SYNTHESIS AND APPLICATION OF CYCLIC TETRAMERS CALIXRESORCINARENES, ALKOXYCALIXARENES, AND ALKENYLCALIXARENES SERIES FOR ADSORPTION OF HEAVY METAL CATIONS

Summary

Heavy metals are common pollutant found in various industrial effluents. The strict environment regulation on the discharge of heavy metals makes it necessary to develop various technologies for heavy metals removal. Waste streams containing low-to-medium level of heavy metals are often encountered in metal plating facilities, electroplating, mining operations, fertilizers, battery manufactures, dyestuffs, chemical pharmaceuticals, electronic device manufactures, and many others. Most heavy metals are highly toxic and are not biodegradable; therefore they must be removed from the polluted streams in order to meet increasingly stringent environmental quality standards.

Many methods including chemical precipitation, electro-deposition, ion exchange, membrane separation, and adsorption have been used to treat such streams of these industrial wastes. Traditional precipitation is the most economic but it is inefficient for dilute solution. Ion exchange and reverse osmosis are generally effective, but they have rather high maintenance and operation costs, and subject to fouling. Adsorption is one of the few promising alternatives for this purpose, especially using low-cost natural adsorbents such as zeolites (Barros *et al*., 2003), granular activated carbon (Dianati-Tilaki and Mahmood, 2004), fly ash (Li *et al*., 2002), and agricultural wastes {maize cob and husk (Igwe *et al.*, 2005), ground pine cone (Low *et al*., 1995), cassava waste (Abia *et al*., 2003)}. Unfortunately, knowing the active compound in natural adsorbents was not an

easy task, hence adsorption phenomena could not be explained satisfactorily. Therefore, new synthetic adsorbents should be developed to obtain an alternative adsorbent with a well-known structure.

Calixarenes are synthetic cyclic oligomers of aromatic residues linked by a bridge. This macromolecule has almost unlimited possibilities of modification, including the modification of type and number of aromatic residues, functional groups, and bridges. This family represents an interesting geometry that exhibits characteristic of cavity or basket shape. This shape allows calixarenes application in host-guest system. Various studies have illustrated their application as a host molecules for various guests, such as cations, anions, and molecules. The family of calixarene has been used for various utilities, namely as an additive in capillary electrophoresis (Britz-Mckibbin and Chen, 1998), liquid membrane, extraction (Jain *et al*., 2005), chemical sensing (Wei *et al*., 2001) and HPLC stationary phase. However, the usage of calixarenes as heavy metal adsorbent was rare.

The utility of calixarenes as adsorbent has been done with immobilization previously (Katz *et al*., 2002; Ohto *et al*., 2001; Li *et al*., 2002, and Sasaki *et al*., 2004). Various reports indicated that the use of calixarene as adsorbent without immobilization had not been done, since calixarene’s water solubility was extremely small, thus the calixarene only floated in water. Unfortunately, it was still needed intensive studies to conduct the immobilization. Therefore, the objective of calixarenes syntheses was to obtain a calixarene that could be used as adsorbent directly.

Calixarene could be synthesized through various ways. The most popular procedure was base-induced of phenol-derived calixarene using *para*-substituted phenol and formaldehyde. Meanwhile, acid-catalyzed procedure gave resorcinol-derived calixarene, which was prepared from resorcinol and aldehyde, and non-hidroxylic calixarene, which was synthesized from *para*-substituted benzylalcohol.

As heavy metals adsorbent, the calixarene must be insoluble in water. Though this requirement is similar with calixarene property that generally is insoluble in water, but previous studies showed that the most effective calixarene in metal ions binding was calixarene with very polar moieties, such as carboxyl, sulphonate, nitro, amino, and phosphate, which were reported to be water-soluble. Therefore, it was interesting to get water-insoluble calixarenes which formed effective complex with heavy metal ions.

There are two general strategies to synthesize water-insoluble calixarenes. Firstly, synthesis of calixarenes that do not have very polar moieties, but have moderate electron donating groups, i.e. hydroxyl, ether, esther, or alkenyl. Secondly, synthesis of calixarenes those have very polar moieties, with an adding of some non-polar groups as well so that calixarene's water solubility can be reduced. This type of synthesis includes polymerizing the calixarenes.

The effective interaction between adsorbent and adsorbate depends on the suitability of hard-soft acid-base properties (Moon *et al*., 2003), and size (Allen and Koumanova, 2005). Since the scope of the heavy metals studied covered hard acids, i.e. Cr(III), Cu(II), and soft acids, i.e. Hg(II), Ag(I), Cd(II), Pb(II), thus the synthesized calixarenes should possess both hard base groups (OH, RO^-, AcO^-, RNH_2) and soft base groups ($CH_2{=}CH_2$, C_6H_5). In addition, regarding the size of the studied heavy metals ions that have diameter of 1.28 – 2.6 Å, then the tetramer calixarenes were the right choice. Hamilton (2003) noted that the cavity size of calix[4]arene, calix[6]arene, and calix[8]arene were 3.0, 7.6, and 11.7 Å, respectively.

Considering some factors mentioned above, thus the scopes of calixarene synthesis were:

1. Synthesis of resorcinol-derived calix[4]arene or calix[4]resorcinarene, via acid-induced procedure of resorcinol with various aldehydes. The used aldehydes were acetaldehyde, 3-methoxybenzaldehyde, 4-hydroxybenzaldehyde, 4-hydroxy-3-methoxybenzaldehyde, 4-benzyloxybenzaldehyde, and 4-ethoxycarbonylmethoxybenzaldehyde.
2. Synthesis of calix[4]resorcinarene derivate via acetylation and Mannich reaction. Acetylation produced esther of acetate groups, whereas Mannich reactions with primary or secondary amine gave alkylamine groups.
3. Synthesis of tetraalkoxycalix[4]arene from 4-alkoxybenzylalcohol and $AlCl_3$.
4. Synthesis of phenol-derived calix[4]arene, i.e. 4-allylcalix[4]arene, and polymonoallyloxycalix[4]arene.

Based on literature studies toward various sources, it could be stated that the synthesized calixarenes, i.e. tetraethoxycalix[4]arene (TEK), tetramethoxycalix[4]arene (TMK), tetrabenzyloxycalix[4]arene (TBK), C-4-hydroxy-3-

methoxyphenylcalix[4]resorcinarene (CHMFKR), C-4-ethoxycarbonylmethoxyphenyl calix[4]resorcinarene (CEKMFKR), C-4-benzyloxyphenyl calix[4]resorcinarene (CBFKR), tetrakis (diethylaminomethyl) C-4-methoxyphenyl calix[4]resorcinarene (TDEACMFKR), N-propyloxazine C-4-methoxyphenyl calix[4]resorcinarene (NPOCMFKR), C-methyl calix[4]resorcinaryl acetate (CMKRAS), C-4-methoxyphenyl calix[4]resorcinaryl acetate (CMFKRAS), C-4-hydroxyphenyl calix[4]resorcinaryl acetate (CHFKRAS) and C-4-hydroxy-3-methoxyphenyl calix[4]resorcinaryl acetate (CHMFKRAS), haven’t been publicized, hence these calixarenes have a chance to be claimed as new calixarenes.

Moreover, the calixarenes utilized as adsorbent in this experiment had not been published as adsorbent either with or without immobilization. Therefore, C-4-methoxyphenyl calix[4]resorcinarene (CMFKR), C-4-hydroxyphenyl calix[4]resorcinarene (CHFKR), C-4-hydroxy-3-methoxyphenyl calix[4]resorcinarene (CHMFKR) and C-methyl calix[4]resorcinarene (CMKR) were considered as new heavy metals adsorbents, especially for Cr(III), Cu(II), Pb(II), Cd(II), Hg(II) and Ag(I).

In the first stage of this study, laboratory investigations were carried out to obtain adsorbents. Various calixarenes of calix[4]resorcinarene, alkoxycalix[4]arene, and alkenyl calix[4]arene series have been synthesized in poor, moderate, or excellent yields. All the synthesized calixarenes and their precursors were analyzed using IR spectrometer, GC-MS, ^{1}HNMR and/or

^{13}CNMR spectrometer. In the next stage, the selected calixarenes were subjected to heavy metals adsorption either in batch or fixed bed column system.

In batch system experiment, adsorption was done by shaking the adsorption sample containing of 10 mL of heavy metal solution and certain amount of calixarene (its particle size < 100 mesh) in certain period of time, concentration, and acidity level. The data obtained was compared and corrected with that given by blank solution. The amount of the metal adsorbed was calculated based on the differences between the concentration of the sample solution before and after adsorption experiments. The metal concentration was then determined by AAS.

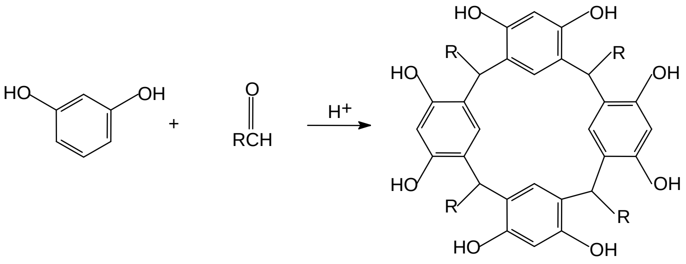
In fixed bed column system, calixarene (0.25 g, particle size is ≥ 100 and ≤ 200 mesh (0.011 - 0.023 mm)) was placed in a 10 cm x 0.5 cm glass column. The dry adsorbent filled column height up to 2.4 cm, and it has bed volume of 1.2 mL Metal solution in certain concentration and acidity level was passed through the column in down flow at a fixed flow rate. The solution that passed through the column was fractionated into 5 cm^3 portions, and the effluent concentration was determined by AAS.

In batch system, experiments were done in three conditions, i.e. variation of pH, shaking time, and mass of adsorbent. Besides to get an optimum condition of adsorption, the experiments were conducted to study the kinetics and the equilibrium of adsorption. The effect of interfering ions was investigated also in order to know the selectivity of the adsorbents. In fixed bed column system, experiments were conducted to establish breakthrough curve. Based on the breakthrough curve, column efficiency, adsorption capacity, some parameters of mass transfer (H_U, H_{UNB}, K_ca, k, and X_m), and adsorption kinetics were then determined. The effect of flow rate and concentration of the feeding solution was studied as well. Desorption process was done sequentially using water and followed by 1N HCl solution to recover the column and estimate the adsorption mechanism.

Synthesis of C-alkylcalix[4]resorcinarene from resorcinol with acetaldehyde, 4-methoxybenzaldehyde, 4-hydroxybenzaldehyde, and 4-hydroxy-3-methoxybenzaldehyde in the presence of acid produced four calixarenes, i.e. C-methyl calix[4]resorcinarene (CMKR), C-4-methoxyphenyl calix[4]resorcinarene (CMFKR), C-4-hydroxyphenyl calix[4]resorcinarene (CHFKR), and C-4-hydroxy-3-methoxyphenyl calix[4]resorcinarene (CHMFKR), respectively. These calixarenes were produced via one stage reaction. Based on their ^{1}HNMR spectrum, the resulted CMFKR and CHFKR were obtained as mixture of C_{4v} and C_{2v} conformations in ratios of either 3:2 or 1:1. This finding that was on calixresorcinarene with aromatic moieties in its bridge was in accordance with the results of the earlier work reported in the literature.

Other calixarenes in C-alkyl calix[4]resorcinarene series, i.e. C-4-benzyloxyphenyl calix[4]resorcinarene (CBFKR), and C-4-ethoxycarbonyl-methoxyphenyl calix[4]resorcinarene (CEKMFKR) were produced in two reaction stages. The first stage of their synthesis route were benzylation of 4-hydroxybenzaldehyde at 80°C for 2 hours which gave 4-benzyloxybenzaldehyde in 63.60%, and alkylation of 4-hydroxybenzaldehyde with ethyl 2-chloroacetate in

78^{o}C for 3.5 hours which gave 4-ethoxycarbonylmethoxybenzaldehyde in 78.27%. The second stage was cyclotetramerization that gave the desired calixarene. The six calixarenes of this series have very poor solubility in water, but they have very good distribution in water (except CBFKR). The reactions condition and the results were shown in Figure S.1.



1

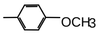
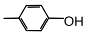
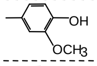
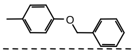
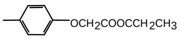
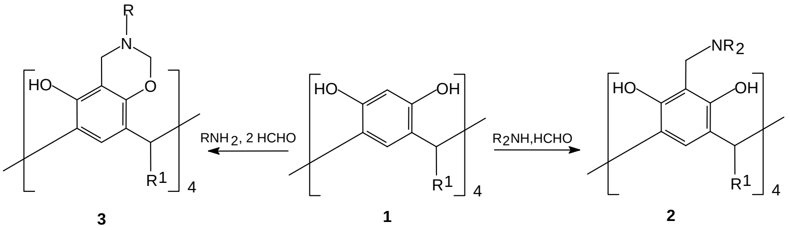
CALIXARENES	R	REACTION CONDITION	PRODUCT
CMKR	CH_3	15^{o}C 30 min,50^{o}C 1 hours, 30^{o}C 4 days	85.00%(C_{4v} :C_{2V} = 9:1)
CMFKR		78^{o}C, 24 hours	90.35%(C_{4v}:C_{2V} = 3:2)
CHFKR		78^{o}C, 24 hours	93.45%(C_{4v}:C_{2V} =1:1)
CHMFKR		78^{o}C, 24 hours	98.36%
CBFKR		78^{o}C, 20 hours	62.27%
CEKMFKR		78^{o}C, 15 hours	95.59%

Figure S.1 C-alkyl calix[4]resorcinarene series

In aminomethylcalix[4]resorcinarene series, it has been synthesized five calixarenes, namely tetrakis(diethylamino)methyl C-methyl calix[4]resorcinarene (TDEACMKR), tetrakis(dimethylamino)methyl C-methyl calix[4]resorcinarene (TDMACMKR), N-propyloxazine C-methyl calix[4]resorcinarene (NPOCMKR), tetrakis(diethylamino)methyl C-methoxyphenyl calix[4]resorcinarene (TDEA-CMFKR), and N-propyloxazine C-methoxyphenyl calix[4]resorcinarene (NPO-CMFKR). The first three calixarenes were synthesized through Mannich reaction toward CMKR, and the rest were synthesized toward CMFKR. Compounds of

TDEACMKR, TDMACMKR, and NPOCMKR were water-soluble calixarenes, but TDEACMFKR and NPOCMFKR possessed lower water solubility. The condition of reactions and the results were shown in Figure S.2.



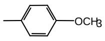
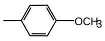
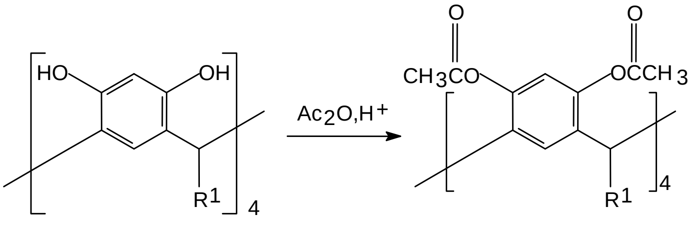
CALIXARENES	R	R^1	REACTION CONDITION	PRODUCT
TDEACMKR	CH$_2$CH$_3$	CH$_3$	30^{o}C, 28 hours	88.23 %
TDMACMKR	CH$_3$	CH$_3$	30^{o}C, 20 hours	35.26%
NPOCMKR	CH$_2$CH$_2$CH$_3$	CH$_3$	70^{o}C, 14 hours	42.46%
TDEACMFKR	CH$_2$CH$_3$		60^{o}C, 4 hours	36.58%
NPOCMFKR	CH$_2$CH$_2$CH$_3$		60^{o}C, 1 hours	37.86%

Figure S.2 Amino calix[4]resorcinarene series

Acetylations of CMKR, CMFKR, CHFKR, and CHMFKR with acetic anhydride produced C-methyl calix[4]resorcinaryl octaacetate (CMKRAS), C-4-methoxyphenyl calix[4]resorcinaryl octaacetate (CMFKRAS), C-4-hydroxyphenyl calix[4]resorcinaryl dodecaacetate (CHFKRAS), C-4-hydroxy-3-methoxyphenyl calix[4]resorcinaryl dodekaacetate (CHMFKRAS), respectively. All of the calixarenes in calix[4]resorcinaryl acetate series were insoluble in water, but they had very good distribution in water. The condition of reactions and the results were shown in Figure S.3.



1 4

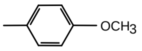
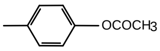
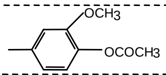
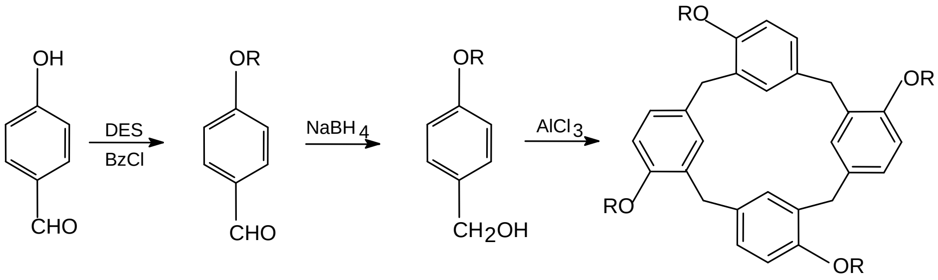
CALIXARENE	R1	REACTION CONDITION	PRODUCT
CMKRAS	CH_3	60^{o}C, 30 min	64.32%
CMFKRAS		60^{o}C,1.5 h	40.28%
CHFKRAS		60^{o}C, 1 h	87.59%
CHMFKRAS		60^{o}C, 1.5 h	61.80%

Figure S.3 Calix[4]resorcinaryl acetate series

In alkoxycalix[4]arene series, it has been synthesized three calixarenes, namely tetraethoxycalix[4]arene (TEK), tetrabenzyloxycalix[4]arene (TBK), and tetramethoxycalix[4]arene (TMK). These calixarenes were produced via alkoxy-benzylalcohol route, which consisted of two or three reaction stages, i.e. alkylation of 4-hydroxybenzaldehyde, reduction of 4-alkoxybenzaldehyde, and cyclotetramerization of 4-alkoxybenzylalcohol. The reactions condition and the results of each stage were shown in the scheme as follows.



5

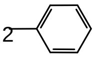
R	condition	product	condition	product	condition	product	calixarene
CH_2CH_3	93^{o}C, 2.5 hours	76.28%	78^{o}C, 3 hours	95.50%	20^{o}C, 2 hours	67.78%	TEK
CH_2 	80^{o}C, 2 hours	63.60%	78^{o}C, 3 hours	81.80%	20^{o}C, 3 hours	90.31%	TBK
CH_3			78^{o}C, 3 hours	83.36%	78^{o}C, 3 hours	92.69%	TMK

Figure S.4 Alkoxycalix[4]arene series

Synthesis of 4-allylcalix[4]arene (AKA) via methyl salicylate route did not work very well. The failure happened at reduction of methyl-2-allyloxybenzoate stage. Nonetheless, AKA has been synthesized through 4-*t*-buthylphenol route that consisted of four stages. This compound was insoluble in water and had very poor distribution in water.

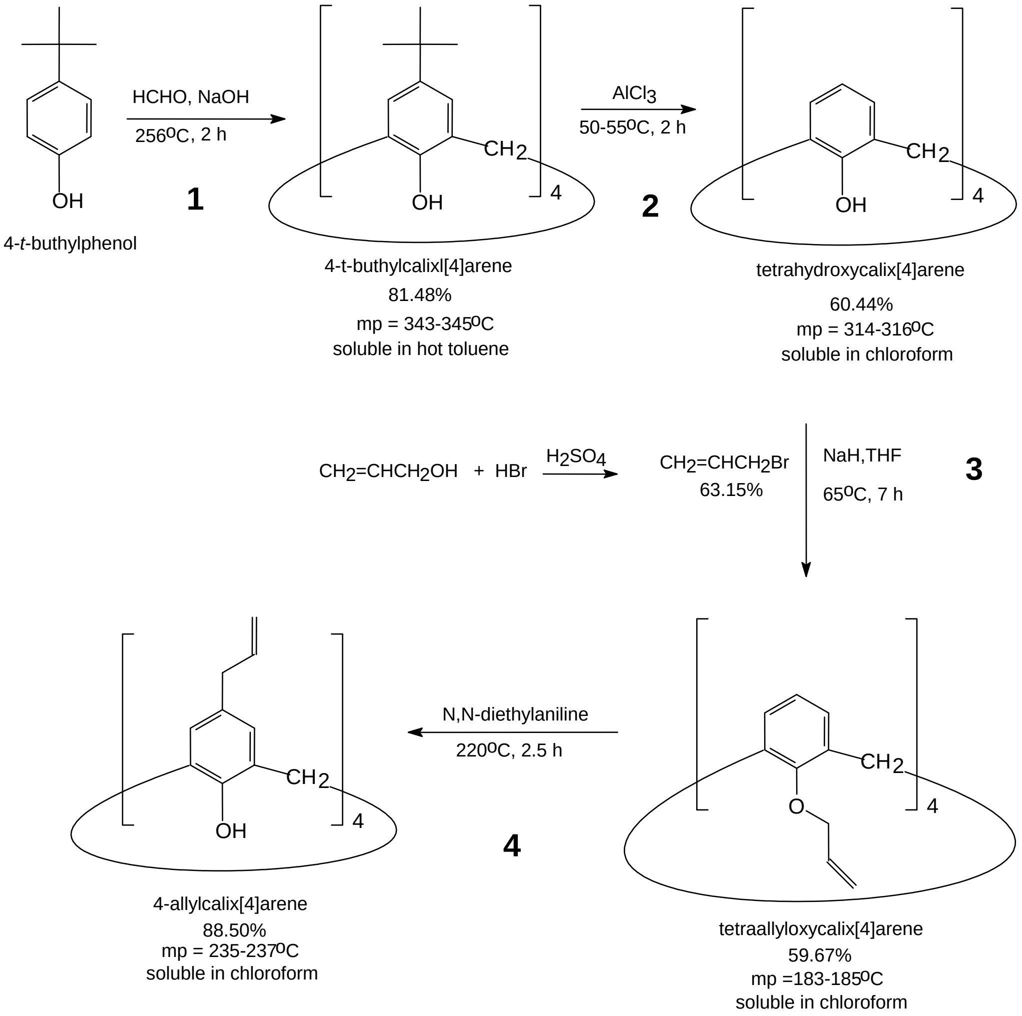


Figure S.5 Reaction routes AKA synthesis

In reaction routes of polymonoallyloxycalix[4]arene (PMAKA) synthesis, five precursors calixarenes have been synthesized, namely 4-*t*-buthylcalix[4]arene, tetrahydroxycalix[4]arene, tribenzoyloxycalix[4]arene, tribenzoyloxymonoallyloxycalix[4]arene, and monoallyloxycalix[4]arene, but PMAKA itself has not been synthesized. The conditions and results of each reaction stage were shown in the following scheme.

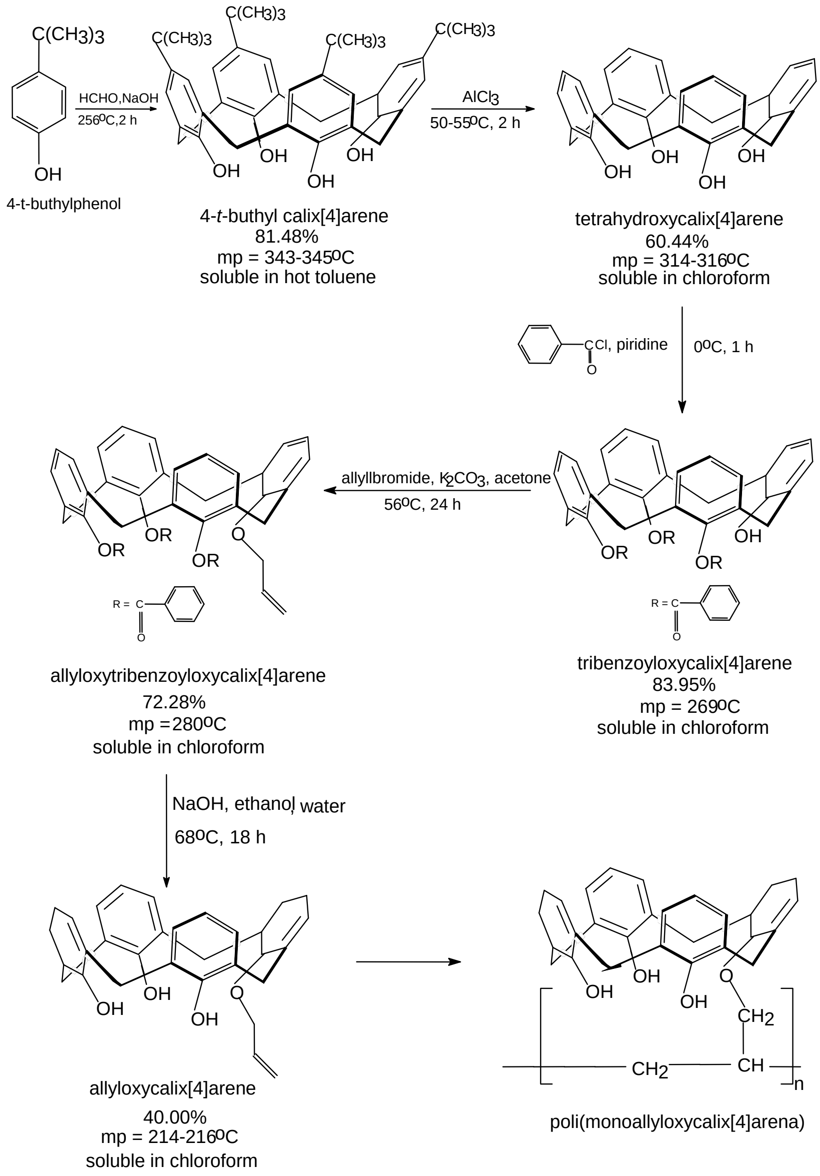


Figure S.6 Reaction routes of polymonoallyloxycalix[4]arene (PMAKA) synthesis

In order to acquire competitive adsorbents, it was then selected some calixarenes from the synthesized calixarenes. The criteria of the chosen adsorbents were water-insoluble but had very good distribution in water, and had low production-cost indicated by short reaction route and high yield. Resultantly, four calixarenes, i.e. CMFKR, CHFKR, CHMFKR, and CMKR had priority to be the adsorbents than the others.

The experiments in batch system investigated that acidity level affected significantly the adsorption percentage of Cr(III), Cu(II), Pb(II), Cd(II), Hg(II) and Ag(I) onto CMFKR, CHFKR, CHMFKR and CMKR. At very acidic condition (pH<4) or relatively basic condition (pH>6), the adsorptions gave low amount in adsorption percentage, but at moderate acidity level (4<pH<6), the adsorptions reached their optimum condition. This fact indicated that at high acidity level, protonation of most donating groups occurred, but at relatively low acidity level, it was deposition process that happened since water-solubility of adsorbent was getting higher.

Adsorption index of acidity level indicated that the differences of pH values caused the differences of adsorption percentages significantly. Therefore, best adsorption needs a pH control tightly. The increase of pH value happened in accordance with the adsorption, and the pH value increased as the adsorption percentage increased. This fact supported that the predominant species adsorbed was M^{n+}. Generally, in water, most metals are hydrolyzed as the reaction follows:

$$M^{n+} + H_2O \rightleftharpoons M(OH)_m^{(n-m)+} + H^+$$

If M^{n+} is taken up by adsorbent, the reaction above will shift to the left, leading to the depletion of protons and, hence, a rise in pH.

Adsorption index of shaking time showed that generally the differences of shaking times caused no difference of adsorption percentage significantly. Kinetics studies of Lagergren pseudo first order and Ho pseudo second order kinetic models showed that all of the studied adsorptions followed pseudo second order model kinetics. The highest rate constant was showed by the adsorption of Ag(I) onto CHFKR. It was possibly due to the best size suitability and the characteristic of the adsorbent which had abundant hydroxyl groups.

Adsorption index of adsorbent dose indicated that the differences of adsorbent doses affected the adsorption percentage insignificantly. The equilibrium data of the adsorption studied were analyzed by using Langmuir, Freundlich, and D-R **(**Dubinin-Radushkevich**)** isotherms. The experimental data were found to fit well on Freundlich and D-R isotherm models. The highest value of X_m (maximum adsorption capacity) calculated by D-R isotherm equation was given by the adsorption of Cr(III) onto CHMFKR. Among all of the studied adsorbate and adsorbent, Cr(III) had characteristic as the hardest acid, and CHMFKR as the hardest base.

Based on their hard-soft acid-base properties, CHMFKR, CHFKR and CMKR were known to be the adsorbents with almost similar characteristic, thus, they adsorbed the heavy metals unselectively. The adsorption capacity would decrease to some greater extent as the increase of the interfering ion concentration and the ion type resemblance, which was considered from the hard-soft acid-base character.

The adsorption Pb(II) onto CMFKR, CHFKR, CHMFKR and CMKR has been conducted in fixed bed column system. It was found that Pb(II) was adsorbed completely (about 100%) at some early fractions until about 14, 4, 3, and 6 fractions or 58, 17, 13, and 25 bed volume (BV) using CMFKR, CHFKR, CHMFKR and CMKR adsorbents, respectively. The column test also presented that the amount of Pb(II) adsorption capacity (q_e) onto CMFKR was 4.17 mg/g. The order of adsorption capacity of Pb(II) onto those four adsorbents was as follows: CMFKR > CMKR > CHMFKR > CHFKR.

Breakthrough curves showed that breakpoint (t_b) occurred at the increasing bed volume (BV) as in the adsorbents order of CHMFKR < CHFKR < CMKR < CMFKR. However, the smallest difference value between exhausted point (t_e) and t_b happened at the adsorption of Pb(II) onto CHFKR, and this difference value was getting higher as in the order of CMKR < CHMFKR < CMFKR. Therefore, the adsorption of Pb(II) onto CMFKR produced the biggest adsorption capacity, but it consumed the highest operational cost as well. The breakthrough curves also indicated that the highest column operation efficiency happened when the column was operated until 50% BT zone.

Some of mass transfer parameters, i.e. the length of used bed (H_U), coefficient of mass transfer (K_ca), and Thomas rate constant (k) gave their highest value on Pb(II) adsorption onto CHFKR. However, the biggest maximum adsorption capacity (X_m) value calculated by Thomas equation was again given by the adsorption of Pb(II) onto CMFKR, which it suited the experiment results.

The increase of flow rate shifted the breakthrough curve; the t_b happened at shorter value and the t_e occurred at longer value, but it has no significant effect in q_e value. Whereas, the increase of the inlet concentration shifted the breakthrough curve with similar pattern that was the t_b happened at shorter value and the t_e occurred at longer value. Nevertheless, the increasing of the inlet concentration increased the q_e value significantly.

Adsorption of Pb(II) onto CMFKR or CHMFKR followed pseudo second order kinetics model, and the adsorption rate of Pb(II) onto CHMFKR was faster than onto CMFKR. Whereas, the adsorption of Pb(II) onto CHFKR or CMKR conformed with pseudo first order kinetics model, and the adsorption rate of Pb(II) onto CHFKR was faster than onto CMKR.

The sequential desorption was conducted by using aquades and 1M HCl solution to recover the column. Generally, aquades leached Pb(II) poorly, whereas 1 M HCl solution leached Pb(II) completely, except for Pb(II) desorption from CHFKR. Based on the desorption test, adsorptions of Pb(II) onto CMFKR, CHFKR, CHMFKR and CMKR were dominated by chemisorptions (about 90%), both via ion exchange and hydrogen bond mechanism. On the contrary, physisorptions ruled adsorption in little portions (less than 10%). Especially for Pb(II) adsorption onto CHFKR, there was 30% of adsorption mechanism estimated via unknown mechanism (possible chelate formation).

The power of desorption agent to liberate Pb(II) was decreased in the order of CMFKR < CMKR < CHMFKR < CHFKR. This fact indicated that the interaction of Pb(II) onto CHFKR was the strongest one, although the amount of Pb(II) adsorbed was the lowest.

According to the experiment results, whether in batch or fixed bed column system, it could be generalized as follows. The parameter of adsorption equilibrium result, i.e. adsorption capacity, was determined by the suitability of hard-soft acid-base character. On the contrary, the parameters of kinetics adsorption process, such as adsorption rate, mass transfer coefficient, and adsorption mechanism, were affected by the suitability of size between adsorbent and adsorbate, and the existence of hydroxyl group, which was strong electron donating (strong base).