polyurethane membranes, which at low pressure show lower DWP. This is due to membrane softening (Fig. 3a). The energy savings associated with reduced DWP does not compensate for the reduction in oxygen transfer efficiency that the membrane undergoes with ageing. The total net effect is an increased energy requirement to operate the aeration system.

Orifice creep is a phenomenon consistently observed with diffuser ageing. All membrane materials we have harvested in fine-pore diffuser installations have exhibited orifice creep. Fig. 6 shows micrographs of a new and used PVC membrane at different magnification ratios. At low magnification the pores may look similar, but magnified images reveal that new pore close well, while pores from used membranes remain open when no tension is applied (i.e., equivalent to zero air flow rate).

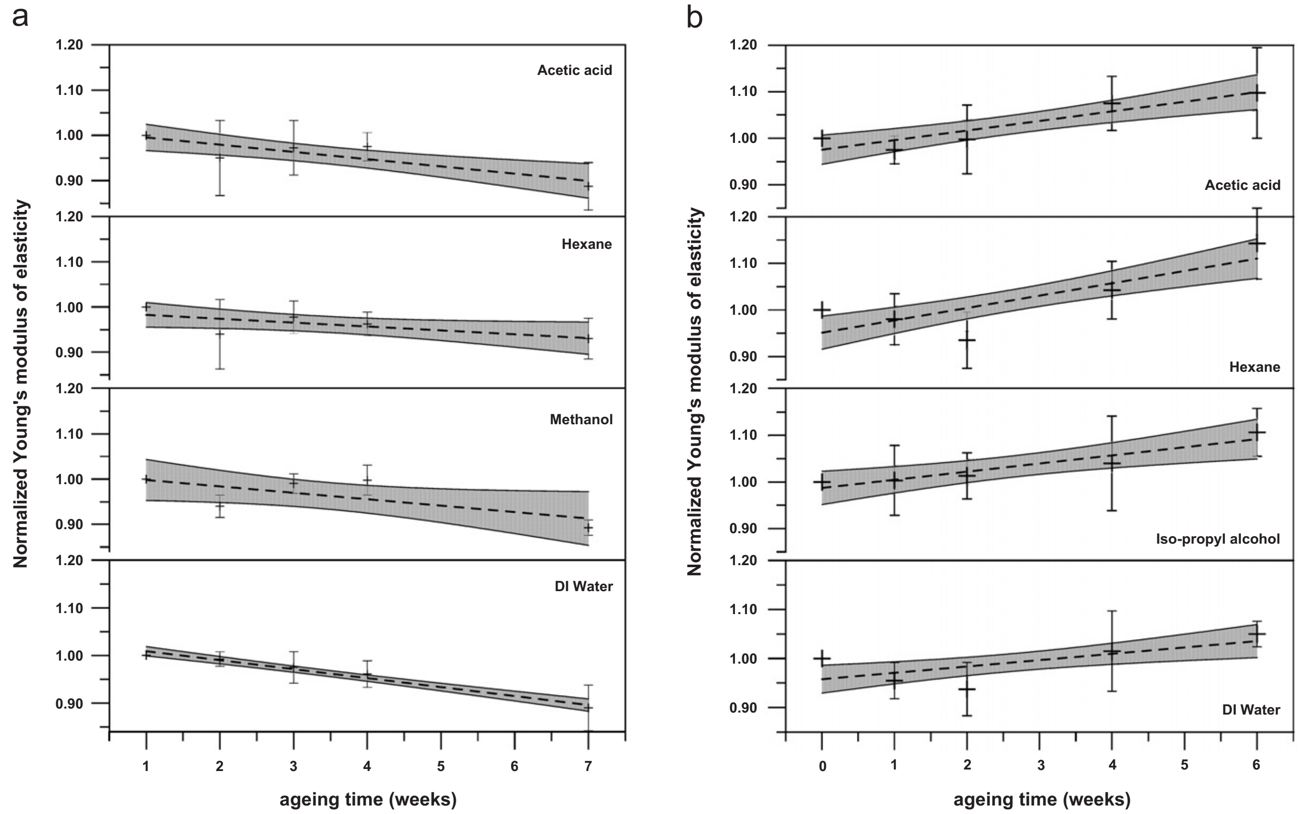

Fig. 3 – (a) Young's modulus of polyurethane membranes versus ageing time. Bars are one standard deviation, and labels show the chemical utilized for accelerated ageing. A common trend for all solutions is that polyurethane membranes show a decrease in Young's modulus. (b) Young's modulus of EPDM membranes versus ageing time. Bars are one standard deviation, and labels show the chemical utilized for accelerated ageing. A common trend for all solutions is that EPDM membranes show an increase in Young's modulus.

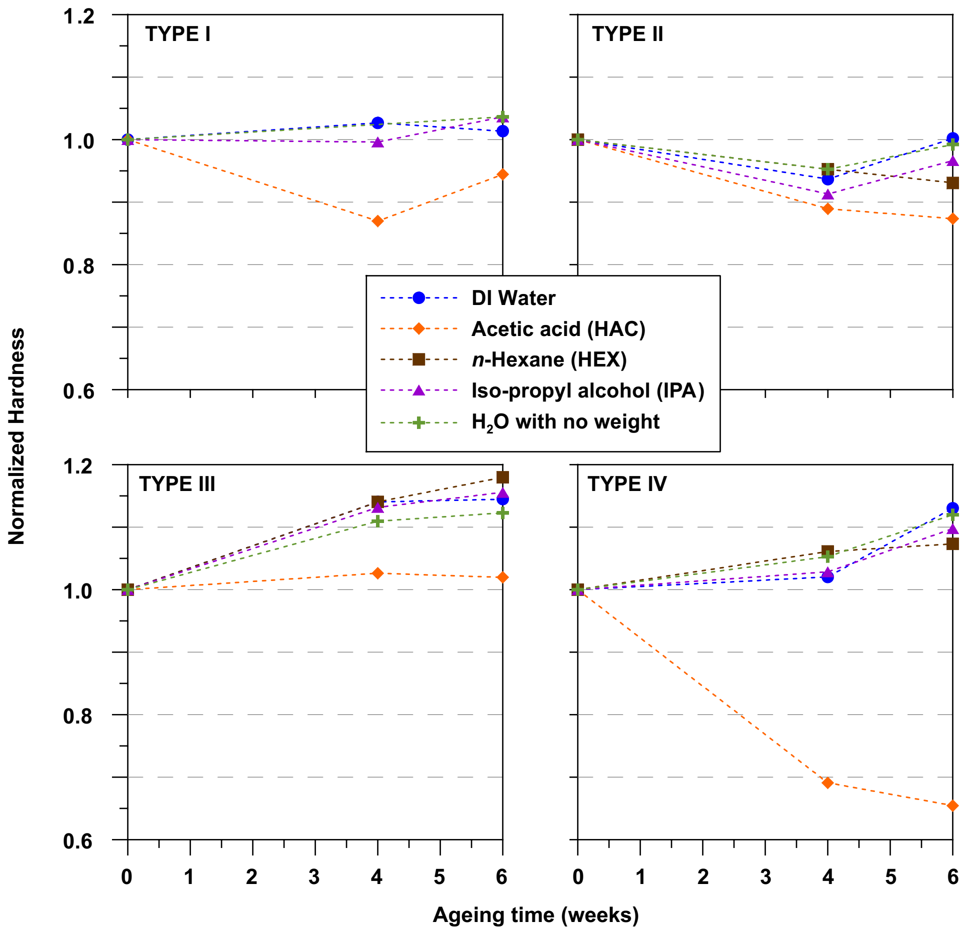

Fig. 4 – Normalized membrane hardness versus time for EPDM membranes soaked in various solvents. Note the apparent incompatibility between acetic acid (HAC) and the EPDM membrane compositions.

Fig. 7 shows a series of pictures of EPDM membrane type 3 specimens exposed to different solvents. Pictures across the top show the orifices without stress. The stress is shown vertically in multiples of 400 mm water column. The vertical column of pictures on the far left shows membrane specimens soaked in DI water, but without weights. If there were no membrane degradation, all the orifices openings would be the same as the orifice openings on the left for each multiple of stress. Note the large difference between ageing with and without weight in DI water solutions. This is an indicator that ageing under stress is required to more accurately describe the differences among solvent solutions effects.

Figs. 8a and b show the orifice creep results for all four EPDM membrane types soaked in distilled water. The horizontal axis shows the stress in multiples of normal operating DWP (400 mm or 16 in of water column). Observations at all 6 times are plotted for types 3 and 4. In DI water, all membranes showed some orifice creep (Fig. 8a). The orifices in the type 1 membranes were approximately 0.04 mm wider after 6 weeks of soaking under stress, for all operating pressures. Membrane type 4 showed the largest change, with orifices being almost 0.3 mm wider after 6 weeks of soaking. Fig. 8b shows similar results for membranes soaked in glacial acetic acid. Type 1 showed the largest change with types 3 and 4 showing minor changes. Similar changes were noted with isopropyl alcohol and hexane. Membrane type 1 generally showed the largest changes in orifice openings. The results plotted in Figs. 8a and b confirm the magnitude of orifice creep from used diffusers. In some cases (e.g., Type II with DI water), the increase in membrane opening is not monotone with time. It is not clear why this occurred, but in all cases the trend shows the smallest opening for new diffusers and increased openings with soaking.

4. Macroscopic effects and other considerations

Fig. 9shows a macroscopic effect of material properties change in membrane diffusers. After a few months in operation, the PVC membrane shrunk to about 85% its initial length, and its DWP grew to over 2500 mm_{H_2O} (100 in_{H_2O}). This represents an incompatibility of the membrane material with the wastewater and usually requires complete membrane replacement. The membrane hardness increased, and orifice creep was observed uniformly along the membrane length. The micrographs in Fig. 6 are images of this membrane specimen. At low airflow rates the orifices remain open, allowing sludge to enter the diffuser, forming a crust inside the membrane. The dried sludge crust blocked a large fraction

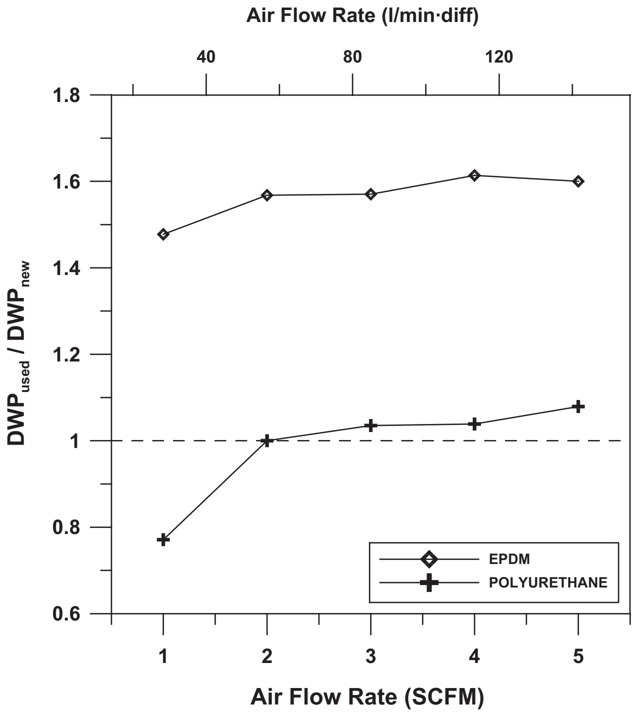

Fig. 5 – Relative ratio of dynamic wet pressure for used and new diffusers. The used diffusers were harvested in wastewater treatment plants in Southern California after 6–7 years in service. These results confirm the results obtained in Figs. 2a and b: used EPDM membranes always have higher DWP than new ones, due to decreased elasticity (i.e., increased Young's modulus) and reduced orifice flexibility. Used polyurethane membranes have reduced DWP at low airflow rates, due to the softening of the membranes (i.e., decreased Young's modulus), which result in higher orifice openings. At airflow rates above 60 l/min diff ($\sim$2 SCFM), used and new membranes show very similar DWP values.

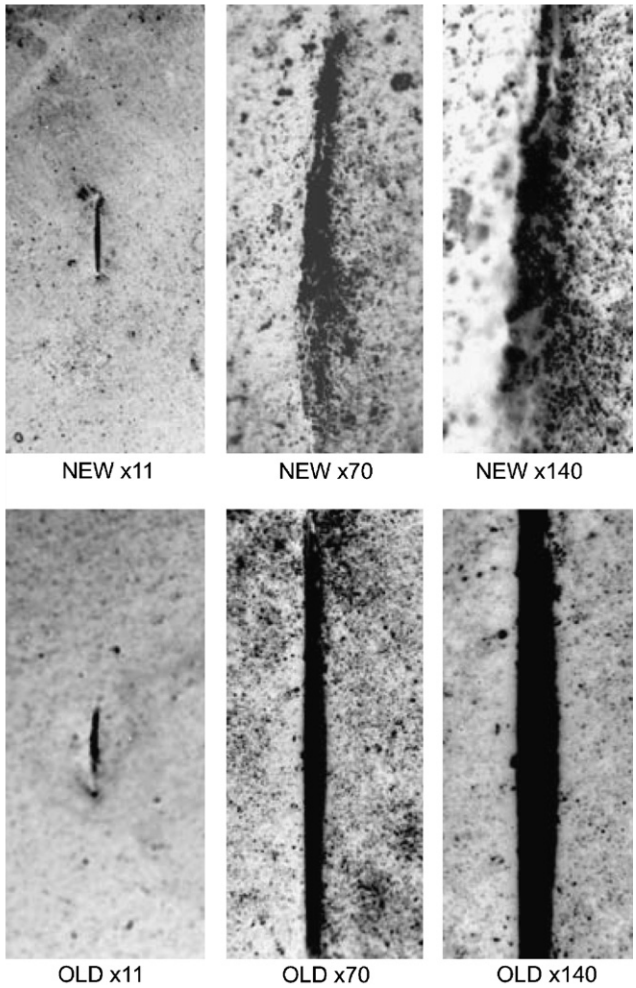

Fig. 6 – Microscopic photographs of new and used PVC membranes at different magnification ratios. Although at low magnification the pores may look similar, more detailed images show that new pore close well, while pores from used membranes remain open when no tension is applied (i.e., equivalent to zero airflow rate).

of the pores, which in this case is particularly visible, considering that the air feed is from the left side of the image, where there is more available air pressure to compensate for pore obstruction. Air does not evenly distribute through this specimen at any airflow rate, and is released through fewer pores as bubbles larger than in a new membrane. This is mostly attributable to the incompatibility between that wastewater and the membrane material.

Another anomaly in membrane property changes is visible in Fig. 10: a polyurethane membrane experienced orifice cracks mainly where the tube folds (the fold is due to extra length included to compensate in case of shrinkage). The detail below shows a microscopic photograph of an orifice at the fold. There are three cracks departing from the extremes of the slit, i.e. where the accumulation of tensile strength is maximum. The overall result of this anomalous ageing is the majority of the air being released as coarse bubbles at the orifice cracks, and low flow over the rest of the diffuser. Most likely, this specimen will tear with time in operation, leading to air leaks and pressure loss in the aeration system.

Orifice creep is a time-dependent phenomenon. The orifices are stretched under normal operation, and this continues for the life of the diffuser. During this time, the diffuser material loses plasticizer and hardens. The hardening occurs because of a combination of plasticizer loss and stress accumulation around the orifice, where hardening would first be expected.

5. Conclusions

This paper describes a series of experiments to simulate fine-pore membrane diffuser ageing phenomena used several methods to monitor performance. Hardness and Young's modulus measurements did not produce consistent trends for all membrane materials and conditions, and generally changed too slowly to predict membrane performance in a series of short laboratory tests. Orifice creep test measurements showed differences in the performance of different EPDM formulations in resisting the effects of solvents. The effects were consistent and are meaningful in that orifice

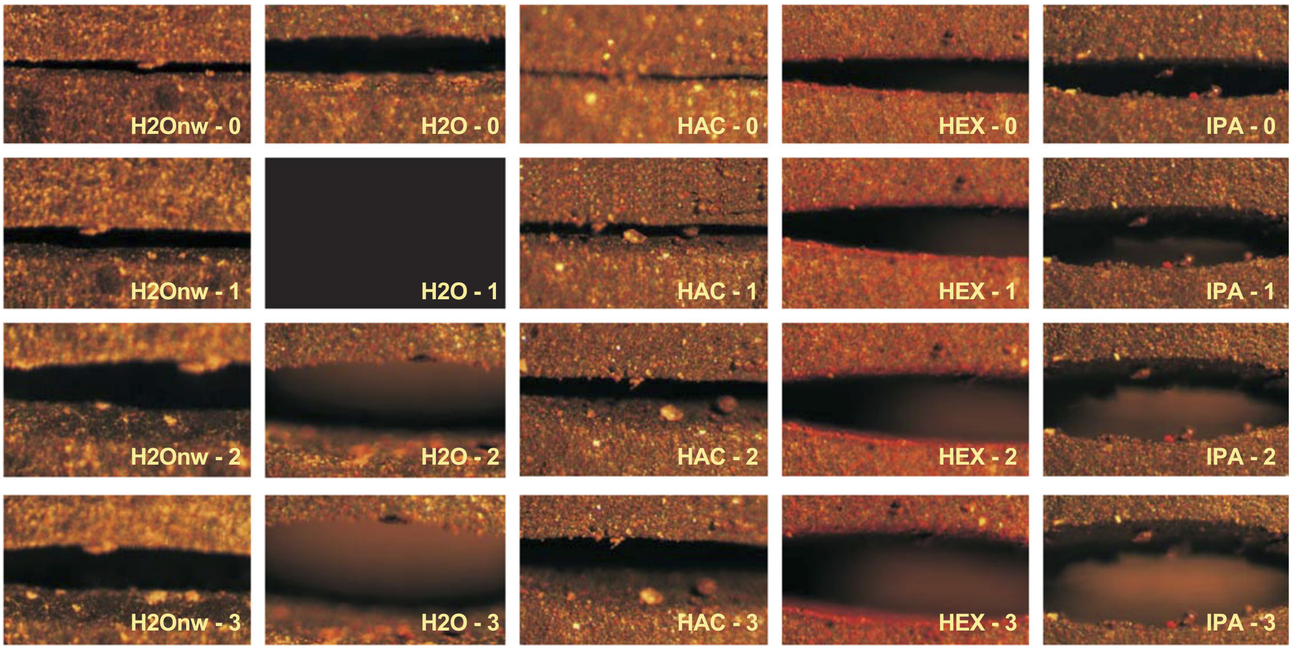

Fig. 7 – Accelerate ageing matrix for EPDM membranes. Label codes are: H_2Onw = DI water with no weight applied during ageing; H_2O = DI water with weight applied during ageing; HAC = 5% aqueous solution of acetic acid and weight applied during ageing; HEX = 5% aqueous solution of hexane and weight applied during ageing; IPA = 5% aqueous solution of iso-propyl alcohol and weight applied during ageing; 0-3 codes are tensions equivalent to DWP values (in mm or inch of water column): 0 = 0 mm (~0 in); 1 = 400 mm (~16 in); 2 = 800 mm (~32 in); 3 = 1200 mm (~48 in). Note the difference between DI solutions with and without weight.

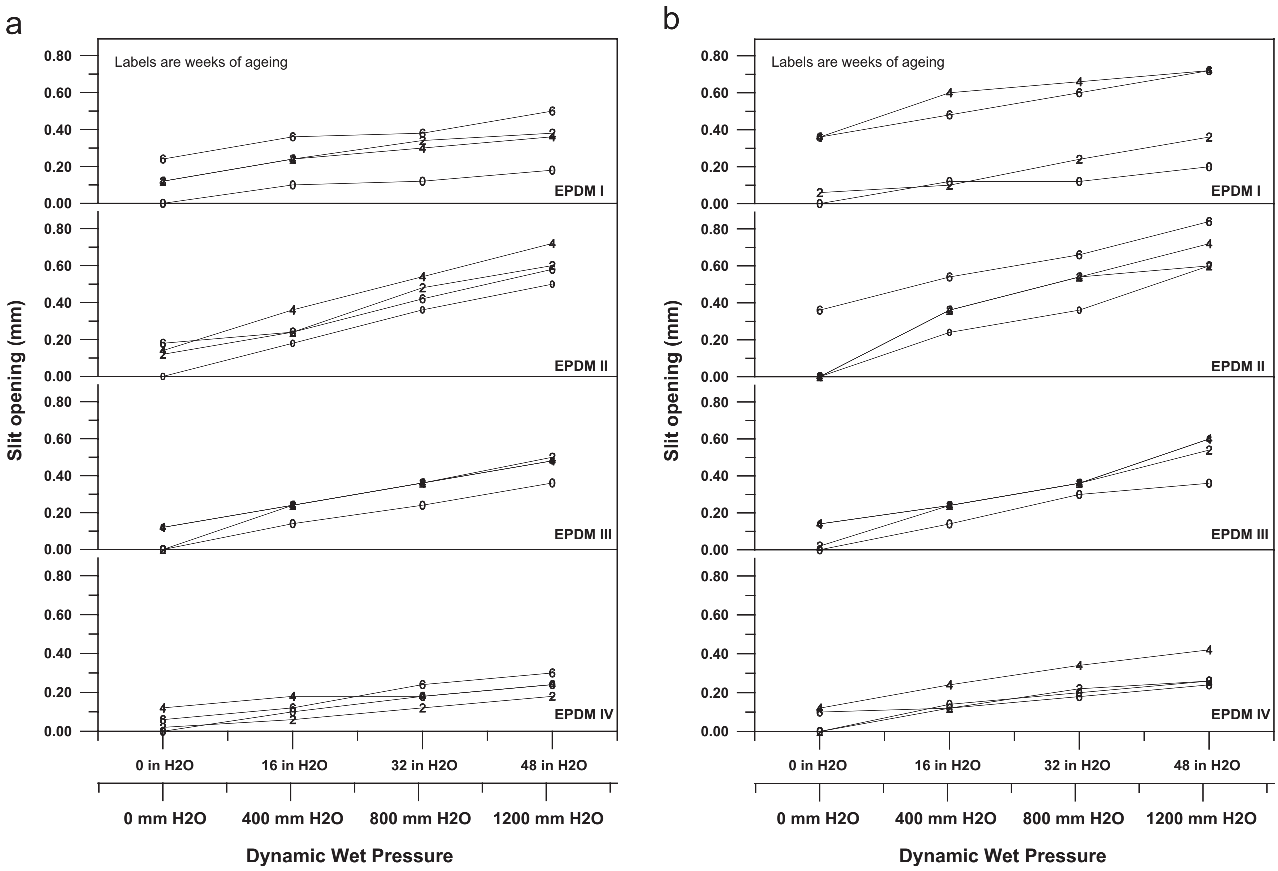

Fig. 8 – (a) Orifice opening versus DWP for four EPDM membranes in DI water solutions. All membrane specimens show orifice creep: (b) orifice opening versus DWP for four EPDM membranes in HAC water solutions. All membrane specimens show orifice creep. EPDM specimens I and II showed the largest creep, especially at no load (e.g., no airflow rate and zero DWP) applied.

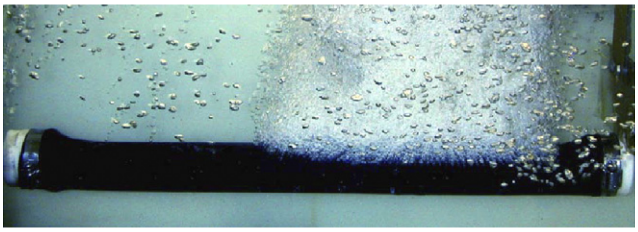

Fig. 9 – Anomaly in membrane property changes: a PVC membrane tube installed in a heavily loaded treatment plant shrank to about 90% its original size; due to heavy shrinkage, the membrane moved from the end clamp, and allowed sludge inside, which clogged some pores from the inside.

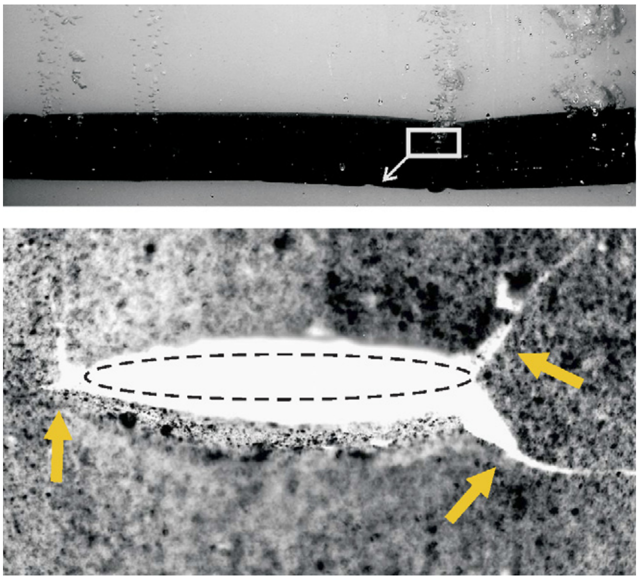

Fig. 10 – Another anomaly in membrane property changes: an EPDM membrane experienced orifice cracks mainly where the tube folds (the fold is due to extra length included to compensate in case of shrinkage). The detail below shows a microscopic photograph of an orifice at the fold. There are three cracks departing from the extremes of the slit, i.e. where the accumulation of tensile strength is maximum. The overall result of this anomalous ageing is few coarse bubbles released at the orifice cracks, and most of the diffuser with zero flow.

enlargement is directly related to reductions in oxygen transfer efficiency. Microscopic techniques allow a more rapid detection of membrane changes. Membranes soaked in solvents but without loading did not represent specimens soaked under loadings typical of field conditions, showing that loading is needed to properly simulate field conditions and detect differences in membrane properties. Orifice creep measurements are useful to predict the decline in diffuser performance, and offer a method to evaluate membrane diffuser performance before installation or monitor diffuser performance during service.

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