Structurally Functionalized Polyurethane Foam for Elimination of Lead Ions from Drinking Water

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Abstract: Polyurethane foams functionalized with Sulfonic acid groups have been found to be strong cation exchangers. This novel property of the foam was used to exchange lead (Pb^{2+}) ions from aqueous solutions. Polyurethane foam synthesis is based on addition polymerization of the highly reactive isocyanate (-NCO) groups of an isocyanate with the hydroxyl (–OH) groups of a polyol to form the urethane species. Toluene-2,4-2,6- diisocyanate was reacted with Polypropylene glycol 1200 in 2:1 molar ratio to form a linear pre-polymer. The linear pre-polymer was further polymerized using a chain extender, N, N-bis (2-hydorxyethyl)-2-aminoethane-sulfonic acid (BES). BES also acts as a functional group to exchange Pb^{2+} ions. A set of experiments were designed to study various process parameters. The functionalized polyurethane foam was characterized by Fourier transform infrared spectroscopy, gel permeation chromatography, scanning electron microscopy, and energy dispersive x-ray spectroscopy. The Pb^{2+} ion exchange capacity was determined using an Inductively Coupled Plasma Mass Spectrometer. The maximum Pb^{2+} ion exchange capacity of the foam was found to be 47 parts per billion per gram (ppb/g) from a 100 parts per billion (ppb) Pb^{2+} solution over a period of 60 minutes. A multistage batch filtration process increased the Pb^{2+} ion removal to 50-54 ppb/3g of foam over a period of 90 minutes.

Keywords: Adsorption, Functionalized, Ion exchange, Polyurethane foams, Sulfonic.

1. INTRODUCTION

Polyurethane foams are considered to be one of the best commercially available insulation materials. It has good thermal insulating properties, low moisture-vapor permeability, high resistance to water absorption, and a relatively high specific strength. Another advantage of polyurethane foam systems is that the synthesis can be tailored to various specific applications. The major components are an Isocyanate and a polyol (or a mixture of polyols). A blowing agent and a catalyst are used to accelerate the foam formation. The foams can be synthesized as open-cell foam or as closed-cell foam based on the initial raw materials concentration. Recently; the cellular polymer has intrigued researchers to device other novel applications for this material [1].

Open cell polyurethane foams have shown to exhibit a reasonable amount of ion exchange capacity and are being considered as suitable ion exchange media for heavy metal ions removal. Farag *et al*. [2] showed that open-pore polyurethane microspheres exhibit low cation exchange capacity. Their research on foams prepared by chemical bonding of specific functional groups (-SH) was used to adsorb mercury ions from mercury (II) chloride and methyl mercury (II) chloride in the range of 0.4 to 400 ppb. This also led researchers to consider the functionalization of

polyurethane foams as another effective technique to eliminate heavy metal ions either by adsorption or pre-concentration mechanisms. Functional groups like hydroxyl, ketone and carboxylic acids have been found to adjust the surface energy and improve the hydrogen binding in polymers [3]. This property is the basis for functionalization of polyurethane foams either by surface or structural modification. Moon *et al*. [4] developed a CEDI (continuous electro deionization) medium to deionize aqueous media to a high level without the need for chemical regeneration by synthesizing functionalized polyurethane foam. A chain extender was used during synthesis to functionalize the pre-polymer. This led to the bulk functionalization of polyurethane foam with an increase in ion exchange capacity as the number of sulfonic acid groups increased. Functionalization of polyurethane foams by surface modification has led to systems capable of adsorbing heavy metal and trace metal ions [5-9].

Research on graft and composite foam systems have established their efficiency to treat heavy metal ions [10-12]. Polyurethane foams modified by grafting acrylo nitrile and acrylic acid by gamma irradiation method reported by Meligi [10] have shown that the adsorption of heavy metal ions like Zn(II), Fe(II), Ca(II), Ni(II), Cu(II) and Pb(II) were affected by pH, atomic weight and initial contaminant concentration. In a study by Jang *et al*. [11], hydroxyapatite (HAP) - polyurethane foams were synthesized for Pb^{2+} ion adsorption. A maximum adsorption capacity was determined to be 150 mg/g for the composite with 50 wt% HAP. The study also concluded that higher HAP

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concentration exhibited higher Pb^{2+} ion adsorption capacity. Less uniform dispersion of HAP in the foam led to slower adsorption and adsorption was dominant at higher pH levels. Another type of polyurethane composite foam containing alginate was synthesized by Sone *et al*. [12], which had a structure similar to a weak cation exchanger. Results from this study showed that Pb^{2+} adsorption was sensitive to lower pH and competing cations and the Pb^{2+} ion adsorption using this foam ranged from 20 ppb to ~ 100 ppb in 2 hrs.

The research summary described above does not address bulk functionalization of polyurethane foams for selective elimination of heavy metal ions. To address this we focused our research work on the development of a bulk functionalized polyurethane foam system using a chain extender. Chain extenders are low-molecular multifunctional species. They can be used to balance the backbone structure of polymers [13]. This makes them suitable for selective elimination of heavy metal ions. In this paper we discuss the modified synthesis process formulated by Moon *et al*. [4] using N, N-bis (2-hydorxyethyl)-2-aminoethane-sulfonic acid (BES) chain extender to eliminate Pb^{2+} ions from aqueous media. In addition, we will present a broad range of characterization of the functionalized foam in order to better understand the capabilities and limitations of the foam to remove Pb^{2+} ions.

2. EXPERIMENTAL WORK

2.1. Materials

Polypropylene glycol 1200 (PPG; Sigma Aldrich Co. LLC) was dried in a vacuum oven at $70^{o}C$ for 24 hours before use. Toluene diisocyanate (TDI; 2,4-80%, 2,6-20%, Alfa Aesar), Dimethyl Sulfoxide (DMSO; Alfa Aesar, 99.9%pure), N,N-Bis(2-hydroxyethyl)-2-aminoethanesulfonic acid (BES; Alfa Aesar,99% pure), Dibutyltin dilaurate (DBTL, Sigma Aldrich Co. LLC, 95% pure), 73311 surfactant (batch 083K11150E), Nitrogen gas (Airgas, O_2 free UHP) were used as received.

2.2. Synthesis of Functionalized Polyurethane Foam

The experimental set up consists of a 3-neck round bottom reaction flask placed in an oil bath fitted with a mechanical stirrer and a condenser at the center neck, nitrogen gas inlet and outlet at the right neck and a drop funnel at the left neck. The reaction was carried out at 65-70°C in an inert atmosphere. The 3-neck flask was initially charged with TDI and allowed to stabilize at $70^{o}C$ in saturated nitrogen atmosphere. A drop funnel was filled with a pre-weighted amount of PPG which was added drop wise and allowed to react with TDI for 3-4 hours until an initial isocyanate content of 11-12% was reached as determined by ASTM D 5155, di-n-butylamine method.

A pre-weighted amount of BES dissolved in DMSO (amount of DMSO used was based on the solubility limit of BES in DMSO) at 70°C was added drop wise into the reaction flask. The reaction was allowed to proceed until a final isocyanate content of 7-8% was reached. The tin catalyst was added at the end and the prepolymer was decanted into a glass mold. Based on the amount of PPG used, a pre-weighted amount of distilled water was added as a blowing agent along with the surfactant. The mixture was then mixed using a mechanical stirrer at 2500-3000 rpm for 10-15 seconds. This initiates the reaction of water with the remaining isocyanate groups forming an intermediate compound and eventually releasing CO_2 gas to form the cellular structure [14].

In order to determine the optimum chain extender (BES) composition, molar ratio of PPG and TDI, and the chain extender reaction time (CERT) a set of experiments were designed. The objective of these experiments was to explore the effect of these parameters on the physical and ion exchange capacity of the foam. Table **1** shows the detailed list of the compositions used to prepare the foam samples. Samples A1-A4 has a variable BES/DMSO content with all other variables being maintained constant. Samples B5-B7 were prepared with varying PPG/TDI ratios; whereas samples C8-C10 have different chain extender reaction times (CERT). Samples A3, B6, and C8 represent the same composition used in the study of the three design variables.

2.3. Sample Preparation for ICP-MS Analysis

An Inductively Coupled Plasma Mass Spectrometer (ICP-MS) was used for trace metal analysis at ppb levels. The demolded functionalized foam was cut into small cubes (1 gram each) maintaining a constant volume. Polyurethane foam requires homogeneous rearrangement of its polymeric bonds for effective ion exchange, as the foam does not experience stress-free conditions after synthesis [4]. The foam cubes were washed in distilled water and conditioned in 2N NaCl solution for 4 hrs to ensure rearrangement of the polymeric bonds for better ion exchange.

Table 1:   Foam Composition Based on the Variables

Variable	Samples	PPG (g)	TDI (g)	BES (g)	DMSO (g)	DBTL (g)	Surfactant (g)	Water (g)	CERT (min)
BES/DMSO	A1	50	18.3	0	0	2	0.25	6	40
	A2	50	18.3	3.4	7.8	2	0.25	6	40
	A3,B6,C8	50	18.3	6.7	15.7	2	0.25	6	40
	A4	50	18.3	10.1	23.5	2	0.25	6	40
PPG/TDI	B5	50	9.1	6.7	15.7	2	0.25	6	40
	B7	50	27.4	6.7	15.7	2	0.25	6	40
CERT	C9	50	18.3	6.7	15.7	2	0.25	6	60
	C10	50	18.3	6.7	15.7	2	0.25	6	90

Standard Pb^{2+} solutions of 100 ppb were prepared from a stock solution of 1 parts per million (ppm). The conditioned foams were soaked in 25ml of Pb^{2+} solution in a beaker with a magnet. The beaker was then covered to avoid contamination and placed on a stirrer. Foams were thus exposed to the Pb^{2+} solution for various time periods. 10 ml of each sample was filtered into 15 ml centrifuge tubes. Nitric acid was added to get a 2% nitric acid solution to stabilize the Pb^{2+} ions in the sample during storage and for ICP-MS analysis.

2.4. Fourier Transform Infrared (FTIR) Spectroscopy

The functionalized polyurethane foam samples were characterized by a BRUKER vector 22 FTIR with a DTGS (deuterated triglycine sulfate) detector and a PIKE 3-12 multi-bounce Zn-Se variable angle ATR. The incidence angle was set to 80 during characterization. The foam samples were cut into strips of 3"x1"x0.5" and were washed in distilled water and dried in a vacuum oven before testing. The IR spectrum was measured from 400 to 4000 cm^{-1} to confirm the presence of sulfonic groups in the polymer structure.

2.5. Gel Permeation Chromatography (GPC)

The polyurethane foam samples were analyzed using a Varian ProStar HPLC system using a PLgel 5mm mixed C column. HPLC grade dimethyl formamide (DMF) was used as the eluent with a flow rate of 1 ml/min. The UV detector was set to detect at 269 nm. Foam samples were dissolved in DMF to get a 0.5% w/v concentration and 25µl of the sample was injected into the column [15]. The main purpose of this analysis was to determine the effect of the chain extender (BES) and the solvent (DMSO) on the foam structure during synthesis.

3. RESULTS AND DISCUSSION

The foam samples prepared according to Table **1** showed that the physical characteristics of the foam; such as its color, odor, pore size and structure depend primarily on the DMSO content. Foam samples A1, A2, and A3 had a similar pale yellow color and were odorless due to the low amounts of DMSO used and lower CERT. Foams with a higer DMSO content and/or higher CERT were much darker in color (brownish). The flexibility of the foam, color and odor seemed to increase with increasing DMSO content and CERT as observed in samples A3, A4, C9 and C10. This may be due to the cleavage of the polymeric bonds connecting the hard segments in the foam by DMSO, since it is a strong organic solvent capable of dissolving the polyurethane foam on prolonged exposures. On the other hand, the rigidity of the foam increased with increasing TDI content (e.g., B7) due to the excess hard segments formed by the quasi pre-polymer in the foam [16]. Lower amounts of TDI in sample B5 did not favor foam formation leading us to the conclusion that the ratio of soft and hard segments (polyol:isocyanate) should be higher then 1:1 to form a isocyanate terminated true pre-polymer [16].

3.1. Fourier Transform Infrared (FTIR) Spectroscopy

The FTIR spectrum of the foam samples A1 to A4 with varying BES/DMSO content is shown in Figure **1**. Sample A1 shows a clear C-O-C peak at 1100 cm^{-1} as it does not contain any chain extender with the sulfonic groups. The O-S-O peaks start to appear at ~1060 cm^{-1} in other samples and this peak partially overlaps with the C-O-C band. The asymmetrically stretched S=O peak appears at 1350 cm^{-1}. The urethane carbonyl peaks appear at 1700 cm^{-1}. The NH band and H-NH band appear at 3000 cm^{-1} [4]. These indicate that the
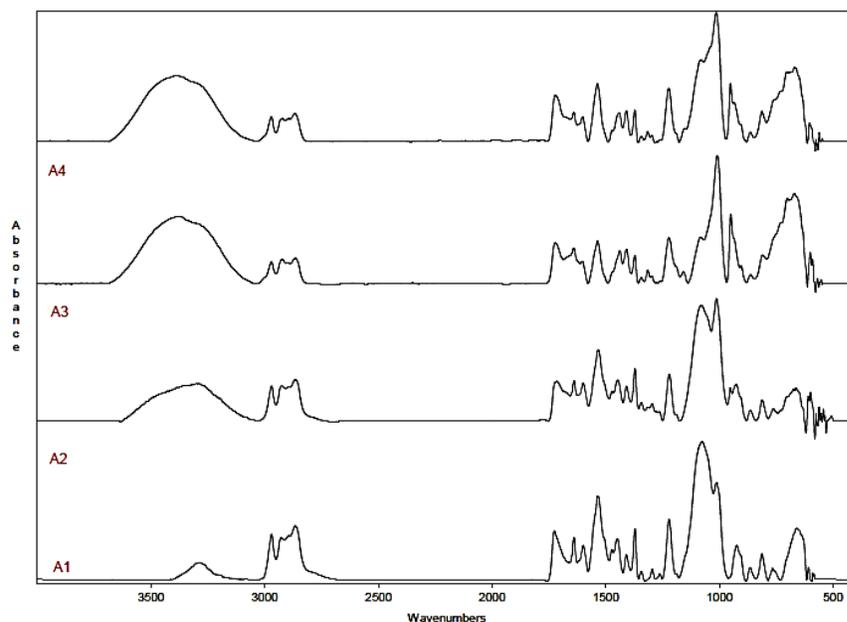
Figure 1: FTIR spectrum of samples A1-A4.

sulfonic acid functional groups were successfully integrated into the polyurethane backbone. The –CH stretching vibrations from the polyol appear at 2850-3000 cm^{-1} followed by the –OH and –NH stretching which can be seen at 3200-3300 cm^{-1} [17]. The –CH bending vibrations due to substitution groups in alkenes and aromatics is usually seen between 850-950 cm^{-1} [18]. The gradual appearance of a peak in this region as the BES content and the CERT is increased (Figure **2**) confirms the substitution of the BES chain extender to the PPG-TDI pre-polymer.

Sung and Schneider [19] have reported that the urea microdomains in polyurethane foams are known to possess bidentate hydrogen bonding which is associated with a 1640 cm^{-1} absorbance observed *via* FTIR. The presence of hydrogen bonding also leads to the hard segments packing in an organized manner. In another study, Aneja *et al*. [20] compared the isomers of TDI and determined that the 1640 cm^{-1} absorbance was found to decrease as the 2,4 TDI isomer content increased and suggested that the symmetry of the isocyanate moiety had a considerable impact on the packing behavior of the urea hard segments. From
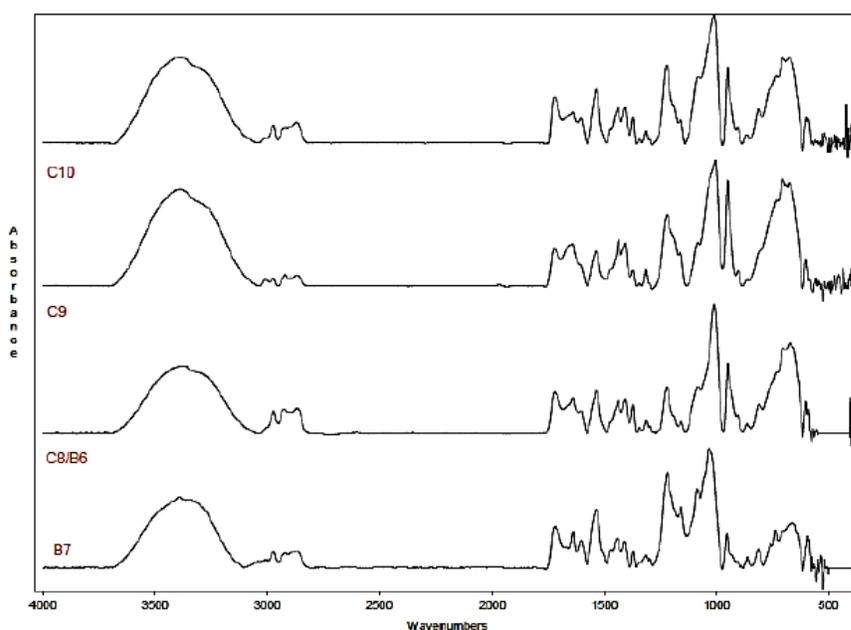

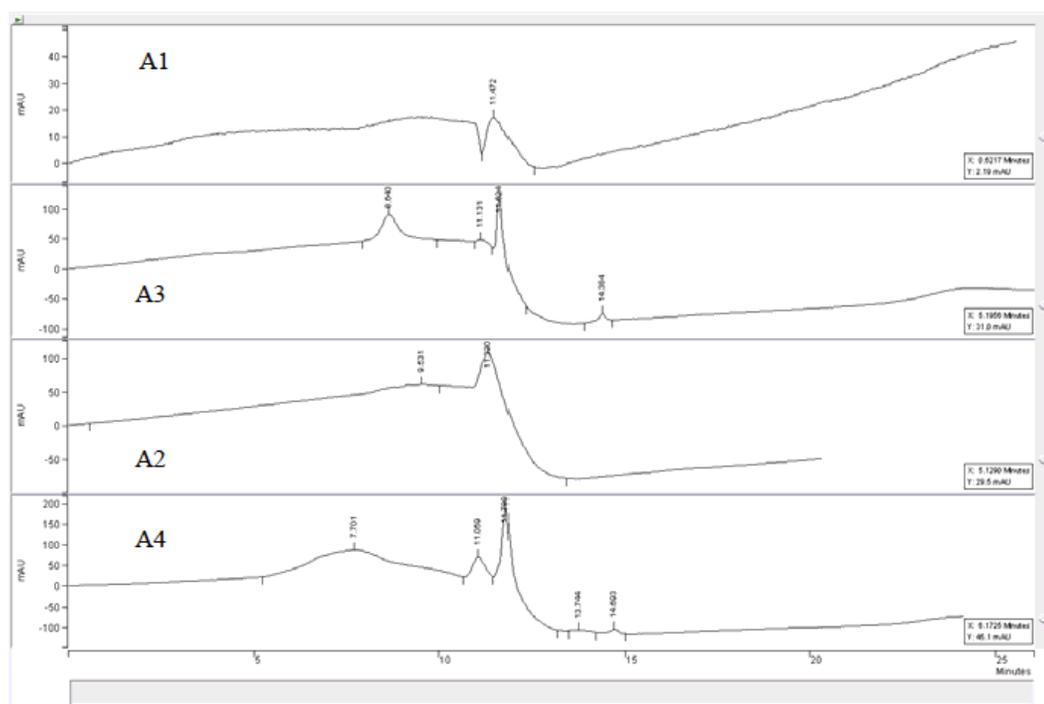**Figure 2:** FTIR spectrum of samples B7-C10.

Figure 3: High and low molecular weight compounds of functionalized polyurethane foam samples based on BES/DMSO content.

Figure **2**, it is clearly evident that samples A3 (B6/C8) and B7 do not show any significant peaks at 1640 cm^{-1}. This may be due to the foam composition since the samples differ only by an excess of 0.5 moles of TDI in each case, which may not be significant to show any changes in absorbance. The effect of CERT can be observed in the absorbance spectrums for samples A3, C9 and C10. The C-O-C and O-S-O peaks start to overlap at 1100 cm^{-1} as the CERT increases; they seem to merge to form a single peak.

3.2. Gel Permeation Chromatography (GPC)

BES is a chain extender that links the isocyanate groups in the linear polymer chains through its hydroxyl groups thereby increasing the molecular weight of polyurethane. DMSO is a strong organic solvent that dissolves polyurethane. Since BES is insoluble in other organic solvents, the use of DMSO cannot be eliminated from the foam synthesis process. Hence both BES and DMSO have an opposing effect in this polyurethane foam system.

GPC analysis shows that the retention time, to elute higher molecular weight or larger molecules, decreases as the DMSO content and CERT increase during synthesis. This can be seen in Figure **3** for samples A1-A4. Sample A1 has no DMSO and it elutes at 11.4 minutes. As the amount of DMSO increases in samples

A2-A4, we can see larger molecules eluting earlier than 11.4 minutes followed by smaller molecules after 11.4 minutes. This can be attributed to the cleavage of polyurethane chains in samples with higher DMSO content in their composition.

The peak retention times for all the samples have been summarized in Table **2**. Samples A2 and B7 seem to show a similar elution trend. A2 has lower amounts of DMSO and B7 has a higher TDI content in its composition. This provides additional isocyanate groups for functionalization, therefore lowering the ability of DMSO to break the polymer chains during synthesis. Hence increasing the TDI content in the foam composition without affecting the structural integrity of the foam may be a way to reduce the cleaving effect of DMSO.

Table 2: Retention Times of Foam Samples

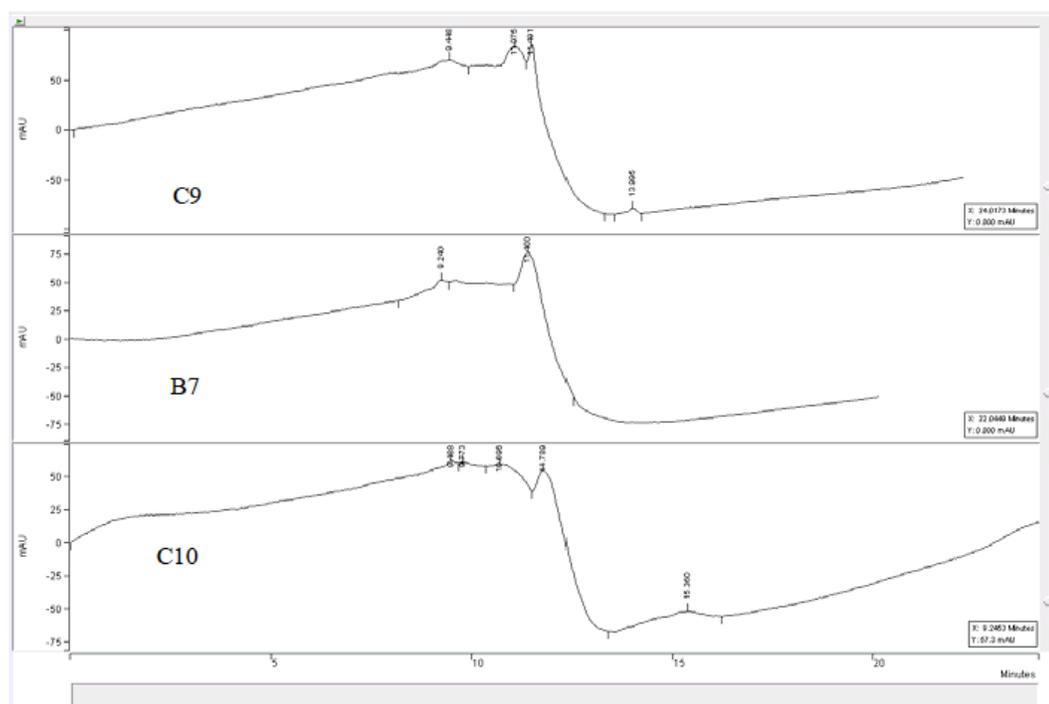| Sample	Peak Retention time (minutes)				
A1	11.4				
A2	9.5	11.3			
A3	8.6	11.1	11.6		
A4	7.7	11.0	11.7	13.7	14.6
B7	9.2	11.4			
C9	9.4	11.0	11.4	13.9	
C10	9.4	9.7	10.6	11.7	15.3

Figure 4: High and low molecular weight compounds of functionalized polyurethane foam.

Similarly, Figure **4** shows GPC analysis for samples B7-C10. It is evident that increasing CERT has the same effect in samples C9 and C10. Even at reasonable amounts of DMSO, higher CERT seems to cleave polymer chains resulting in a large molecular weight distribution in the foam sample. These factors influence the distribution of the functional group in the foam and may affect the Pb^{2+} ion removal capacity of the foam.

3.3. Scanning Electron Microscopy and Energy Dispersive X-Ray Analysis (SEM/EDX)

Foam samples were analyzed using a Topcon SM-300 SEM/EDX instrument. The samples were coated using a sputter coater before analysis. Figure **5** confirms the open cell structure of an unconditioned A3 foam sample. Elemental analysis by EDX performed on the foam sample after soaking in 100 ppb standard Pb^{2+} solution for 2 hrs shows the presence of Pb^{2+} ions in the bulk of the foam sample along with sulfur and various other elements, as shown in Figure **6**. This confirms the Pb^{2+} ion exchange with sulfonic acid groups in the functionalized polyurethane foam.

3.4. Inductively Coupled Plasma –Mass Spectro-meter (ICP-MS)

ICP-MS is a powerful analytical technique that allows detection of trace elements at parts per billion

and parts per trillion levels. Pb^{2+} ion exchange capacity of the foam was measured using ICP-MS.

Foam samples A1 to C10 were analyzed at 1, 2 and 12 hr time intervals and the results are shown in Figures **7-9**; respectively. A1 foam samples (0 moles BES) showed some Pb^{2+} removal in the absence of sulfonic functional groups, this indicates that the mechanism of Pb^{2+} ion removal is not solely by ion exchange [21]. Polyurethane foams are well known for their adherence properties and it may have contributed to the Pb^{2+} ion removal without any BES content in the
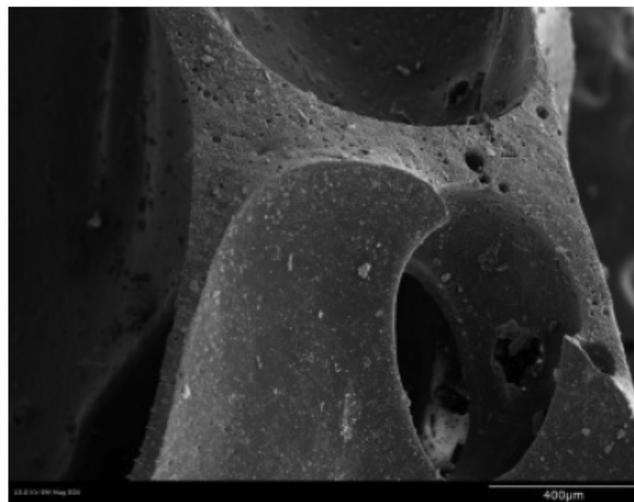

Figure 5: SEM image of functionalized polyurethane foam at 50X magnification.
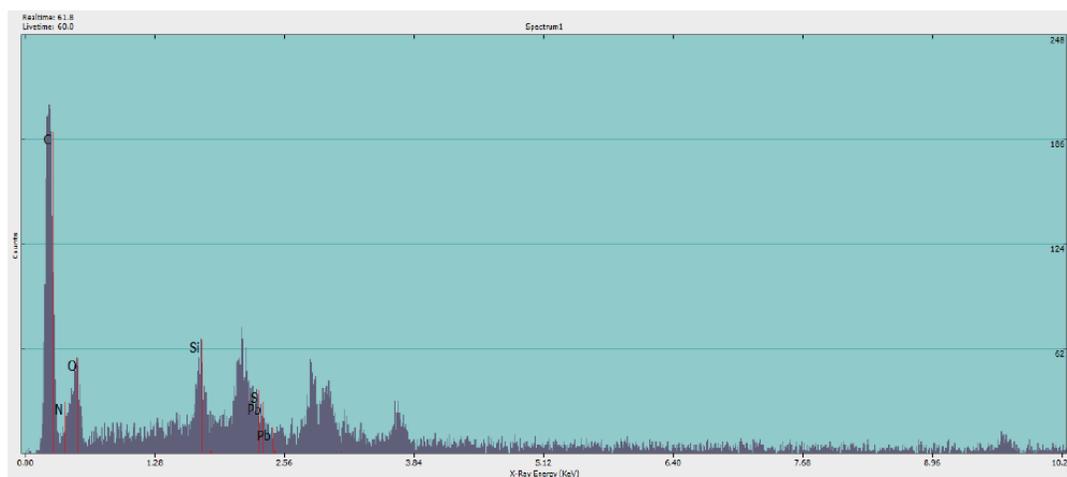
Figure 6: EDX Elemental analysis of functionalized polyurethane foam.

foam composition. It can also be observed that this behavior changes with exposure time. Initial exposure of 1 hr resulted in 36 ppb/g removal rate compared to 24 ppb/g after 12hrs. This may be due to the leaching of Pb^{2+} ions back into the solution from the foam surface.
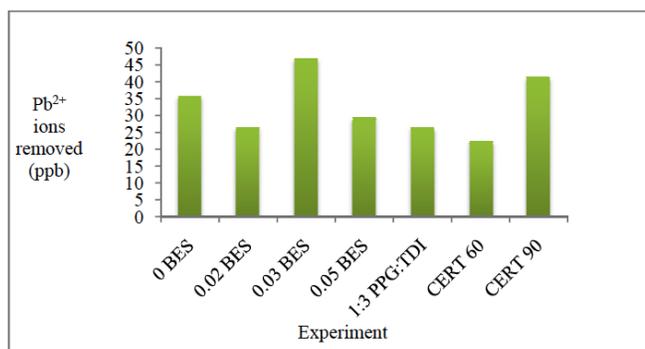

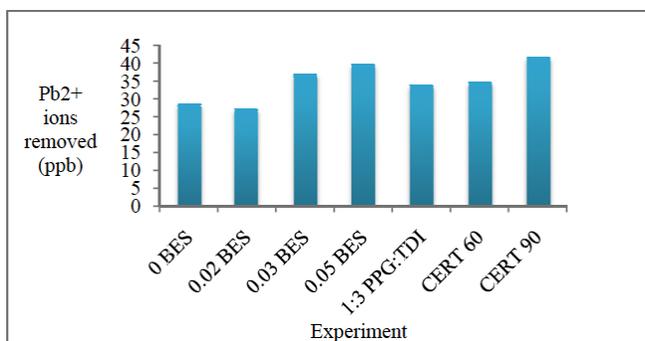**Figure 7:** Pb^{2+} ions removed by foam samples after 1 hr exposure.

Figure 8: Pb^{2+} ions removed by foam samples after 2hrs exposure.

Foam samples A2 (0.02 moles BES) showed a steady increase in Pb^{2+} ion removal from 26 to 30 ppb/g over a period of 1-12 hrs. This can be attributed

to the lower amounts of BES used during synthesis. The availability of fewer functional groups for ion exchange along with surface adsorption may be the main reason for this behavior. However, A3 foam samples (0.03 moles BES) seemed to exchange higher amounts of Pb^{2+} ions (47 ppb/g) at lower time intervals and the Pb^{2+} ion removal capacity seemed to reach a saturation limit between 2 and 12 hrs. Further exposure to the Pb^{2+} solution did not show any significant increase in Pb^{2+} ion removal capacity.
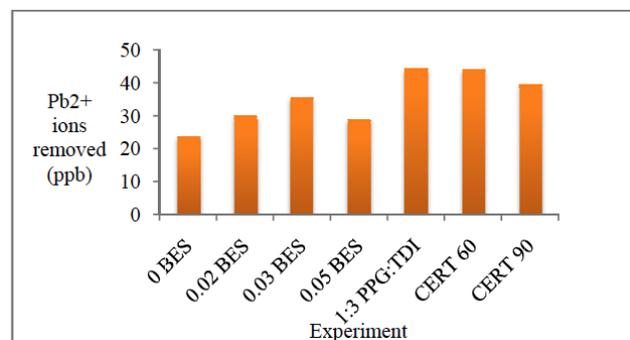

Figure 9: Pb^{2+} ions removed by foam samples after 12hrs exposure.

The foam samples of A4 (0.05 moles BES) showed a rather unique trend in comparison to A2 and A3. With higher BES content, one would assume the foam to show a higher and faster Pb^{2+} removal capacity due to the increase in sites for ion exchange. On the contrary, ICP results showed a steady increase in Pb^{2+} ion removal at lower time intervals (29 ppb/g after 1 hr and 40 ppb/g after 2 hrs) and a tapered down and saturated level at prolonged exposures. This behavior may be attributed to the composition of A4 samples which lacks additional isocyanate groups necessary to bond with the additional sulfonic groups from BES. In addition,

the presence of excess DMSO used to dissolve BES may have led to structural disintegration at the molecular level limiting the uniform availability of functional groups for ion exchange in the foam.

The composition of B5 (1:1 PPG:TDI) was unsuitable to synthesize the foam and hence there are no results on Pb^{2+} removal capacity from these samples. Composition of B6 (1:2 PPG:TDI) and C8 (40 min CERT) are similar to that of A3 and the Pb^{2+} removal capacity results are the same as discussed earlier.

The foam sample of B7 (1:3 PPG:TDI) was quite rigid compared to its counterparts due to higher amounts of TDI in the composition. Pb^{2+} ion removal increased steadily with time in this foam composition from 26 to 45 ppb/g. This can be attributed to the availability of excess isocyanate groups for the chain extender (BES) to react with and provide additional sites for ion exchange.

For samples C9 (60 minutes CERT) and C10 (90 minutes CERT), the amounts of PPG/TDI and BES/DMSO was maintained the same as in A3 and the CERT was increased from the initial 40 minutes to 60 and 90 minutes; respectively. The Pb^{2+} ions removal capacity of C9 increased steadily from 22 to 44 ppb/g. This may be due to the additional bonding of the –OH groups from BES to the –NCO groups in TDI leading to a higher degree of functionalization of the polymer back bone with longer CERT. C10 foam samples with the highest CERT of 90 minutes performed similar to A3. However the higher CERT affected the foam structure, color, and odor and made it less appealing. This may be due to the effect of DMSO which tends to disintegrate the foam structure similar to A4 and C9 compositions.

From the above results, the foam samples of A3 composition showed the highest Pb^{2+} ion removal capacity of 47 ppb/g of the foam for an exposure period of 1 hr and C10 had removed 42 ppb/g in 2 hrs. For the exposure time of 12 hrs, B7 had the best Pb^{2+} ion removal capacity of 45 ppb/g followed by C9 at 44 ppb/g. Based on these results, it seems that higher amounts of BES does not necessarily improve the Pb^{2+} removal capacity of the foam due to the absence of additional isocyanate groups needed to bond with the chain extender to provide sites for ion exchange. The presence of excess DMSO also seems to affect the Pb^{2+} ion removal capacity of the foam as it disintegrates the foam structure preventing uniform distribution of functional groups in the bulk of the foam. Higher CERT also showed a similar effect due to the excess time available for DMSO to break up the polyurethane chains.

In order to improve the Pb^{2+} removal capacity of the foam, a multi stage batch filtration method was set up as shown in Figure **10**. Foam samples with compositions A3 and C10 were selected for this study. In this method, based on the number of stages, multiple pieces of virgin foam were soaked in standard Pb^{2+} solution for a period of 30 minutes consecutively as opposed to a single piece of foam soaked in a 25 ml solution for a period of 1, 2 and 12 hrs time intervals.

This set up improved the Pb^{2+} removal efficiency of the A3 foam to 50 ppb and the C10 foam to 54 ppb over a period of 1.5 hrs. The results are shown in Figure **11**. One would expect this process to be more efficient and render the solution Pb^{2+} free after multiple runs; however the Pb^{2+} removal efficiency of the foams seems to slow down as the Pb^{2+} concentration decreases in the solution. This may make it difficult for the few Pb^{2+} ions to efficiently seek ion exchange sites or merely adsorb on the foam surface. Additional experiments, results of which are not included in this study, have shown that the Pb^{2+} removal capacity of the foam is lower and much slower in solutions containing less than 50 ppb Pb^{2+} ions.
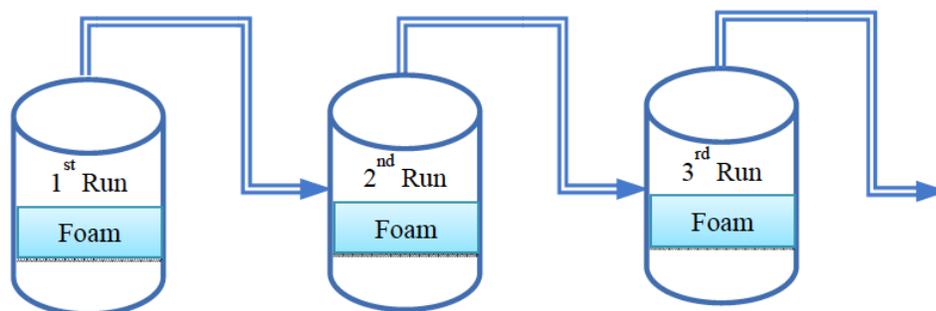

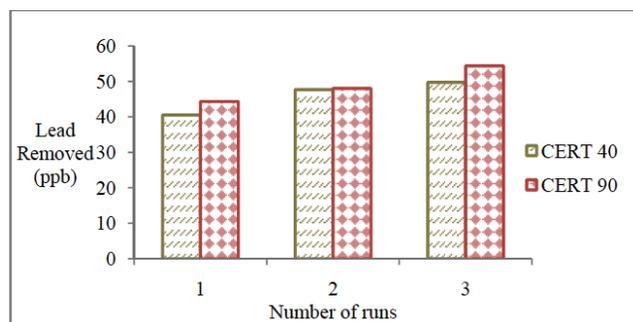**Figure 10:** Multi stage batch filtration process set-up.

Figure 11: Pb^{2+} removal capacity based on multistage batch filtration process.

Based on the above results A3 foam samples were analyzed at 6.5 and 8.5 pH levels over a period of 2 days, the results of which are shown in Figure **12**. Since the foam is considered for drinking water applications, it was not tested at other pH levels. The Pb^{2+} removal capacity of the foam seemed to be unaltered at a pH of 6.5. The maximum Pb^{2+} removal capacity was measured to be 51 ppb/g after soaking the foam for a period of 2 hrs in Pb^{2+} solution. The Pb^{2+} removal capacity of the foam seemed to taper down and saturate after 2 hrs. Pb^{2+} removal capacity of the foam also seemed to decrease as the pH of the solution increases to 8.5. This may be due to the neutralization of sulfonic acid groups at higher pH levels which in turn diminishes the availability of functional groups for ion exchange. The foam seems to have a better Pb^{2+} removal capacity at lower pH values for the same reason.
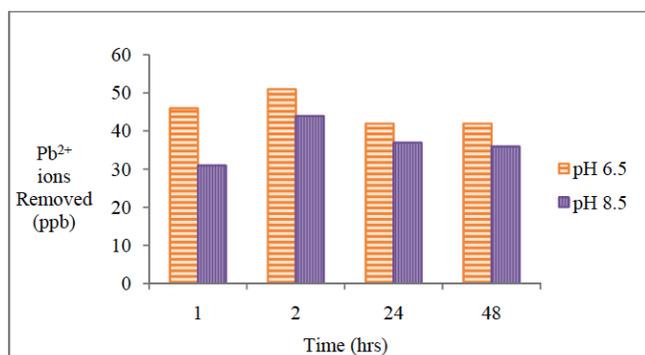

Figure 12: pH analysis of functionalized polyurethane foam.

As the research is ongoing, the foam system is being investigated to determine the effect of competing cations on the Pb^{2+} ion removal efficiency, flow through filtration system and regeneration techniques. The results will be reported in future publications.

SUMMARY AND CONCLUSIONS

Polyurethane foams containing PPG and TDI with sulfonic acid functional groups were synthesized using

BES chain extender dissolved in DMSO for Pb^{2+} ion removal from aqueous solutions. The maximum measured Pb^{2+} removal efficiency of the foam was between 42 – 47 ppb/g of the foam. The Pb^{2+} removal mechanism seemed to be due to the combination of adsorption and ion exchange mechanisms in the functionalized foam. To improve the Pb^{2+} ion removal efficiency another experiment was set up to simulate a multistage batch filtration process where multiple 1g foam samples were soaked in the same Pb^{2+} solution for a period of 30 minutes; consecutively. This increased the Pb^{2+} removal efficiency to 50-54 ppb. Thus, higher Pb^{2+} removal capacity can further be achieved by increasing the foam volume in a multi stage batch filtration set up. pH analysis of the foam showed reduction in its Pb^{2+} removal capacity at higher pH level due to neutralization of sulfonic acid groups which lowered the functional sites for ion exchange.

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