

# REFERENCES

- [1] James J. Spivey. Recovery of volatile organic from small industrial source. *Environmental Progress*, 7(1):31-40, 1988.
- [2] M. John Ruhl. Recover vocs via adsorption on activated carbon. *Chemical Engineering Progress*, 89(7):37-41, 1993.
- [3] Chang-HaLee, Sang Hoon Byeon, and Gerald D. Holder. Adsorption characteristics of toluene and naphthalene on silica gel under the subcritical and supercritical conditions using chromatographic techniques. *Journal of Chemical Engineering of Japan*, 29(4), 1996.
- [4] F.B. Carleton, L.S. Kershenbaum, and W.A. Kakeham. Adsorption in non-isobaric fixed-beds. *Chem.Eng.Sci*, 33:1239-1246, 1978.
- [5] P. Schneider and J.M. Smith. Adsorption rate constants from chromatography. *AIChE J.*, 14:762-771, 1968.
- [6] Motoyuki Suzuki. *Adsorption Engineering*. Kodansha Ltd., 1990.
- [7] Charles W. Chesterman. Perlite. *Industrial Minerals and Rocks*, 1978.
- [8] R.E. Barnes. *Perlite Industry*, volume 220. Tran. SME/AIME, 1961.

- [9] Harold J. Schroeder. Pumice. *Mineral Facts and Problems*, pages 1171–1178, 1970.
- [10] S. Lowell. *Introduction to powder surface area*. John Wiley & Sons, New York, 1979.
- [11] A.E. Rodrigues, M.D. Levan, and D. Tondeur. *Adsorption: Science and Technology*, volume 158. Kluwer Academic Publishers, 1989.
- [12] C.L. Mantell. *Adsorption*. Mc Graw-Hill, 1951.
- [13] Douglas M. Ruthven. *Principles of Adsorption and Adsorption Processes*. John Wiley & Sons, Inc., 1984.
- [14] P.W. Atkins. *Physical Chemistry*, 4<sup>th</sup> ed. Oxford University Press, 1990.
- [15] H.W. Haynes and P.N. Sarma. Model for the application of gas chromatography to measurements of diffusion in bidisperse structured catalysts. *AIChE J.*, 19:1043–1046, 1973.
- [16] R. Byron Bird, Warren E. Stewart, and Edwin N. Lightfoot. *Transport Phenomena*. John Wiley & Sons, Inc., 1976.
- [17] Ralph E. Grim. *Clay Mineralogy*, 2<sup>nd</sup> ed. McGRAW-HILL Book Company, 1968.
- [18] C.S. Ross and E.V. Shannon. Minerals of bentonite and related clays, and their physical properties. *J. Am. Ceram. Soc.*, 9:77–96, 1926.

- [19] C.S. Ross. The mineralogy of clays. *Soil Sci.*, 4:555–556, 1928.
- [20] H. van Olphen. *An Introduction to Clay Colloid Chemistry*. Interscience, 1963.
- [21] Robert H. Perry, Don W. Green, and James O. Maloney. *Perry's Chemical Engineers' Handbook*, 6<sup>th</sup> ed. McGraw - Hill Book Company, 1984.



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# Appendix A

## Clay and Analysis method

### A.1 Definition of Clay

Clay is used as a rock term and also as a particle-size term in the mechanical analysis of sedimentary rocks, soils, etc. As a rock term it is difficult to define precisely, because of the wide variety of materials that have been called clays. In general the term clay implies a natural, earthy, fine-grained material which develops plasticity when mixed with a limited amount of water. By plasticity is meant the property of the moistened material to be deformed under the application of pressure, with the deformed shape being retained when the deforming pressure is removed. Chemical analyses of clays show them to be composed essentially of silica, alumina, and water, frequently with appreciable quantities of alkalis and alkaline earths.

The term clay has no genetic significance. It is for material that is the product of weathering, has formed by hydrothermal action, or has been deposited as a sediment. As a particle-size term, the clay fraction is that size fraction composed of the smallest particles. The maximum size of particles in the clay size

grade is defined differently in different disciplines. The term "clay" is here applied to the finely divided crystalline material. In soil science the term "clay" is often used for the soil fraction with an equivalent Stokes diameter  $< 2\mu$  [18].

So, it is convenient to use the expression clay material for any fine-grained, natural, earthy, argillaceous material.

## A.2 Composition of Clay Material

In 1924 the U.S. Geological Survey began a study of the mineral composition of clays that led to a series of monumental papers on the subject. Working particularly with bentonites at first, but within a few years with a variety of clays used in industry and a variety of soils, it was shown, on the basis of extremely careful and painstaking optical work with a petrographic microscope supplemented by excellent chemical data, that the components of clay materials were largely essentially crystalline and that there was a limited number of such crystalline components, to which the name clay minerals was applied. A classification of the clay minerals was suggested [19].

According to the clay-mineral concept, clays generally are essentially composed of extremely small crystalline particles of one or more members of a small group of minerals which have come to be known as the clay minerals. The clay minerals are essentially hydrous aluminum silicates, with magnesium or iron proxying wholly or in part for the aluminum in some minerals and with alkalis or alkaline earths present as essential constituents in some of them. Some clays are

composed of a single clay mineral, but in many there is a mixture of them.

### A.3 Classification of Clay Minerals

The classification of clay minerals have been discussed both nationally and internationally for many years. At the present time, suggested the classification shown as below. It is based distinctions on the shape of the clay minerals and the expandable or nonexpandable character of the 2:1 and 1:1 layer silicates.

#### 1. Amorphous

- Allophane group

#### 2. Crystalline

2.1. Two-layer type (sheet structure composed of units of one layer of silica tetrahedrons and one layer of alumina octahedrons)

2.1.1. Equidimensional such as Kaolinite group (e.g. Kaolinite, nacrite)

2.1.2. Elongate (e.g. Halloysite group)

2.2. Three-layer types (sheet structures composed of two layers of silica tetrahedrons and one central dioctahedral or trioctahedral layer)

2.2.1. Expanding lattice

2.2.1.1. Equidimensional such as Montmorillonite group (e.g. Montmorillonite, sauconite, Vermiculite)

2.2.1.2. Elongate such as Montmorillonite group (e.g. Nontronite, saponite, hectorite)

2.2.2. Nonexpanding lattice such as Illite group

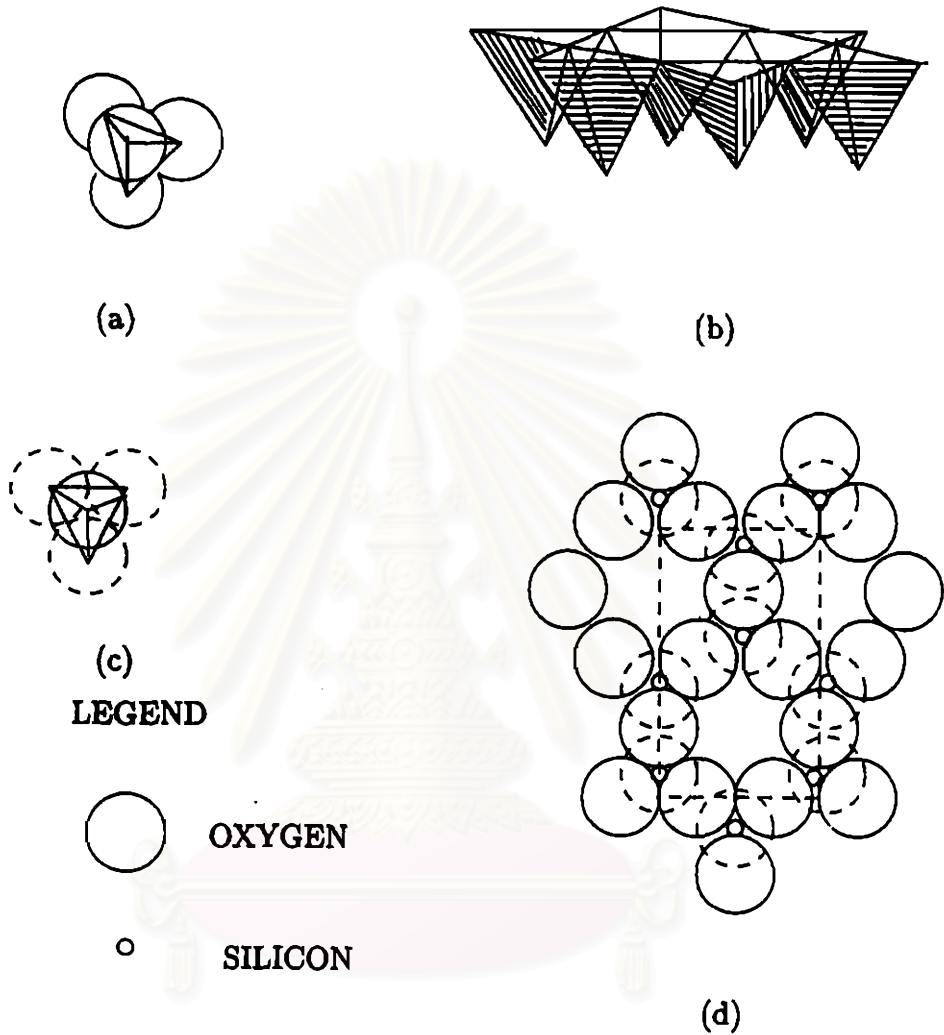
2.3. Regular mixed-layer types (ordered stacking of alternate layers of different types such as Chlorite group)

2.4. Chain structure types (hornblende-like chains of silica tetrahedron linked together by octahedral groups of oxygens and hydroxyls containing Al and Mg atoms such as Attapugite, Sepiolite, Palygorskite)

## A.4 Principle of Structure

The principle building elements of the clay minerals are two-dimensional arrays of silicon-oxygen tetrahedra and two-dimensional arrays of aluminum- or magnesium-oxygen-hydroxyl octahedra. In most clay minerals, such sheets of tetrahedra and of octahedra are superimposed in different fashions.

In the silicon-oxygen sheets, the silicon atoms are coordinated with four oxygen atoms. The oxygen atoms are located on the four corners of a regular tetrahedron with the silicon atom in the center Figure A.1(a). In the sheet, three of the four oxygen atoms of each tetrahedron are shared by three neighboring tetrahedra. The fourth oxygen atoms of each tetrahedron is pointed downward in the sketched arrangement in Figure A.1(b). Projections of this arrangement are shown in Figure A.1(c) and (d). These figures demonstrate the hexagonal symmetry of such a sheet, in which rings of six oxygen atoms appear. The holes in



(a) Tetrahedral arrangement of Si and O

(b) Perspective sketch of tetrahedron linking

(c) Projection of tetrahedron on plane of sheet

(d) Top view of tetrahedral sheet

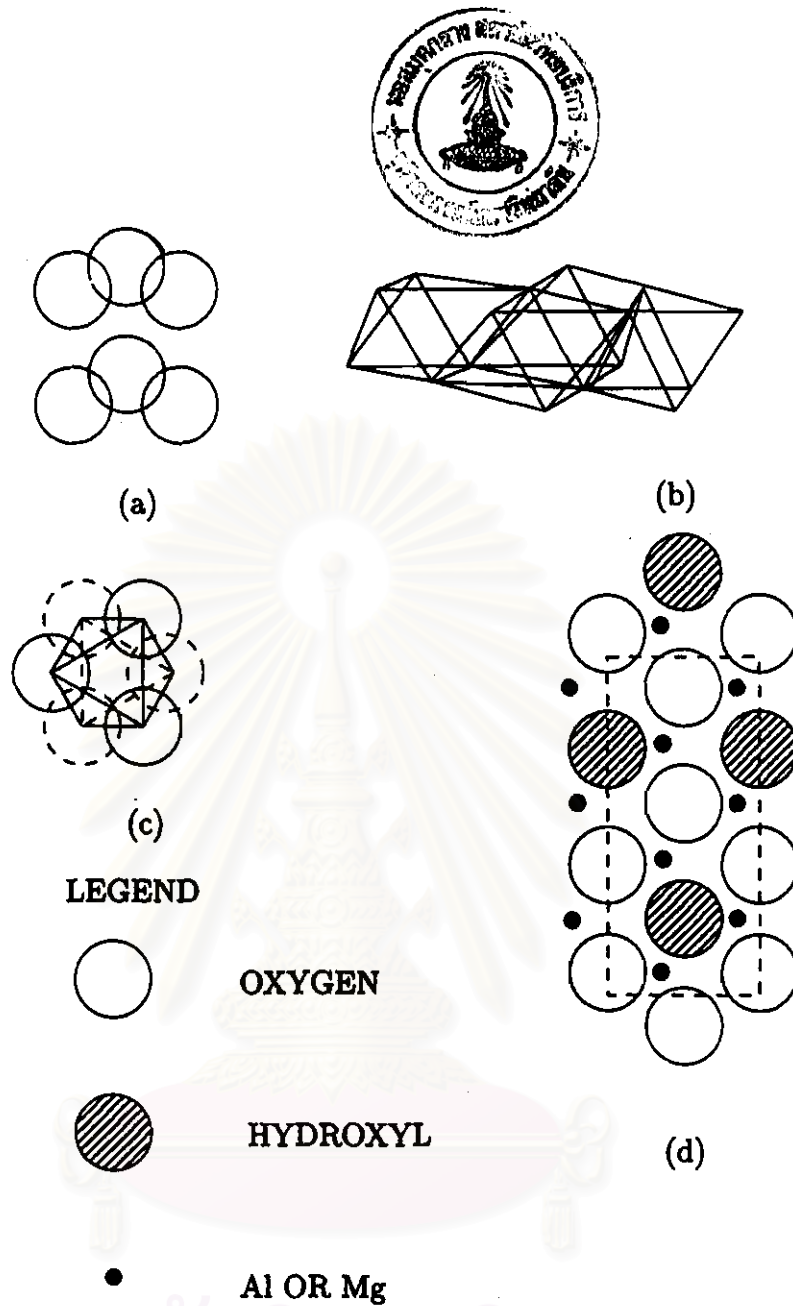
Figure A.1: Structure of the tetrahedral sheet



these rings are clearly visible in the picture of a three-dimensional model sketched in Figure A.3(a). The silicon-oxygen sheet is called the tetrahedral sheet or the silica sheet.

In the Al-, Mg-O-OH sheets, the Al or Mg atoms are coordinated with six oxygen atoms or OH groups which are located around the Al or Mg atom with their centers on the six corners of a regular octahedron Figure A.2(a). The sharing of oxygen atoms by neighboring octahedrons results in a sheet such as that shown in perspective in Figure A.2(b). The oxygen atoms and hydroxyl groups lie in two parallel planes with Al or Mg atoms between these planes. The projection of the sheet Figure A.2(d) shows that the oxygen atoms and hydroxyl groups form a hexagonal close packing. This sheet is called the octahedral sheet or the alumina or magnesia sheet, also called gibbsite layer or brucite layer respectively. A three-dimensional model is shown in Figure A.3(b).

The analogous symmetry and the almost identical dimensions in the tetrahedral and the octahedral sheets allow the sharing of oxygen atoms between these sheets. The fourth oxygen atom protruding from the tetrahedral sheet is shared by the octahedral sheet. This sharing of atoms may occur between one silica and one alumina sheet, as is the case in the so-called two-layer minerals. In the three-layer minerals, one alumina or magnesia sheet shares oxygen atoms with two silica sheets, one on each side. The combination of an octahedral sheet and one or two tetrahedral sheets is called a unit layer. Most clay minerals consist of such unit



- (a) Octahedral arrangement of Al or Mg with O or OH  
 (b) Perspective sketch of octahedron linking  
 (c) Projection of octahedron on plan of sheet  
 (d) Top view of octahedral sheet

Figure A.2: Structure of the octahedral sheet

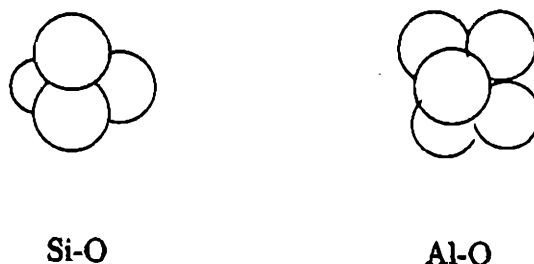


Figure A.3: Model of silicon-oxygen tetrahedron and aluminum-oxygen octahedron

layers, which are stacked parallel to each other.

Within each unit layer a certain unit of structure repeats itself in a lateral direction. For easy reference, this unit structure will be called the unit cell in the following discussion. However, the crystallographically defined unit cell extends from a certain plane in one unit layer to the corresponding plane in another parallel unit layer of the crystal. In this way, the features of the geometry of stacking of unit layers are included.

A schematic representation of the atom arrangements in a "unit cell" is shown in Figure A.4 for a two-layer clay and in Figure A.5 for a three-layer clay. The latter structure is usually referred to as the Hofmann structure. In these figures the atoms are not designed to scale in order to show the arrangement of the atom bonds. However, the scale model Figure A.3(a) and (b) give an indication of the packing of the atoms in the lattice.

The dimensions of the unit cell ( $a_0 \sim 5.15 \text{ \AA}$ ;  $b_0 \sim 8.9 \text{ \AA}$ ) determined from the X-ray diffraction patterns.

The neutral three-layer structure of Figure A.5 represents the structure of the

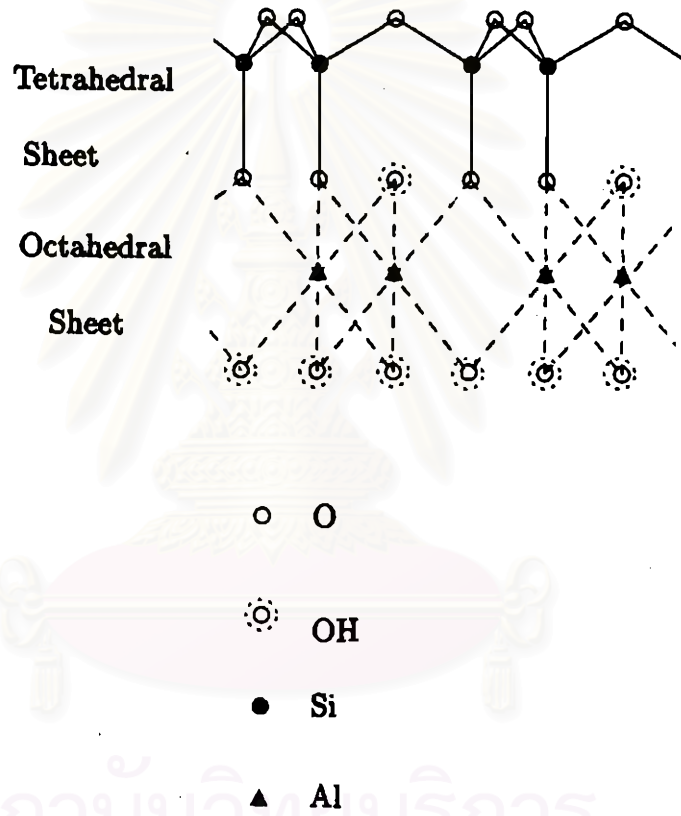


Figure A.4: Atom arrangement in the unit cell of a two-layer mineral

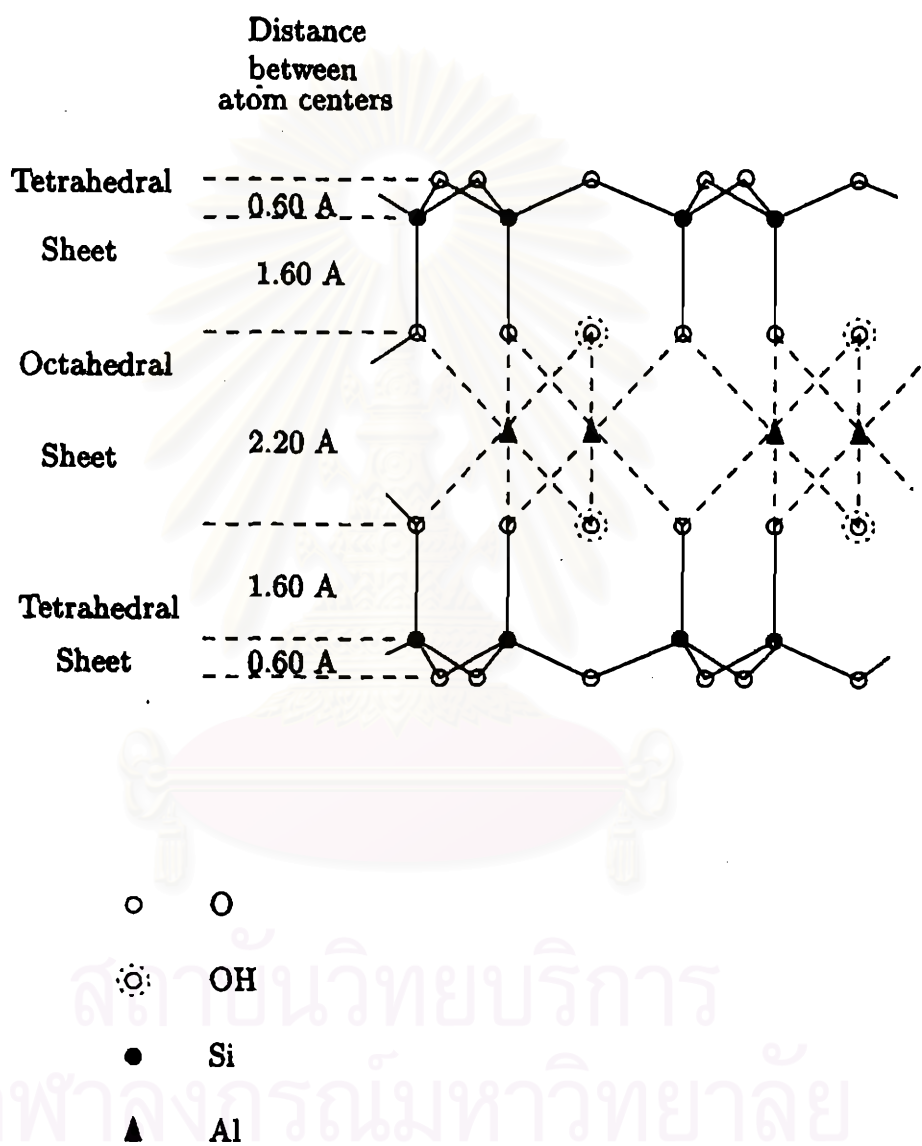


Figure A.5: Atom arrangement in the unit cell of a three-layer mineral

mineral pyrophyllite. Since in this mineral two of the three possible octahedral positions are occupied by trivalent Al, this structure is called dioctahedral. If the three octahedral positions are filled by three divalent Mg atoms, the electroneutral structure of the mineral talc is represented. This arrangement is called trioctahedral.

#### A.4.1 Formation of montmorillonite

Conditions leading to the formation of montmorillonite contrast with those under which kaolinite is developed. It is expected that the chemical system in which montmorillonite is formed will be characterized by a high Si:Al ratio, and a small amount of Mg, Fe, Ca, Na, and K. In terms of parent material, mafic rocks and volcanic ash of intermediate composition, which are relatively rich in Mg, Fe, and Ca, supply the cations which occur between the O-Si-Al sheets of montmorillonite clay minerals, and therefore are more likely to alter to montmorillonite than to kaolinite. Furthermore, the divalent cations tend to flocculate silica and thus tend to retain the high Si:Al ratio in montmorillonite.

The climate of the weathering environment and the efficiency of drainage are just as important as parent material in the following ways. If the climate is semi-arid (i.e., precipitation less than potential evaporation) hydrolysis of the silicate occurs while it is wet, but as drying ensues, the solution of cations originally dilute becomes saturated with respect to Mg, Ca, Fe, Na, etc., and their combination with O-Si-Al during drying can develop montmorillonite.

Thus, by utilization of the divalent ions in the ground water even granitic rocks (rich in K and Na, but typically in Ca) can alter to montmorillonite in a semi-arid climate, whereas if rainfall on them had exceeded evaporation they would have given rise to kaolinite. At the other extreme in climate, excess of rainfall over evaporation, if the drainage is poor so that the concentration of Mg, Ca, etc., builds up, the chemical system again produces montmorillonite. Hence, the interplay of materials and energy governs the precise product formed, and climate and material are descriptive of the process and product only to the degree of precision with which they describe the chemical system.

#### **A.4.2 Structure of Montmorillonite**

The structure of the minerals of the montmorillonite group of clay minerals is derived from that of the prototypes pyrophyllite and talc by substitution of certain atoms for other atoms. The following types of atom substitutions have been observed in representative minerals of this group.

In the tetrahedral sheet, tetravalent Si is sometimes partly replaced by trivalent Al. In the octahedral sheet, there may be replacement of trivalent Al by divalent Mg without complete filling of the third vacant octahedral position. Al atoms may also be replaced by Fe, Cr, Zn, Li, and other atoms. The small size of these atoms permits them to take the place of the small Si and Al atoms.

## Size and Shape of Clay

A serious difficulty in the evaluation of particle size is that natural samples always contain particles of a wide range of sizes, even after the sample is fractionated by sedimentation in a centrifuge by which the size range is only narrowed. Therefore, with the various technique, only an average value for the dimensions is obtained, depending on different methods.

## Surface Area of Clay

For clays with platelike particles, the total surface area per gram of clay, including each side of such unit layer in the stack, may be computed from unit-cell dimensions and from the unit-cell weight [20]. In Montmorillonites, this unit-layer surface area per gram of clay represents both the external and the internal surface areas which are accessible to adsorb organic molecules. This total surface area is as high as  $800 \text{ m}^2/\text{g}$ .

The total external area of the flat part of the surface per gram of clay is found by dividing the total unit-layer surface area by the number of unit layers which are stacked in the particle. This number derived from the thickness of the particle.

The total edge surface area per gram of clay would be computed if the diameter of the particles is known from a direct method. The direct method for the determination of the surface area of a powdered solid from the adsorption isotherm for a vapor on the solid has been developed by Brunauer, Emmett, and



Teller. When the data are plotted in a certain way (the "BET" plot), the weight of gas or vapor may be determined at which the surface of the solid is covered with a monomolecular layer of the vapor. Since the surface area which is covered by one molecule of the vapor is known the surface area can be computed from the weight of the monolayer. The surface area per molecule is obtained by calibration using different types of solids with samples of known surface area. Vibrations of surface area per molecule with different types of solids are observed, and the value applied in the BET evaluation is an average value.

Commonly, nitrogen gas is used in the routine BET method. When applied to clay, the total external surface area per gram of clay including the edge surface area is determined. This is also true for Montmorillonites since the nitrogen molecules do not penetrate between the layers.

## A.5 Calculation

### A.5.1 Concentrations of Toluene and Acetone Vapors.

The concentrations of toluene and acetone vapors are calculated from the ratio of vapor pressure and total pressure of the system.

The adsorbate concentration were sufficiently low that the equilibrium relationship between the gas and adsorbed phase concentrations could be assumed linear.

#### Toluene vapors,

$$\begin{aligned}
 \text{Vapor pressure of toluene at } 30^{\circ} \text{ C [21].} &= 37.31 \text{ mmHg} \\
 \text{Total pressure} &= 760 \text{ mmHg} + 1.33 \text{ mmHg} \\
 &= 761.33 \text{ mmHg} \\
 \text{Hence, mole fraction} &= \frac{37.31}{761.33} \\
 &= 0.049
 \end{aligned}$$

#### Acetone vapors,

$$\begin{aligned}
 \text{Vapor pressure of toluene at } 30^{\circ} \text{ C [21].} &= 286.90 \text{ mmHg} \\
 \text{Total pressure} &= 760 \text{ mmHg} + 1.58 \text{ mmHg} \\
 &= 761.58 \text{ mmHg} \\
 \text{Hence, mole fraction} &= \frac{286.90}{761.58} \\
 &= 0.377
 \end{aligned}$$

## A.6 Approximated Concentration in column

$$\begin{aligned}
 \text{Average minimum flowrate} &= 10 \text{ ml/min} \\
 \text{Amount of the injection} &= 50 \mu\text{l} \\
 \text{Time of the injection} &= 2 \text{ sec} \\
 \text{Volume of carrier gas within 2 sec} &= 0.33 \text{ ml} \\
 \text{Amount of acetone in } 50 \mu\text{l} &= 0.37/50 \\
 &= 0.0074 \text{ ml} \\
 \text{Percent by volume of acetone} &= 0.0074/0.33 \\
 &= 0.022 \\
 \text{Amount of toluene in } 50 \mu\text{l} &= 0.049/100 \\
 &= 0.0049 \text{ ml} \\
 \text{Percent by volume of toluene} &= 0.0049/0.33 \\
 &= 0.0148
 \end{aligned}$$

## A.7 Adsorption equilibrium constants

### A.7.1 Calculation of Adsorption equilibrium Constants

The first absolute moment,  $t_R$  characterizes the position of the center of gravity of the chromatogram. For linear isotherm system, first moment data give reasonably accurate adsorption as belows

$$t_R = \frac{\int_0^{\infty} c(t)tdt}{\int_0^{\infty} c(t)dt}$$

And can be rearranged as

$$t_R = \frac{L}{v} \left( 1 + \left\{ \frac{1-\epsilon}{\epsilon} \right\} K \right)$$

When rearrange this equation, we obtained the adsorption equilibrium constant.

$$K = \frac{\text{slope}}{1 + \left( \frac{1-\epsilon}{\epsilon} \right)}$$

Adsorption equilibrium constant can be calculated from the plot of  $\frac{L}{v}$  versus  $t_R$  as belows.

Where slope of the straight line obtained from the plot of  $t_R$  versus  $\frac{L}{v}$  is equal to  $1 + \left( \frac{1-\epsilon}{\epsilon} \right) K$ . With bed porosity = 0.5636. Hence,

$$\begin{aligned} K &= (\text{slope} - 1) \left( \frac{\epsilon}{1-\epsilon} \right) \\ &= (m - 1) \left( \frac{\epsilon}{1-\epsilon} \right) \\ &= (143.52 - 1) \left( \frac{0.5636}{1-0.5636} \right) \\ &= 184 \end{aligned}$$

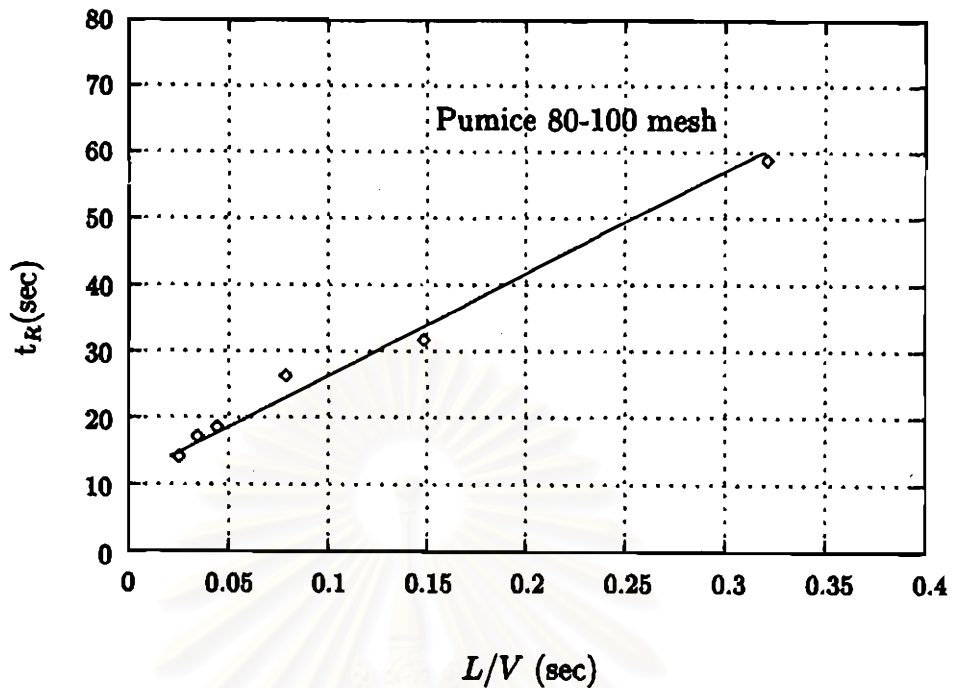


Figure A.6: The first moment plot of adsorption of acetone on pumice 80-100 mesh at 90 ° C

## A.8 Heats of adsorption

### A.8.1 Calculation of heats of adsorption

From Van't Hoff Equation

$$\frac{d \ln K}{dT} = \frac{\Delta H}{RT^2}$$

When this equation was integrated, it became

$$K = K_0 \exp\left(\frac{-\Delta H}{RT}\right)$$

$$\ln K = \ln K_0 + \left(\frac{-\Delta H}{RT}\right)$$

Slope of the plots of  $\ln K$  versus  $1/T$  determined heat of adsorption

So,

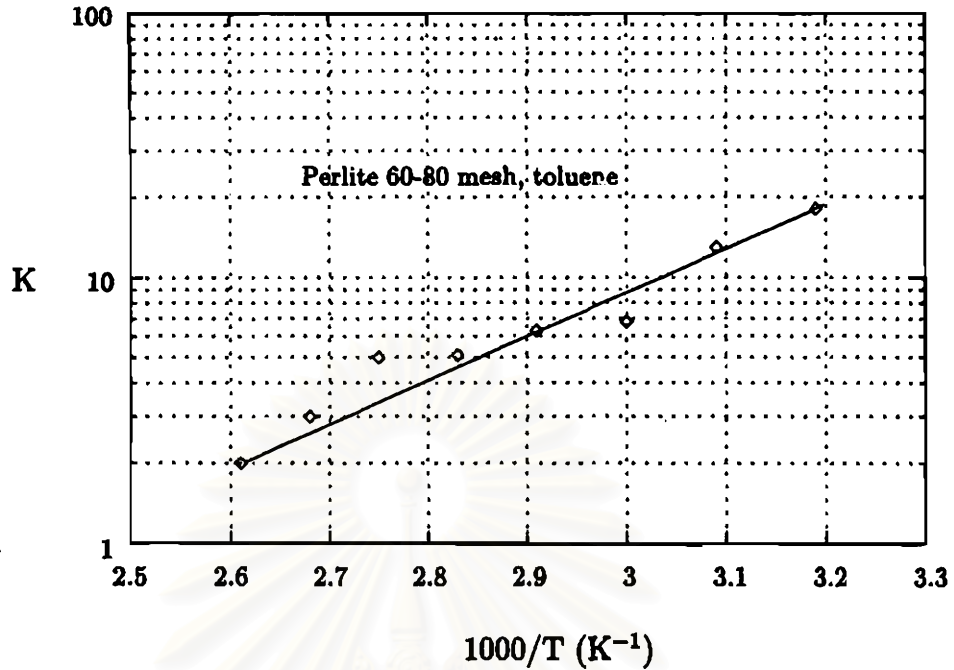


Figure A.7: Adsorption equilibrium constants of toluene on Perlite and Pumice volcanic rocks

$$\begin{aligned}
 -\Delta H &= \text{slope} \times R \\
 &= 3259.56 \times 8.314 \text{ J/mol} \\
 &= 27.10 \text{ kJ/mol}
 \end{aligned}$$

## A.9 Overall mass transfer coefficients

From the equation of

$$\frac{\sigma^2}{2t_R^2} = \frac{D_L}{vL} + \frac{v}{L} \left( \frac{\epsilon}{1-\epsilon} \right) \frac{1}{kK} \left( 1 + \frac{\epsilon}{(1-\epsilon)K} \right)^{-2}$$

or

$$\frac{\sigma^2}{2t_R^2} \frac{L}{v} = \frac{D_L}{vL} + \left( \frac{\epsilon}{1-\epsilon} \right) \frac{1}{kK} \left( 1 + \frac{\epsilon}{(1-\epsilon)K} \right)^{-2}$$

The plot of  $\frac{\sigma^2}{2t_R^2} \frac{L}{v}$  versus  $\frac{1}{v}$  as shown in Figure A.8 had yield a straight line

provides

1. The overall mass transfer coefficient determined from the intercept.

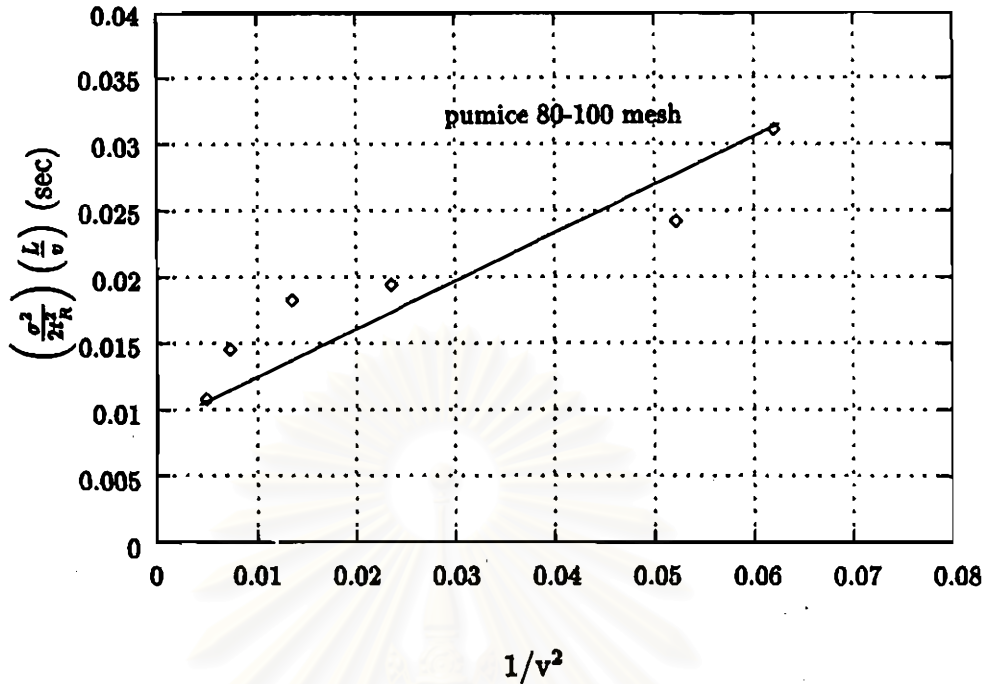


Figure A.8: The second moment plot of adsorption of acetone on pumice 80-100 mesh at 90° C

2. Axial dispersion coefficient determined from the slope of the plot.

From

$$\frac{\sigma^2 L}{2t_R^2 v} = \frac{D_L}{vL} + \left(\frac{\epsilon}{1-\epsilon}\right) \frac{1}{kK} \left(1 + \frac{\epsilon}{(1-\epsilon)K}\right)^{-2}$$

$$\text{intercept} = \left(\frac{\epsilon}{1-\epsilon}\right) \frac{1}{kK} \left(1 + \frac{\epsilon}{(1-\epsilon)K}\right)^{-2}$$

$$\text{slope} = D_L$$

Hence, the overall mass transfer coefficient of acetone on Pumice 80-100 mesh can be determined from

$$k = \frac{1}{\text{intercept}} \left(\frac{\epsilon}{1-\epsilon}\right) \frac{1}{kK} \left(1 + \frac{\epsilon}{(1-\epsilon)K}\right)^{-2}$$

$$3.56 \times 10^{-2} = \left( \frac{\epsilon}{1-\epsilon} \right) \frac{1}{kK} \left( 1 + \frac{\epsilon}{(1-\epsilon)K} \right)^{-2}$$

$$k = \frac{1}{3.56 \times 10^{-2} \cdot 184} (1.291)(0.986)$$

$$k = 11.52 \text{ min}^{-1}$$

$$k = 0.192 \text{ sec}^{-1}$$

### Axial dispersion

$$\begin{aligned} D_L &= \text{slope} \\ &= 19.8 \text{ cm}^2/\text{min} \\ &= 0.33 \text{ cm}^2/\text{sec} \end{aligned}$$

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# Appendix B

## Experimental Data

### B.1 Weighted mean residence time and Variances

Table B.1: The weighted mean residence time and variances on various flowrate of toluene on pumice 40-60 mesh

T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )	T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )
40	3.118	317.480	94063.520	80	2.759	129.612	17634.130
	5.316	207.197	47025.045		5.496	68.595	8696.460
	8.161	84.184	10872.290		8.167	75.469	8110.769
	10.833	70.975	9481.730		10.505	68.704	7373.963
	13.550	64.990	9327.230		12.833	64.590	6561.327
50	2.770	316.490	92158.980	90	2.797	94.305	11358.870
	5.584	168.890	22993.800		6.442	67.515	7680.080
	8.174	102.640	18725.010		9.282	65.300	9331.320
	9.610	85.450	13083.520		12.666	61.150	9028.310
	13.550	67.040	10633.610				
60	2.742	203.330	51309.870	100	2.798	89.553	10686.686
	5.709	127.870	24459.260		5.496	73.701	8421.125
	8.372	94.760	7849.190		8.286	65.742	6151.153
	10.643	84.224	6663.090		12.970	55.579	4669.250
	13.510	71.960	5163.090				
70	2.880	111.019	13229.427	110	2.714	75.487	5399.310
	5.797	71.448	7658.425		5.287	57.254	5364.985
	8.147	52.917	5327.840		8.133	53.886	4926.190
	10.713	50.800	4033.245		10.979	50.818	4717.620
	13.399	48.288	3733.245		13.362	48.738	4499.420



Table B.2: The weighted mean residence time and variances on various flowrate of toluene on pumice 60-80 mesh

T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )	T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )
40	2.063	141.073	24684.140	80	1.829	91.244	18223.640
	3.675	79.080	9800.560		3.622	74.158	6686.910
	5.428	70.289	9558.540		5.296	65.050	6351.090
	7.434	59.930	8035.590		7.400	53.530	5903.950
	9.157	44.827	6274.570		9.209	49.800	3709.760
50	2.031	127.700	22007.170	90	1.820	86.690	16980.570
	3.734	69.130	9255.590		3.680	63.090	6912.020
	5.701	55.100	7175.120		5.366	54.070	6632.630
	7.285	54.620	4675.050		7.237	52.140	6447.450
	9.081	49.770	5242.700		8.957	49.760	6230.480
60	2.050	118.977	21444.920	100	1.858	71.660	14611.580
	3.675	75.524	8862.760		3.523	60.347	7773.250
	5.575	66.135	8450.780		5.137	55.228	6790.830
	7.142	59.300	8221.040		7.100	53.830	6280.890
	9.081	57.665	7558.990		8.802	45.120	5865.400
70	1.806	101.848	20853.990	110	1.785	60.390	11868.360
	3.642	70.781	12023.890		3.563	53.120	7317.030
	5.437	56.327	8732.590		5.401	51.180	6868.360
	7.005	53.130	6617.720		7.367	44.470	5241.690
	9.106	52.082	6390.490		8.812	42.120	4356.920

Table B.3: The weighted mean residence time and variances on various flowrate of toluene on pumice 80-100 mesh

T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )	T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )
40	1.927	75.080	7862.470	80	0.843	84.440	6599.760
	3.183	53.040	4796.470		4.015	28.730	686.230
	5.803	37.920	2588.510		6.514	24.690	514.170
	6.436	30.940	1424.060		11.710	19.850	446.710
50	2.204	62.730	6827.210	90	0.935	59.780	1794.840
	3.570	43.370	3303.410		2.021	31.710	423.710
	5.240	36.500	2375.370		3.817	26.330	521.900
	7.457	29.280	2136.310		6.801	18.535	368.530
	8.605	28.760	2102.230		11.880	14.075	382.410
60	2.038	61.080	6727.210	100	0.670	60.290	2455.280
	2.971	46.420	3296.990		2.801	25.290	382.660
	5.300	34.190	2369.910		4.720	19.470	421.030
	7.597	30.780	2235.390		6.210	18.780	578.390

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<i>continued from previous page</i>							
T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )	T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )
	9.036	25.610	1756.360		8.650	17.230	346.650
70	2.101	52.236	4128.130	110	3.089	26.830	4904.080
	4.331	37.180	2093.738		4.252	23.960	731.730
	6.041	30.100	1959.650		6.411	21.375	826.570
	6.716	29.270	1573.608		10.490	20.560	725.000

Table B.4: The weighted mean residence time and variances on various flowrate of acetone on pumice 40-60 mesh

T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )	T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )
40	3.880	335.100	121638.730	80	3.130	178.530	43972.620
	5.880	165.740	43559.810		5.880	168.100	61783.200
	8.270	120.690	21636.540		8.080	107.480	26125.750
	12.470	78.300	12470.990		11.030	68.720	12333.050
50	4.263	264.670	84478.270	90	3.590	112.740	17271.350
	5.710	115.080	17113.430		6.150	71.190	8937.450
	9.300	103.900	19023.100		8.150	41.140	3292.320
	11.980	75.510	11214.030		12.870	40.890	4216.550
60	3.490	263.120	81084.990	100	2.960	126.420	31299.960
	6.300	182.380	55215.380		5.590	70.760	9293.780
	8.780	141.560	40643.170		7.720	46.200	3862.540
	11.280	64.330	8477.620		10.220	34.860	2601.200
	13.400	54.050	5580.430		15.490	31.580	2358.530
70	2.730	199.380	66666.400	110	3.44	60.050	4522.470
	5.690	89.300	14719.560		4.938	43.390	2847.550
	8.160	58.510	6842.240		7.448	34.480	2422.160
	10.305	45.820	4664.390		9.747	29.670	1895.770
	13.220	37.630	3328.200				

Table B.5: The weighted mean residence time and variances on various flowrate of acetone on pumice 60-80 mesh

T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )	T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )
40	2.420	225.640	92593.250	80	2.380	114.960	18770.430
	3.830	141.560	33405.430		4.080	52.650	4643.020
	6.210	104.870	23613.330		6.340	43.780	4483.010
	8.980	51.640	6271.790		8.957	39.670	4329.820
	12.610	42.220	5297.240		10.310	38.460	4208.570

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T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )	T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )
50	1.750	249.650	69684.540	90	1.590	136.080	19255.120
	4.052	174.140	53760.480		4.454	72.820	9870.360
	6.820	79.730	15792.530		6.430	53.650	7121.480
	9.370	60.440	10330.110		8.719	39.750	4270.970
	11.670	42.000	6085.740		11.750	35.370	3615.870
60	1.670	262.110	89314.590	100	2.035	67.910	7482.840
	4.650	137.960	41113.280		3.911	49.940	4979.300
	6.430	86.480	16517.100		6.530	46.950	4393.660
	9.210	48.550	6458.310		8.566	43.220	4381.710
	10.820	47.010	6692.760		10.410	36.650	4030.980
70	2.170	147.960	25814.520	110	1.570	64.540	4153.930
	4.187	59.570	6089.600		3.610	45.090	3875.890
	6.280	49.430	7405.340		5.100	30.360	1587.320
	8.560	39.730	3816.040		10.860	29.690	2006.390
	10.930	35.830	3414.910		12.810	26.590	1563.550

Table B.6: The weighted mean residence time and variances on various flowrate of acetone on pumice 80-100 mesh

T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )	T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )
40	1.960	124.360	28628.770	80	1.570	51.380	3942.380
	4.487	62.930	7756.740		2.990	39.570	2155.910
	6.348	43.330	3736.920		4.790	31.200	2004.340
	8.605	39.300	3317.250		6.348	30.130	1902.900
50	1.390	123.470	21256.180	90	1.820	48.600	3864.410
	3.800	53.920	4569.100		4.340	34.360	2357.740
	6.720	37.100	2902.420		6.501	32.850	2052.410
	8.690	32.080	2256.070		8.605	30.760	1751.060
	11.260	28.160	1763.270		9.090	28.110	1688.410
60	1.530	100.120	16242.320	100	1.710	46.200	3058.300
	4.290	38.620	1924.570		3.910	39.990	2494.980
	6.540	32.890	1573.100		5.440	35.210	1538.270
	8.610	27.800	1588.420		7.590	27.250	1250.470
	10.430	26.570	1444.250		8.190	25.180	1158.320
70	1.880	64.310	6186.180	110	1.880	43.350	2995.640
	3.630	38.470	2399.510		4.390	34.530	1928.950
	6.830	29.120	1239.510		5.660	32.100	1458.260
	8.150	23.970	986.790		6.540	27.950	1049.610
	10.920	20.860	726.480		8.360	26.430	989.360

Table B.7: The weighted mean residence time and variances on various flowrate of toluene on perlite 40-60 mesh

T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )	T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )
40	1.970	300.720	9017.270	80	1.970	55.650	207.590
	4.022	159.490	4205.360		2.960	47.300	120.810
	6.020	119.930	2934.010		5.910	29.390	47.690
	7.760	90.280	1081.940		7.830	27.460	49.060
	10.090	80.630	1203.490		9.850	22.380	32.770
50	1.800	153.480	4449.050	90	0.985	78.350	291.130
	4.020	77.090	749.720		1.950	53.010	104.510
	6.020	68.740	1708.480		4.940	35.950	34.820
	7.980	52.670	451.430		6.840	29.920	21.650
	10.013	43.690	275.540		8.790	20.340	12.170
60	1.970	92.760	1721.920	100	0.980	66.100	180.420
	2.950	71.010	647.400		3.960	28.540	7.890
	3.920	53.650	319.200		5.910	24.800	8.160
	5.870	42.360	216.640		7.830	23.750	12.190
	7.850	35.060	167.100		9.770	18.220	2.990
70	0.990	112.560	1256.440	110	0.930	63.440	275.330
	2.950	56.890	193.720		1.920	44.100	64.740
	3.950	45.360	145.020		3.930	29.840	20.160
	4.910	37.990	135.100		5.870	24.420	3.120
	5.890	33.150	100.540		7.820	23.210	5.280
	7.890	30.890	65.460		9.880	18.350	4.060

Table B.8: The weighted mean residence time and variances on various flowrate of toluene on perlite 60-80 mesh

T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )	T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )
40	0.790	322.280	30541.580	80	1.060	80.250	1164.190
	2.480	135.810	7346.760		2.940	35.310	92.450
	4.110	86.750	2950.520		5.460	21.160	34.620
	6.542	66.390	2435.320		7.720	19.150	21.410
50	1.270	150.190	4644.120	90	0.930	89.620	1715.970
	4.240	62.350	1043.610		3.500	35.910	104.140
	6.100	46.430	652.290		5.840	22.370	56.510
	8.410	38.260	442.600		7.360	21.230	24.730
	10.040	33.500	379.870				
60	0.7710	142.470	10954.080	100	0.810	69.990	454.180
	2.800	59.780	1004.200		1.800	37.870	69.290
	4.880	44.610	618.480		3.580	25.500	28.680

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T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )	T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )
	6.190	33.430	266.260		5.100	19.310	13.950
	8.580	25.750	313.360		7.150	18.480	18.180
70	0.960	105.270	3128.590	110	0.840	58.310	194.270
	2.540	48.590	360.890		2.560	28.680	27.330
	4.530	32.330	175.460		4.070	19.840	18.590
	6.320	29.170	111.830		6.0530	17.430	14.490
	8.920	23.580	71.130		8.320	13.240	10.340

Table B.9: The weighted mean residence time and variances on various flowrate of toluene on perlite 80-100 mesh

T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )	T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )
40	0.92	101.86	782.14	80	1.22	49.72	62.08
	1.49	71.22	302.13		2.46	31.59	17.71
	2.56	49.49	78.76		3.64	28.15	16.78
	3.60	40.64	56.76		7.07	18.68	5.34
	6.16	30.16	28.34				
50	0.92	83.73	206.30	90	1.18	53.47	234.19
	1.32	59.84	81.12		2.54	42.45	52.05
	2.74	39.00	53.07		3.50	29.61	50.13
	4.47	30.23	13.97		4.53	25.99	13.32
	6.97	23.37	10.20		6.96	21.26	12.37
60	0.87	73.69	140.66	100	1.43	38.98	31.33
	1.35	56.69	78.43		3.22	37.24	9.23
	2.74	35.02	24.95		4.37	18.64	7.12
	3.26	29.56	15.06		5.32	18.37	7.57
	5.46	24.05	14.51		7.03	18.24	1.27
70	0.85	75.22	237.56	110	0.74	62.40	222.29
	1.28	45.74	84.46		1.11	50.24	50.22
	3.88	30.38	11.89		3.39	25.42	14.24
	5.88	20.70	17.88		4.35	19.33	15.91
	7.20	18.89	9.31		6.34	15.24	9.26

Table B.10: The weighted mean residence time and variances on various flowrate of acetone on perlite 40-60 mesh

T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )	T (° C)	v (cm/sec)	$t_R$ (sec)	$\sigma^2$ (sec <sup>2</sup> )
40	1.73	188.69	18804.72	80	1.57	105.67	10630.56

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T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )	T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )
	3.74	56.74	2658.79		3.24	71.84	5790.51
	6.21	46.27	2621.44		4.93	47.07	2356.48
	7.70	32.50	1593.29		7.92	42.13	2786.98
50	1.59	150.56	16056.96	90	1.85	85.90	8240.87
	3.34	81.97	7034.85		3.28	51.59	2417.55
	4.95	88.74	9425.89		6.54	41.41	2664.81
	6.75	59.21	5943.41		8.05	33.62	1402.16
	8.09	61.84	6308.37				
60	1.81	121.88	9643.50	100	1.66	78.26	7172.65
	3.24	76.84	5281.29		3.13	46.59	1842.57
	5.2	59.66	4514.00		4.88	32.89	1133.06
	6.64	50.56	4029.32		6.59	32.00	1031.22
	8.07	50.99	3988.22		7.78	28.55	870.65
70	1.75	110.92	11351.87	110	1.37	64.05	2713.39
	3.17	71.42	4889.18		3.42	39.45	1240.79
	5.17	57.64	3895.75		4.68	30.63	902.55
	6.48	48.74	3801.68		6.51	30.12	877.75
	8.16	50.78	3342.26		7.60	21.96	567.65

Table B.11: The weighted mean residence time and variances on various flowrate of acetone on perlite 60-80 mesh

T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )	T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )
40	2.03	225.29	35818.16	80	2.01	90.53	5778.04
	4.12	162.60	17667.56		4.00	59.97	32239.06
	6.10	134.00	14454.71		6.05	54.34	3553.86
	7.79	113.89	8710.54		8.07	44.49	2247.57
	9.87	86.96	10839.17		9.77	39.52	1849.19
50	2.13	160.97	19083.58	90	2.011	77.34	3481.60
	7.63	115.10	17169.13		3.98	46.87	1988.47
	10.12	104.76	10938.30		5.88	42.82	1981.66
60	2.06	101.73	6924.93	100	2.03	61.97	2057.39
	3.96	81.39	6872.09		3.99	43.62	1530.67
	5.93	58.49	4075.98		6.03	36.58	1186.71
	7.84	52.75	2913.73		7.95	31.53	1017.06
	9.98	48.08	5725.03		9.72	31.36	837.71
70	2.16	92.53	5710.44	110	2.21	51.81	1908.94
	3.95	69.23	4156.91		3.98	39.79	1264.20
	5.98	59.52	5665.03		5.86	30.13	690.16
	7.61	44.13	2284.43		7.77	28.18	585.35

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T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )	T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )
	9.98	43.09	4151.00		9.79	23.18	505.66

Table B.12: The weighted mean residence time and variances on various flowrate of acetone on perlite 80-100 mesh

T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )	T (° C)	v (cm/sec)	t <sub>R</sub> (sec)	σ <sup>2</sup> (sec <sup>2</sup> )
40	1.775	120.021	14369.760	80	1.551	57.230	457.124
	3.465	96.690	10202.260		2.544	39.510	260.160
	5.179	70.490	3527.267		3.403	36.683	167.440
	6.741	59.176	2690.081		4.604	31.263	162.360
	8.778	52.413	2091.390		6.086	23.090	75.440
50	1.737	82.442	4399.336	90	1.613	50.070	233.860
	3.558	55.390	2173.222		2.415	36.655	159.830
	5.316	47.594	1829.640		3.374	28.601	85.280
	6.916	40.174	1105.030		4.407	27.840	78.270
	8.802	33.868	844.156		5.616	21.470	49.660
60	1.789	62.352	2097.040	100	1.286	52.296	224.650
	3.477	46.580	1394.490		2.591	29.830	83.310
	5.247	39.360	829.010		3.421	25.620	71.830
	7.007	29.890	527.284		4.233	23.680	50.470
	8.730	25.360	409.446		5.481	21.435	33.910
70	1.910	54.320	1290.970	110	1.219	51.440	174.690
	3.507	38.310	681.022		2.325	33.560	77.500
	5.334	31.571	475.050		3.250	27.190	38.310
	6.813	26.905	281.430		4.210	24.960	27.460
	8.321	25.540	250.660		5.056	19.780	17.680

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## B.2 Pressure drop and flowrate

Table B.13: Pressure drops and flowrates of each adsorbent

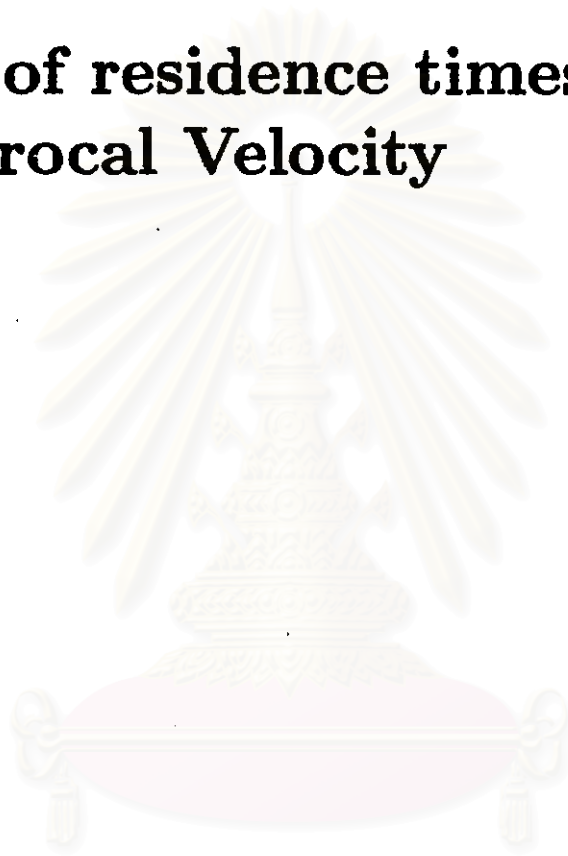
Mesh size	Pumice		Perlite	
	$\Delta P$	Q	$\Delta P$	Q
	(kg/cm <sup>2</sup> )	(ml/min)	(kg/cm <sup>2</sup> )	(ml/min)
40-60	0.0021	20.1572	0.1177	82.7974
	0.0111	26.7463	0.2201	137.8296
	0.0165	37.3459	0.3166	201.3422
	0.0224	47.619	0.4075	272.727
	0.0262	60.4047	0.5016	339.6354
	0.0320	70.8717	0.5952	407.249
60-80	0.0015	20.979	0.1617	19.9111
	0.0047	34.5502	0.2892	39.0472
	0.0062	50.142	0.4157	59.8026
	0.0071	66.6661	0.5376	86.9565
	0.0111	79.3021	0.6601	113.2075
	0.0124	95.2569	0.7911	127.302
80-100	0.0016	6.7643	0.0299	6.9686
	0.0037	21.8451	0.1618	19.8242
	0.0071	35.1576	0.2924	34.4827
	0.0109	48.0000	0.4237	48.387
	0.0108	65.6958	0.5528	65.2173
	0.0123	81.4553	0.6807	83.7287
	0.0149	95.7548	0.7963	120.00

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## Appendix C

### Plots of residence times with the Reciprocal Velocity



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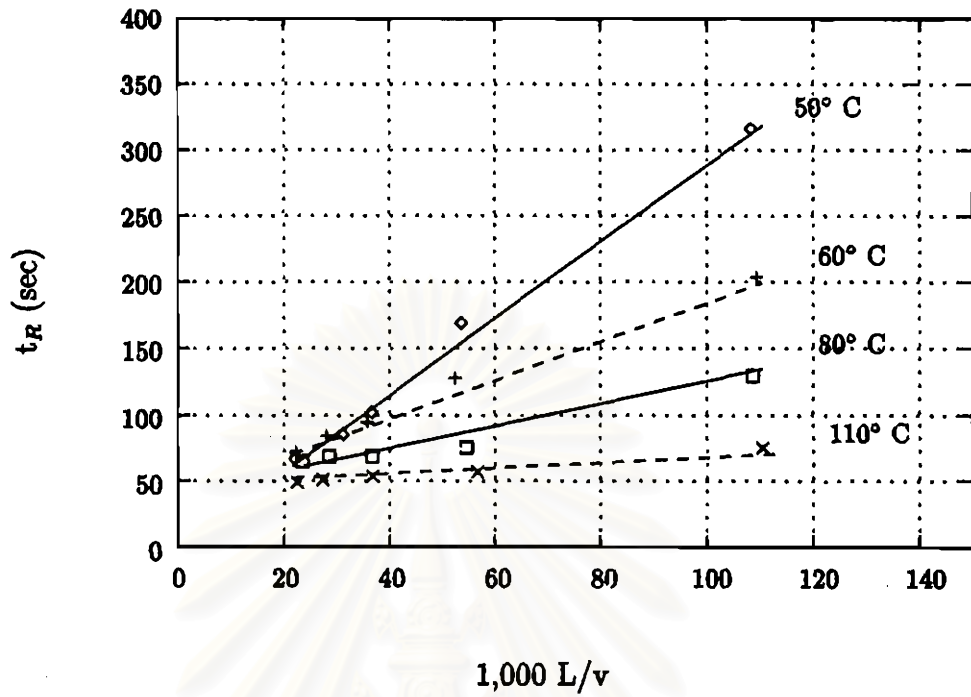


Figure C.1: The plot of Weighted mean residence times of Toluene on Pumice 40-60 mesh

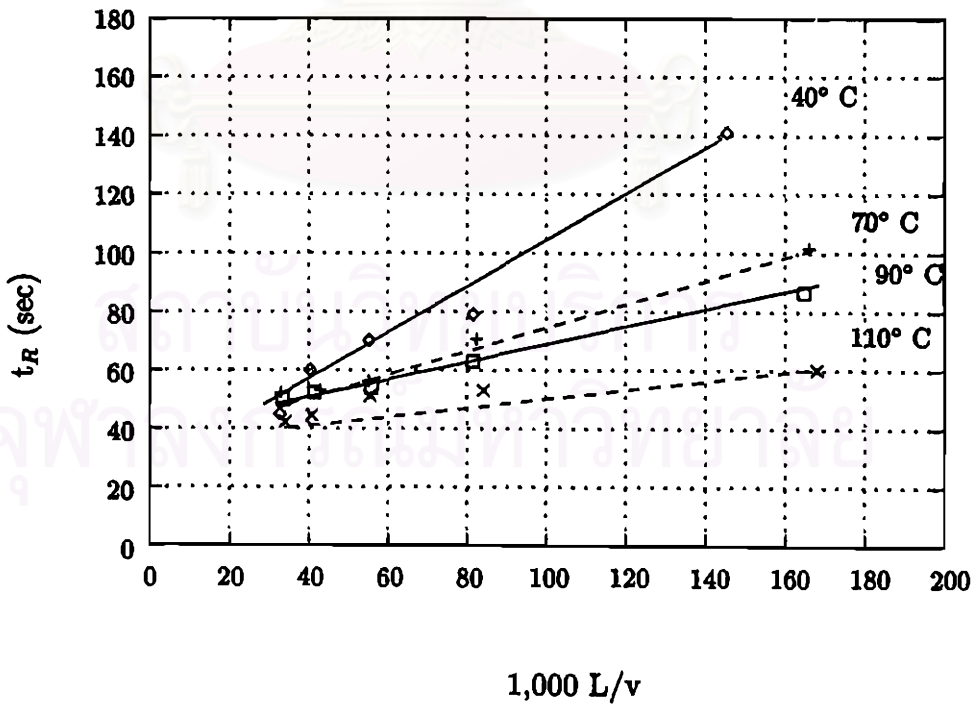


Figure C.2: The plot of Weighted mean residence times of Toluene on Pumice 60-80 mesh

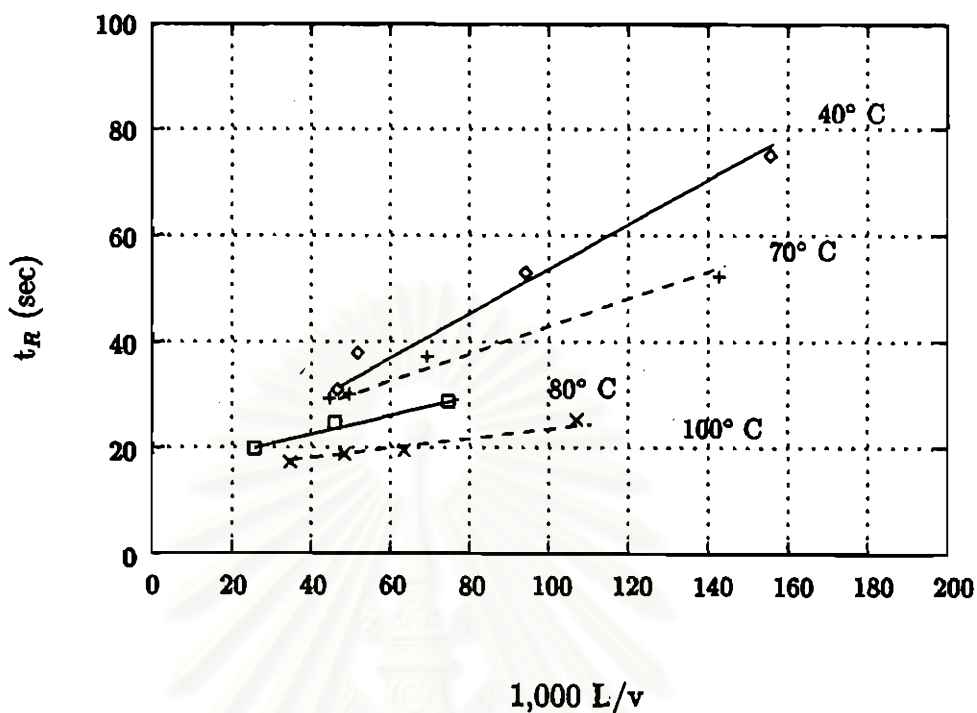


Figure C.3: The plot of Weighted mean residence times of Toluene on Pumice 80-100 mesh

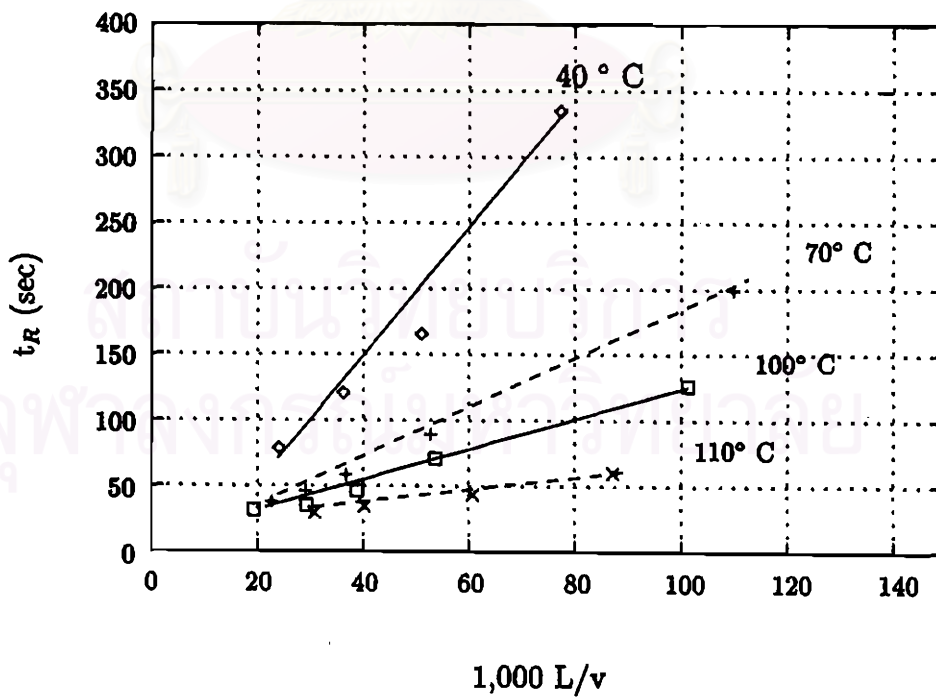


Figure C.4: The plot of Weighted mean residence times of Acetone on Pumice 40-60 mesh

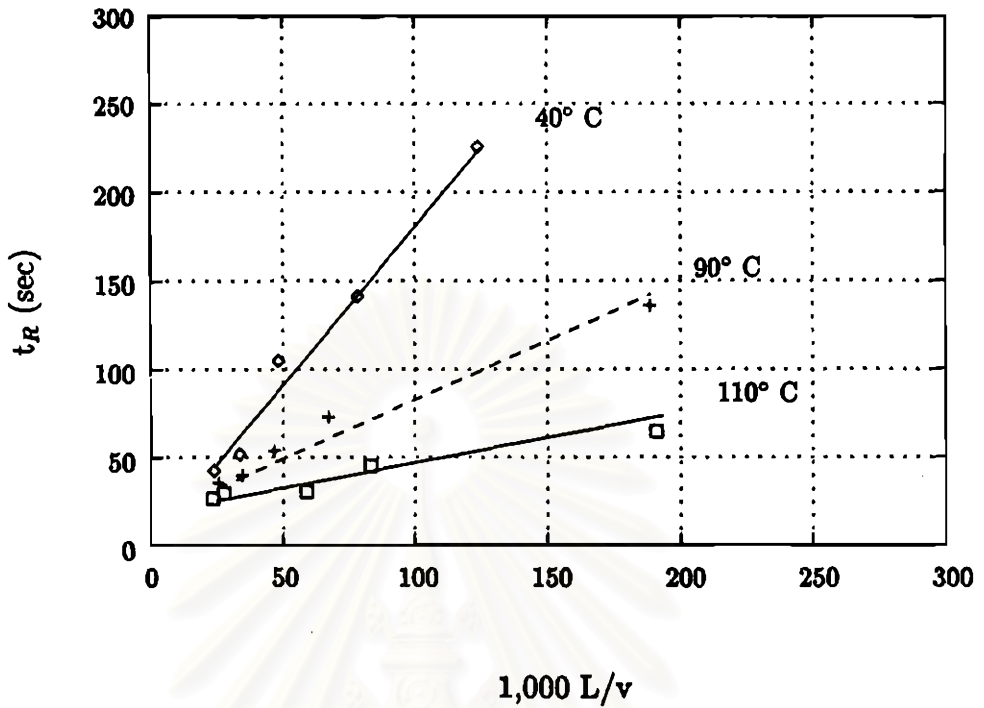


Figure C.5: The plot of Weighted mean residence times of Acetone on Pumice 60-80 mesh

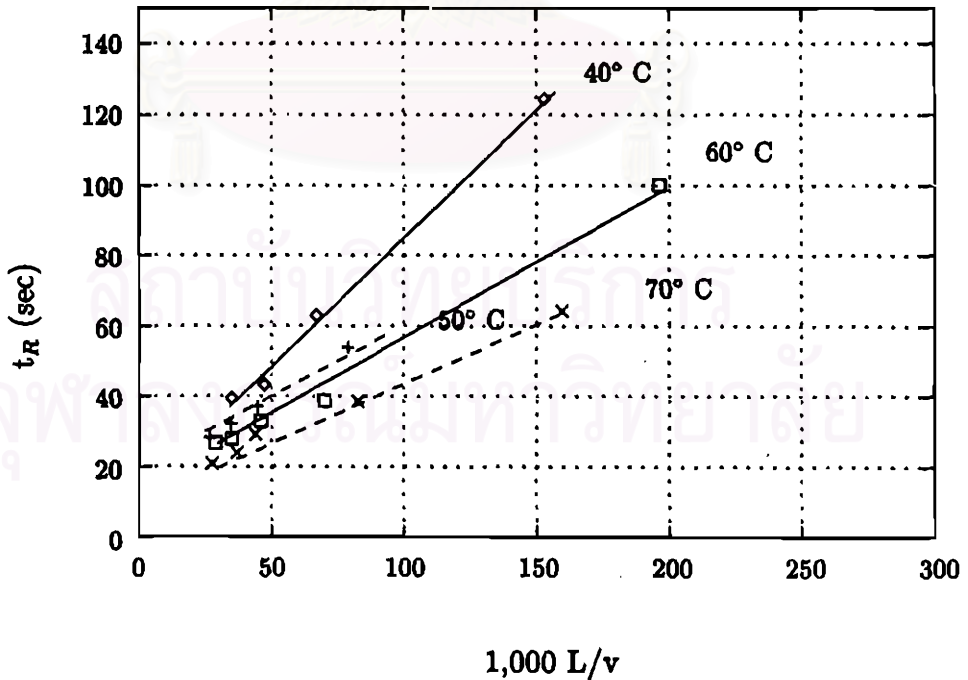


Figure C.6: The plot of Weighted mean residence times of Acetone on Pumice 80-100 mesh

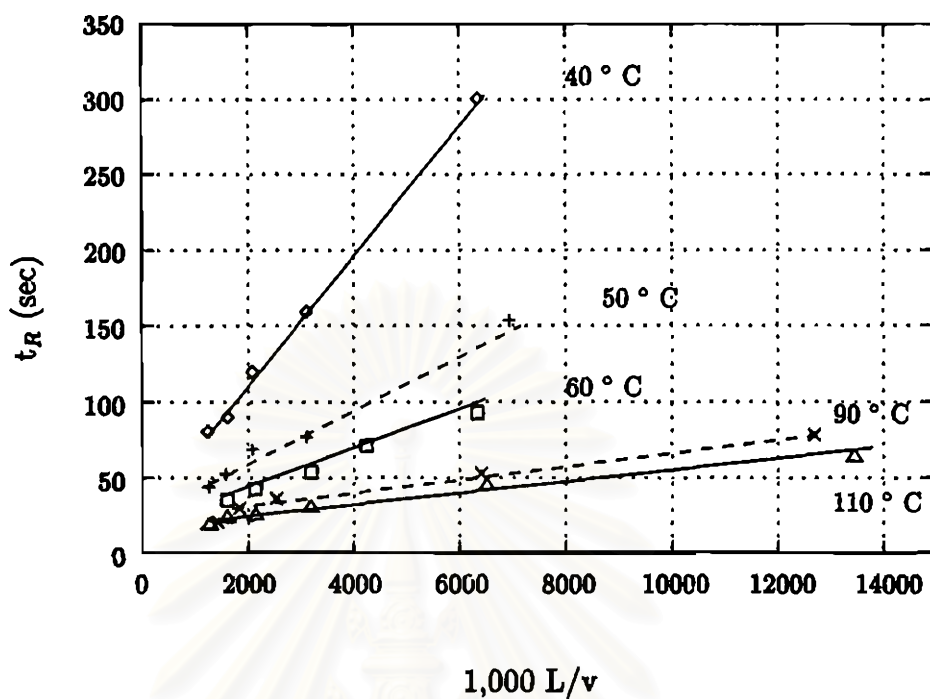


Figure C.7: The plot of Weighted mean residence times of Toluene on Perlite 40-60 mesh

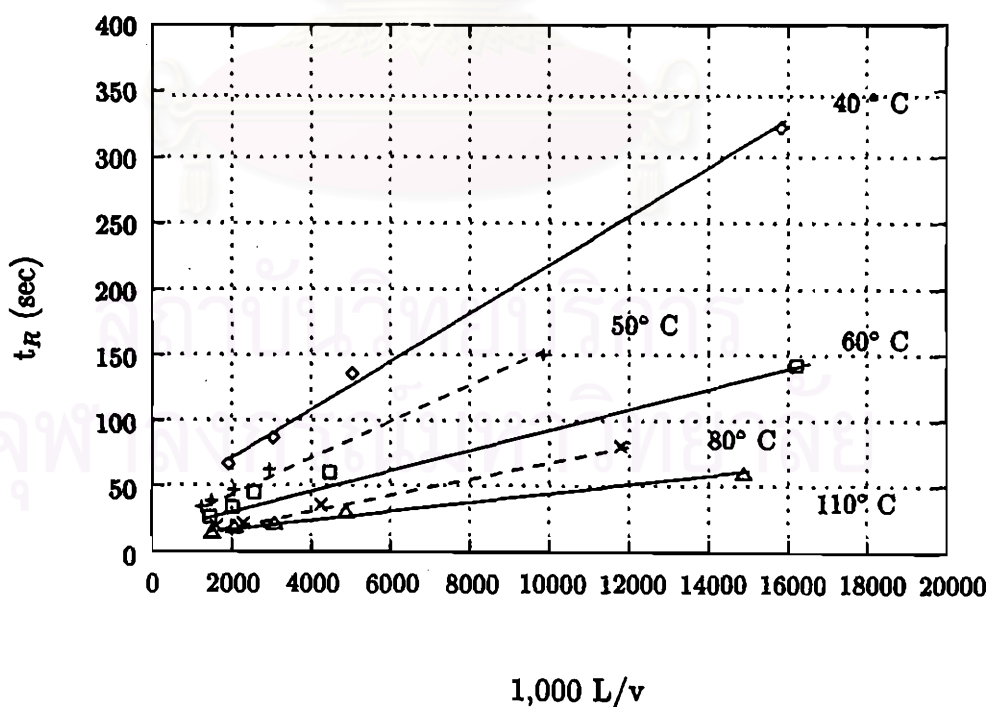


Figure C.8: The plot of Weighted mean residence times of Toluene on Perlite 60-80 mesh

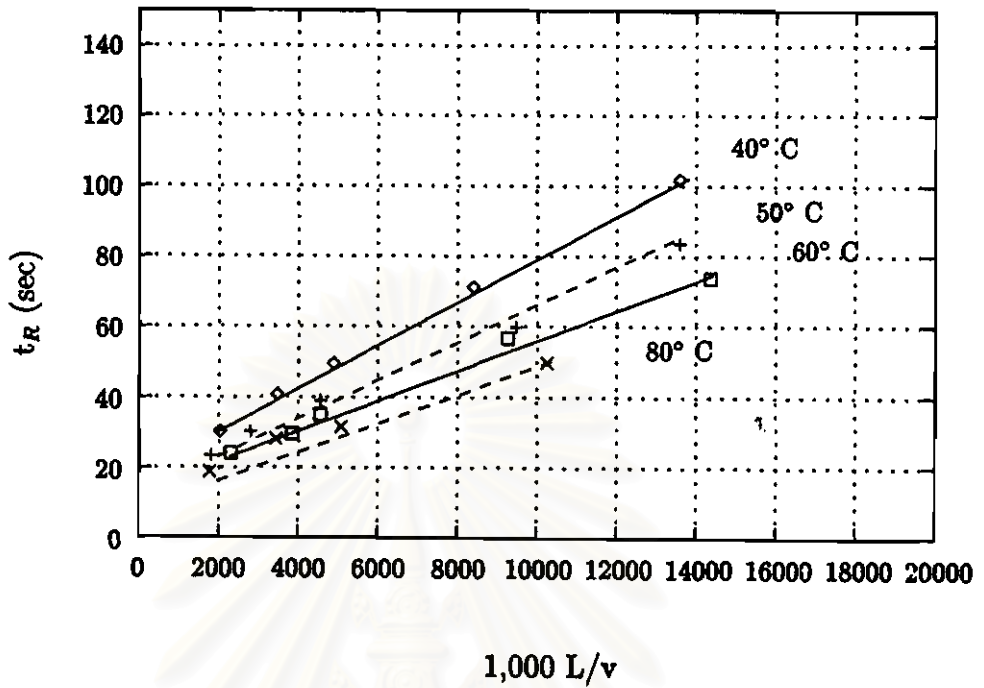


Figure C.9: The plot of Weighted mean residence times of Toluene on Perlite 80-100 mesh

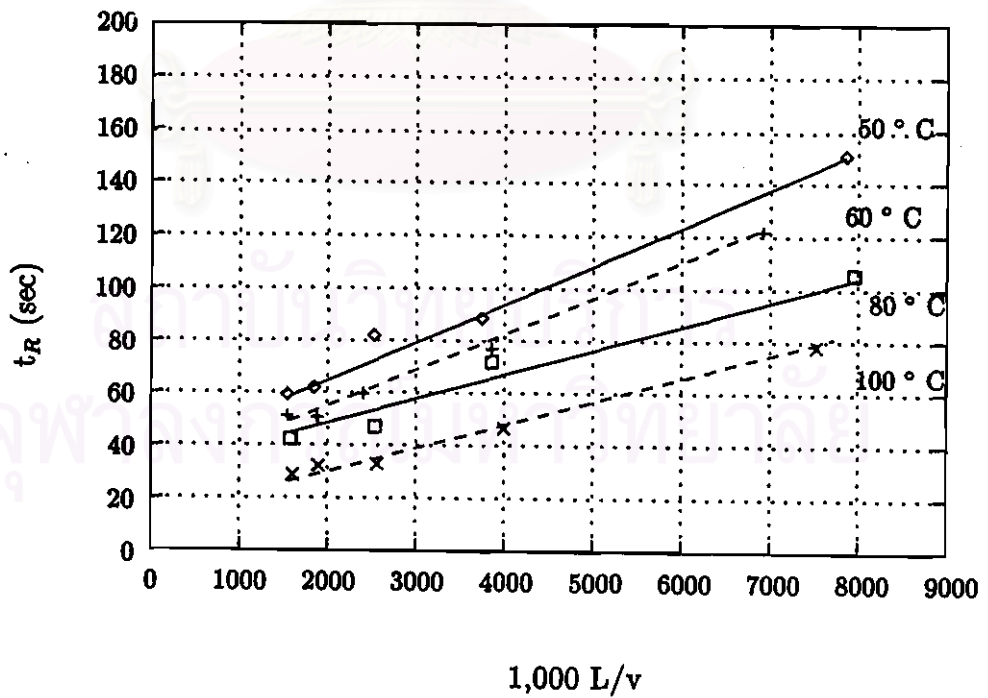


Figure C.10: The plot of Weighted mean residence times of Acetone on Perlite 40-60 mesh

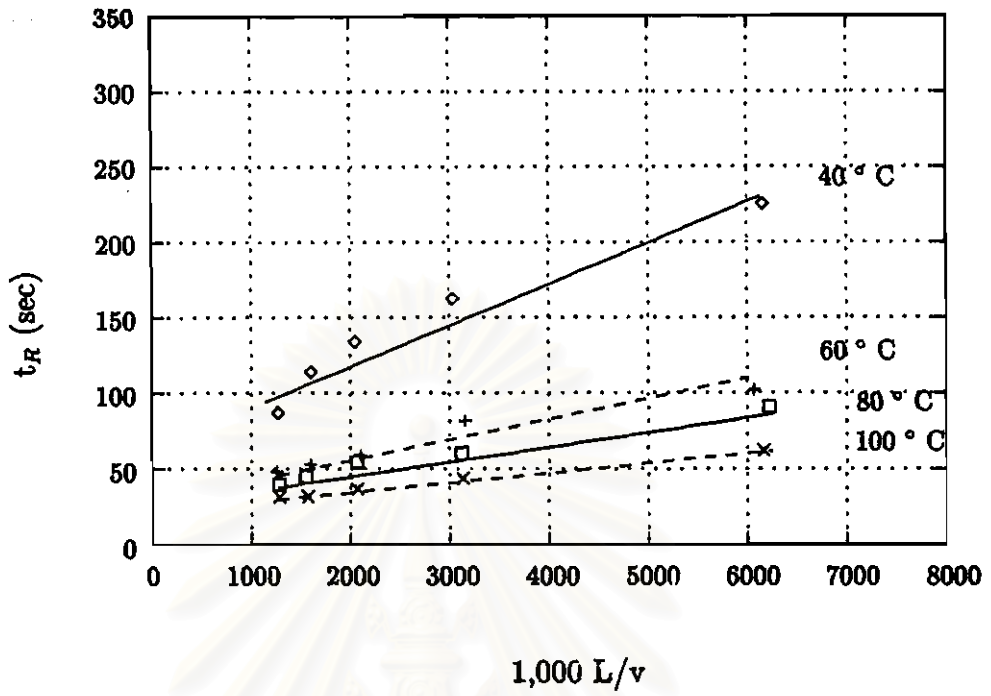


Figure C.11: The plot of Weighted mean residence times of Acetone on Perlite 60-80 mesh

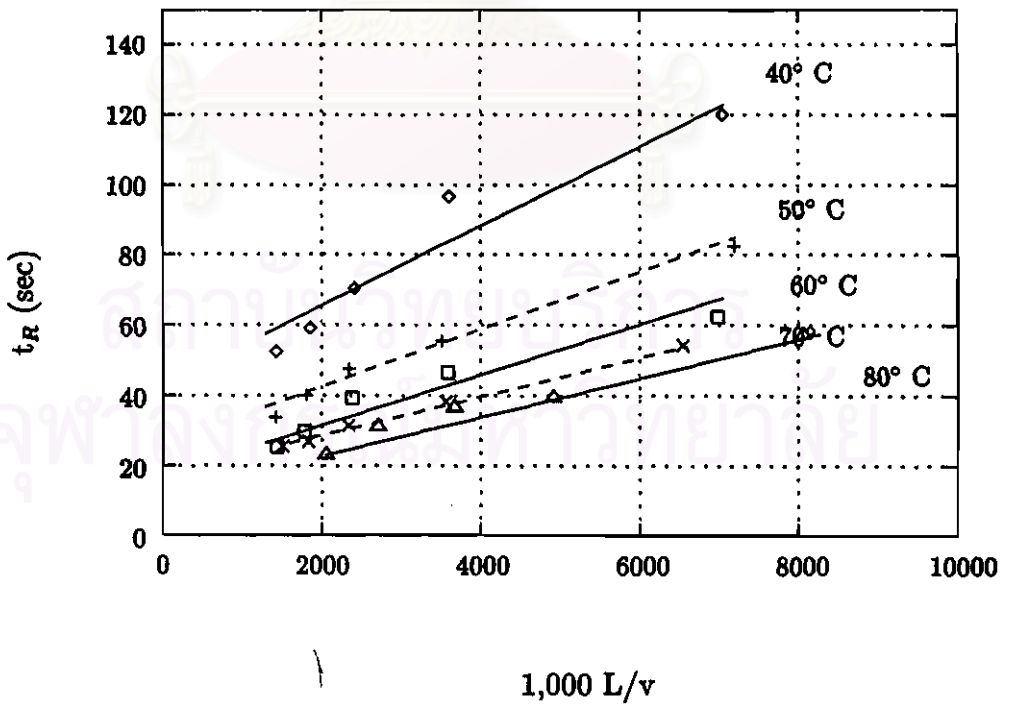


Figure C.12: The plot of Weighted mean residence times of Acetone on Perlite 80-100 mesh

## Curriculum Vitae



Miss Vorawan Norasucha was born in September, 1972 in Bangkok. She graduated high school from Benjamaracharai school in 1990. She received a Bachelor's Degree of Science from Kasetsart University in 1994. Subsequently, she completed the requirements for a Master's Degree in Chemical Engineering at the Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University in 1998.

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