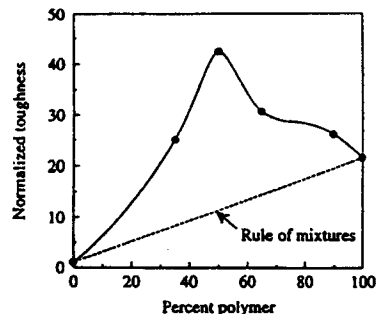
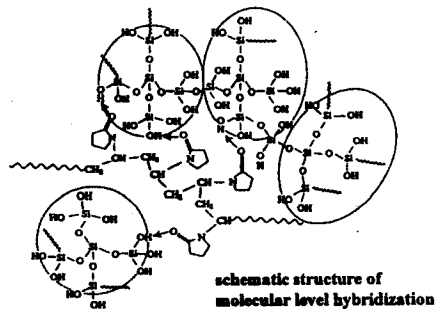
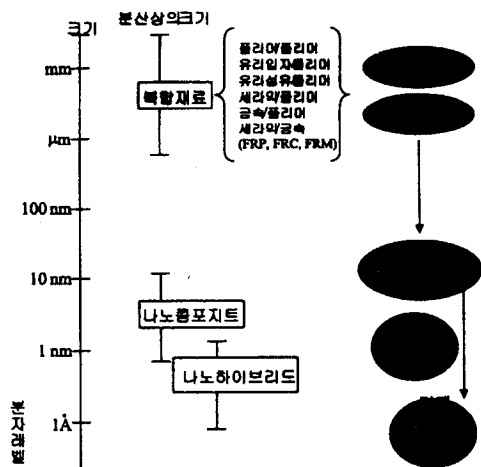


Why polymer/silica nanohybrid?



Normalized toughness of a series of PHEMA-SiO₂, SIPN hybrids

Polymer Hybrids Research Center, KIST

The application of organic/inorganic nanohybrid materials



Industry	Potential Market in Japan (1996)
Paint and coating	¥724 billion
Die packaging	\$860 billion (world)
Optical lenses for CD, VTR, projection TV, eyeglasses, contact lenses (plastic material)	¥650 billion (¥150 billion)
Optical devices for DVD, CD-R, MO-disk	¥3.85 trillion

Source : KRI (1998)

Polymer Hybrids Research Center, KIST

	Transparent materials										
	Eye lenses including hard coating	Contact lenses	Industrial lenses	Optical waveguide	Fine-patterning process	Pain and coatings	Anti-fogging	Conductive polymers	LC displays	IC sealing materials and other electronics parts	Autosensitive parts
Polyamide-SiO ₂ ¹⁾	○			○	○	○		○			○
Polyurethane-SiO ₂											○
Polyimide-SiO ₂			△	△					○		
PMMA, HEMA, MSM, SiO ₂ or other metal oxide	○	○	○		● ²⁾	○	○	○	● ²⁾		○
Epoxide-SiO ₂ , TiO ₂	○	○			●	○			●		
PEG-metal oxide				○		○	○				○
PVAc, PVA, PVF-SiO ₂ , Al ₂ O ₃		○				○				○	○
Nylon 6-Clay (intercalation compound)									●	●	○

△: research target, ○: under development, ●: commercially available
¹⁾ Polyamide includes polymers containing amide groups such as POZO, PVP and nylon.
²⁾ Acrylic resin-SiO₂ hybrid material.

Source: KRI

Nanocomposites showing promise in automotive and packaging roles

In plastics, it is indeed a small world after all. After more than a decade of research, nanocomposites are close to commercial payoff. Through modification of any plastics matrix using tiny clay particles, a new class of materials, termed nanocomposites, can be developed.

The particles, due to their extremely high aspect ratios (surface to width), promise to improve structural, mechanical, flame retardant, thermal and barrier properties with out significant loss of clarity, toughness, or impact strength.

This is a fundamentally new way of reinforcing plastics. It's not just another type of filler of glass, carbon, or mineral fibers, but a new type of reinforcement, called nanocomposites. The Matrix is now a polymer, based in St. Louis, is now one of dozens of companies that are developing nanocomposite technologies (table).

Company	Location	Polymer type	Role
Toyota Central R&D Labs Inc. 4350	Nagatsuta, Aichi, Japan	Nylon 6	Original technology developer, no current uses of nanocomposites
Ube Industries 4351P	Ube City, Japan	Nylon 6, nylon 66, nylon 12	First Toyota licensee and developer for use in fishing boat cover
Manacor 432P	Arlington Heights, IL	Focus on, but not limited to, polypropylene, polyester, PP	Research was started by Allied International to develop nanocomposite technology using its own patents and intellectual property
Dow Chemical 4353P	Midland, MI	Not specified	Participant with Magna International in study of nanocomposites use in vehicle manufacturing
ICI Polyester 4354P	Midwestborough, England	Polyester	Commercializing their barrier film using nanocomposite coating
Ford Motor 4355P	Dearborn, MI	Polypropylene	Evaluating nanocomposites for interior and exterior automotive applications
AlliedSignal 4356P	Warren, MI	Nylon 6	Holds patents on nanocomposites
Solutia Inc. 4357P	St. Louis, MO	Nylon 6, 66, and copolymers	Company has developed technology and is selling nanocomposites to automotive manufacturers
Claytec 4358P	Lansing, W	Epoxy	Startup by professor at Michigan State University, commercialization, epoxy encasement
Dupont 4359P	Wilmington, DE	Fluoropolymers	World's largest that is currently aimed at using nanocomposites as coatings
Reliance Technology Research 4360P	Tarapur, Taiwan	Conducting polymers, polystyrene and polyester	Searching for compounds with improved anisotropic, gas barrier, and mechanical properties

Table 1. A list of companies developing nanocomposites technology. Numbers in parentheses refer to the company's website.

Moreover, clay surfaces can be modified to absorb organic chemicals (referred to as intercalants) instead of water through a substitution reaction. Spacing between the clay layers, which resemble a deck of cards, can be increased so that the clay can be separated so that the surface area is increased. This is called "exfoliation."

Nanocomposites are developed by mixing polymer with organo-clay, carbon nanotubes, carbon fibers, carbon nanocomposites, layered silicates,

and other plastics. The matrix is now a polymer, based in St. Louis, is now one of dozens of companies that are developing nanocomposite technologies (table).

Initial research on nanocomposites began in Japan in the 1980s at Toyota Central Research Labs, which has a lot of patents. Today, efforts are being conducted in Taiwan, England, the U.S., and elsewhere. Such research programs are being conducted by other plastics manufacturers.

The first significant commercial applications for nanocomposites are in films, but they also can be used in molded and thermoformed parts. Koles now emerging for the materials include:

- **Tougher, yet lighter, auto auto parts.**
- **Improved gas barrier properties for packaging.**
- **Improved barrier properties for packaging.**
- **Improved barrier properties for packaging.**
- **Improved barrier properties for packaging.**

TERMOPLASTIC ELASTOMERS

Olefin-based nanocomposites hold potential for automotive

Monell North America and General Motors Research and Development have developed thermoplastic olefin elastomer-based nanocomposites that hold great potential in expanding plastics use in the automotive industry, particularly in large structural applications.

The breakthrough technology is claimed to be the first development of nanocomposites in nonpolar materials. Other efforts primarily in polar polymers like nylon.

Development work in this arena has been running at a feverish pace worldwide. Nanocomposites are fundamentally a new class of materials that use tiny clay platelets to improve mechanical properties. The monomers are 25-30 nm (28). The monomers have aspect ratio, offer an array of improved properties. In olefins, nanocomposites promise reduced weight, improved dimensional stability and improved properties as stiffness and low temperature impact strength.

"It's like finding the holy grail," William Windischel, director of sales and marketing for Monell's automotive business group, said during a re-

cent press briefing at the firm's Automotive and Technology Center in Troy, Mich.

"Everyone in automotive wants high stiffness, without sacrificing toughness," at low weight.

GM and Monell have developed a proprietary process to produce injection molded parts including a rear quarter panel and exterior door panel. Material validation is underway. The process is expected to be completed within 12 to 18 months.

Eusebi, polymers development at GM's R&D, says any commercial use would require material validation. He says that new market potential has opened up by materials that show greater freedom to use plastic in the greater freedom to use plastic in the car. 44006

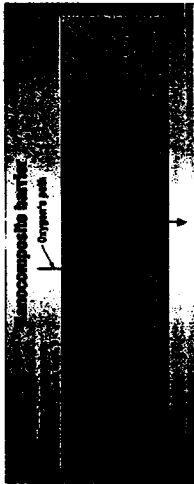


Monell and GM officials examine prototype exterior door and rear quarter panels which are injection molded of novel POE-based nanocomposites. (Photo: GM, Monell)

searched by General Motors and GM Products Inc. The technology is being developed at about 100 GM facilities. The evolution is a spin-off technology from GM's research on the use of nanoparticles and the plastics and

markets include automotive interior and exterior. Thus, the National Institute of Standards and Technology in the U.S. recently awarded Dow Chemical and Magna International a \$7.8-million grant to develop nanocomposites for use in lightweight vehicles.

Another company eagerly awaiting larger quantities of nano clays is Ford Motor Co., Dearborn, Mich.



Nanocomposites are said to form a barrier path through any plastic.

"What we really like about these materials is that they increase stiffness without causing a loss in impact strength, which is usually the case with fillers," comments Jack Chu, materials engineer for Ford's Visteon Automotive Systems Group.

"We are focusing on PP because that is the trend in cars, particularly scratch-resistant PP with molded-in color," says Chu. The PP nanocomposites are used for interior and exterior parts.

The first licensee of ICI's commercial nylon 6 nanocomposites are glass reinforced. Target markets are automotive, thinwall reinforcement equipment, and lawn and garden products. A major attraction of the new series will be reduced fuel wear, comments Guy A. Vaughan, automotive marketing manager.

Certainly, one might expect that potential in durable goods applications. Research by Professor F.P. Giannelis of Cornell University, Ithaca, N.Y., indicates that the low flammability of nanocomposites is due to excellent barrier properties that slow the movement of volatile fuels.

Barrier is a barrier. Nanocomposites also have potential in films. ICI has introduced two grades of potential applications for NCH film with next generation packaging and food packaging. ICI is currently testing them in liquid gasoline tanks and fuel-line tubes.

ICI reports two applications in the Far East for its nylon 6

nanocomposites. A three-layer food packaging film for fresh produce and shock absorber for a laundry machine chamber. An auto part requiring good thermal properties is under development. Nylon nanocomposites appear to absorb less moisture than other filled nylons, an important benefit in molded parts, Ube reports.

Major efforts are also under way in the U.S. to develop proprietary nylon nanocomposites. ICI has

clays, they are superior to Evox and PVO. The ICI films are clear and flexible. The ICI films are clear and flexible to nitrocellulose inks. Food contact is approved in Europe.

The nano-coated film, however, overcomes a problem associated with inorganic coated films - loss of barrier during conversion and handling. That is according to ICI's S.W. Sankey, who spoke at Specialty Plastics conference held last December in Chicago. ICI has an application in chloride check valves, ball valves and coated metals in Germany.

The clay platelets used by ICI are untreated vermiculite supplied by W.R. Grace, Cambridge, Mass. Vermiculite offers an even higher aspect ratio than other synthetic clays - from 1000 to 15,000, according to Leon Babouziarian, product manager of the Specialty Vermiculites Group at W.R. Grace.

Another U.S. company, Claytec, Laney, Mich., has developed a nanocomposite technology for epoxy. Claytec has exclusive rights to commercially develop patented inventions in epoxy nanocomposites granted to Thomas J. Pinnavaia, University Distinguished Professor of Chemistry at Michigan State University. Work at MSU indicates that nanocomposites contribute significantly to the tensile strength and flexural modulus, as well as gas-barrier properties. Epoxy composites are used in aircraft.

Superior results. Epoxy composites are used in aircraft. Epoxy composites are used in aircraft. Epoxy composites are used in aircraft. Epoxy composites are used in aircraft.

Due for completion in April is a contract to produce clear, colorless, and odorless epoxy resin (name Nanosol). Annual production, Nanosol is expected to be spending some \$4.5 million on nanocomposites.

John Hughes, CEO of Amcol, says that market prospects are good for nanocomposites, although he concedes that development has been slower than expected.

"We originally targeted an opening price per pound of 1997," says Hughes. "We are now targeting a price of 1999 and to a 2000 price."

(Continued on p. 30)

History of Nanocomposite-Synthesis

Year	Group	Title	Comments
1987	O. Kamigaito (Toyota)	Polyamide Nanocomposite Synthesis using Caprolactam and Montmorillonite treated with protonated 12-Aminolauric acid	IS=51-210 A, HDT: 65->152 °C, Tensile Strength: 69->107 MPa, Tensile Modulus: 1.1->2.1 MPa
1988	C. Kato (Waseda Univ.)	Polymerization-Intercalation of PAN, firstly for Kaolinite : Kao-DMSO → Kao-Ammonium Acetate → AN-Intercalation → Polymerization (Kao-PAN)	IS=7.1 A
1993	E. P. Giannelis (Cornell Univ.)	Direct Intercalation of Polystyrene Melts in Layered Montmorillonite using dioctadecyldimethylammonium ion as an Intercalant	IS=22A, MW=35,000 and 400,000 163 °C and 25 hr
1994	T. J. Pinnavaia (MSU)	Montmorillonite-Epoxy Nanocomposite using Long Chain (n>=12) Alkyl Ammonium Ion as an Intercalant and Jeffamine 2000 as a Curing Agent	IS=80-150A 40-60 % elongation at break for 15 wt% loading of Montmorillonite
1996	C. Deterlier (U. of Ottawa)	Synthesis of Kaolinite-PEG by Direct Intercation of PEG Melts using Kao-DMSO	IS=4.0 A MW=1,000 and 3,400
1997	O. Kamigaito (Toyota)	Preparation of Montmorillonite-Polypropylene Nanocomposites by Compounding Method	Perfectly Exfoliated Nanocomposite 80 % Increase in Dynamic Modulus
1999	G. S. Sur (Youngnam Univ.)	Synthesis of Montmorillonite-PEO Nanocomposite by Direct Intercation of PEO Melts without Organic Intercalant	IS=4.6A 10-13 Multilayer Silicates

KIST
Nano Materials Technology

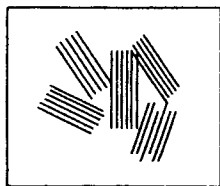
Companies in Structural Nanocomposites

Who's who in nanocomposites*			
Company	Location	Polymer Type	Role
Toyota Central R&D Lab Inc.	Nagakute, Aichi, Japan	Nylon6	Original technology developer; no current uses of nanocomposites
Ube Industries	Ube City, Japan	Nylon 6, nylon 66, nylon 12	First Toyota licensee and developer of nylon 6 compounds for use in timing belt cover
Nanacor	Arlington Heights, IL	Focus on, but not limited to, nylon, polyester, PP	Nanacor was created by Amcol International to develop nanocomposite technology using its own patents and nonexclusive Toyota license
Dow Chemical	Midland, MI	Not specified	Participant with Magna International in study of nanocomposites use in vehicle manufacture
ICI Polyester	Middlesborough, England	Polyester	Commercializing clear barrier film using nanocomposite coating
Ford Motor	Dearborn, MI	Polypropylene	Evaluating nanocomposites for interior and exterior automotive applications
Allied Signal	Morrisstown, NJ	Nylon 6	Holds patents on nanocomposites
Solutia Inc.	St. Louis, MO	Nylon 6, 66, and copolymers	Company has developed technology and is eyeing automotive applications
Cleytec	Lansing, MI	Epoxy	Startup by professor at Michigan State University; commercializing epoxy end-uses
DuPont	Wilmington, DE	Fluoropolymers	Holds patent that is apparently aimed at using nanocomposites as coatings
Industrial Technology Research Institute	Taipei, Taiwan	Conducting polymers, polystyrene, polyester	Searching for compounds with improved antibiotic, gas barrier, and mechanical properties

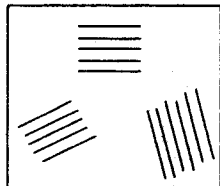
*: Partial list of companies developing nanocomposite technology. Numerous other development programs are confidential or academic in nature.

KIST
Nano Materials Technology

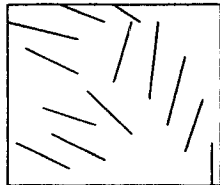
Advantages of Organic/Inorganic Nanocomposites



Conventional Intercalated (No polymer intercalation) (Limited intercalation)



Intercalated (Limited intercalation)

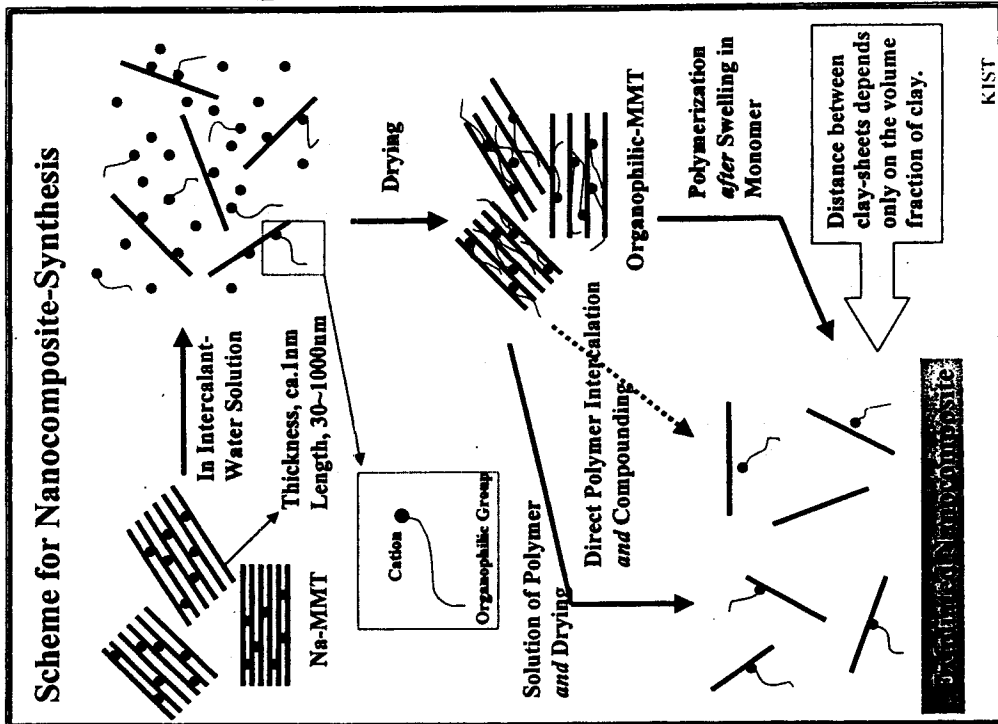


Exfoliated (Extensive intercalation)

- High Mechanical Properties
- Thermal Properties (High HDT)
- Gas and/or Water-Barrier Properties
- Rheological Properties
- High Insulating Properties
- Protective Coating Properties

Matrix	Filler	Filler Content, %	% Improvement
Epoxy	Clay	10	67
	Clay	4.1	216
PP	Talc	40	13
	Glass Fiber	30	103
PA6	Glass Fiber	30	56
	Glass Fiber	30	94

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표 2-9-2. Nylon 6/ Montmorillonite 복합체의 물리적 특성

	Nylon 6	NCC*	NCH**
Montmorillonite content (wt%)	0	5.0	4.2
Tensile strength (MPa)	69	61	107
Tensile modulus (GPa)	1.1	1.0	2.1
Charpy impact strength (KJ/m ²)	6.2	5.9	6.1
HDT (1.82N) (°C)***	65	89	152
Water absorption, 23°C, 1day (%)	0.87	0.90	0.51
CTE($\times 10^{-5}$ cm/cm°C) †	11.7	10.3	6.3
‡	11.8	13.4	13.1

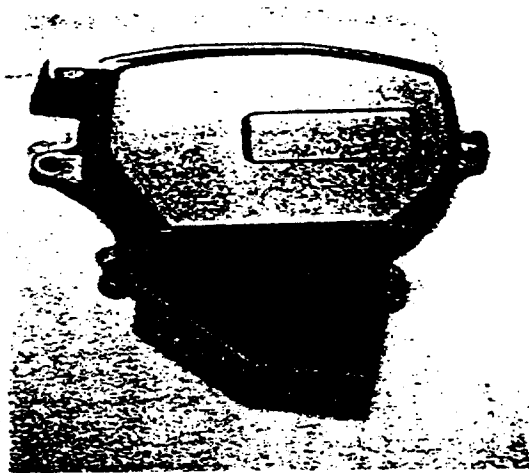
*Nylon 6/Mont composite by the conventional method

**Nylon 6/Mont nano-composite

***Heat distortion temperature

Polymer Hybrid Center, KIST

그림 2-3. NCH 나노 복합체의 사출
성형품인 timing belt cover



Polymer Hybrid Center, KIST

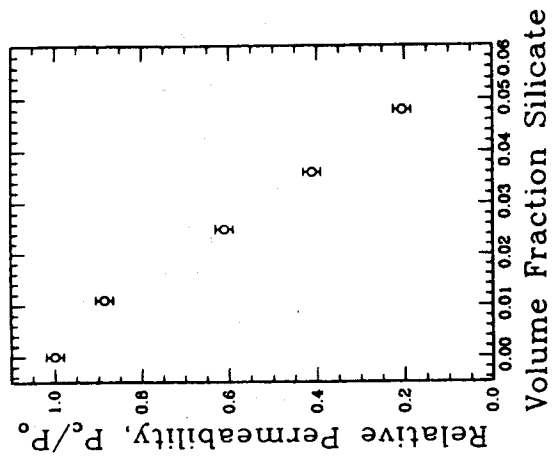


그림 2-4. clay/Poly(epsilon-caprolactone)
나노복합재의 수증기 투과능

표 2-9-3. PP/Talc, PP/Montmorillonite 복합체의 기계적 특성

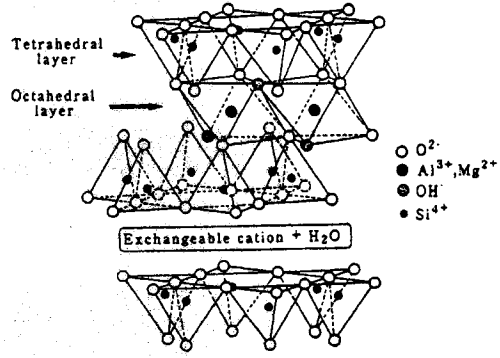
Composition (wt%)	PP	PP/talc	PP/Mont*
PP-1	50	47.5	44
PP-2	50	47.5	44
talc	0	3.0	0
MDH**	0	0	12
Density (g/cm ³)	0.1	0.92	0.93
Melt index (g/10min)	23	16	12
Tensile strength (MPa)	31	35	39
Tensile modulus (MPa)	-	-	2.1
Elongation (%)	300<	92	22
Flexural strength (MPa)	38	45	53
Flexural modulus (MPa)	1.5	1.9	2.4
Izod impact strength (KJ/m ²)	97	72	72
HDT (°C)	120	-	130

*Montmorillonite 3wt%, **chemically-modified PP/Mont complex

•Filler의 요건

Matrix인 polymer 와 친화성 부여

- 점토광물
- 층상구조
- High aspect ratio
- 큰 팽윤성



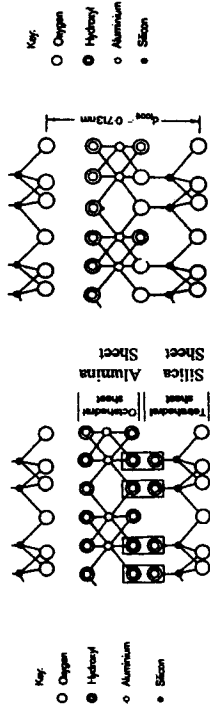
Montmorillonite(MMT) 구조

Polymer Hybrid Center, KIST

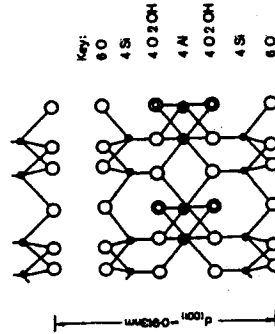
Molecular structure of clay

The structural framework of clay minerals is basically composed of layers comprising silica and alumina sheets, joined together in varying proportions and stacked in a certain way

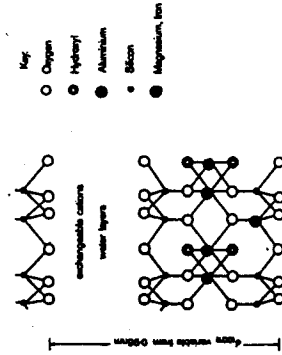
Kaolinite Group 1:1 ratio



Pyrophyllite Group 2:1 ratio



Montmorillonite 2:1 ratio



Substitution occurs such as
 $Al^{3+} \rightarrow Mg^{2+}, Fe^{2+}$ and $Si^{4+} \rightarrow Al^{3+}$

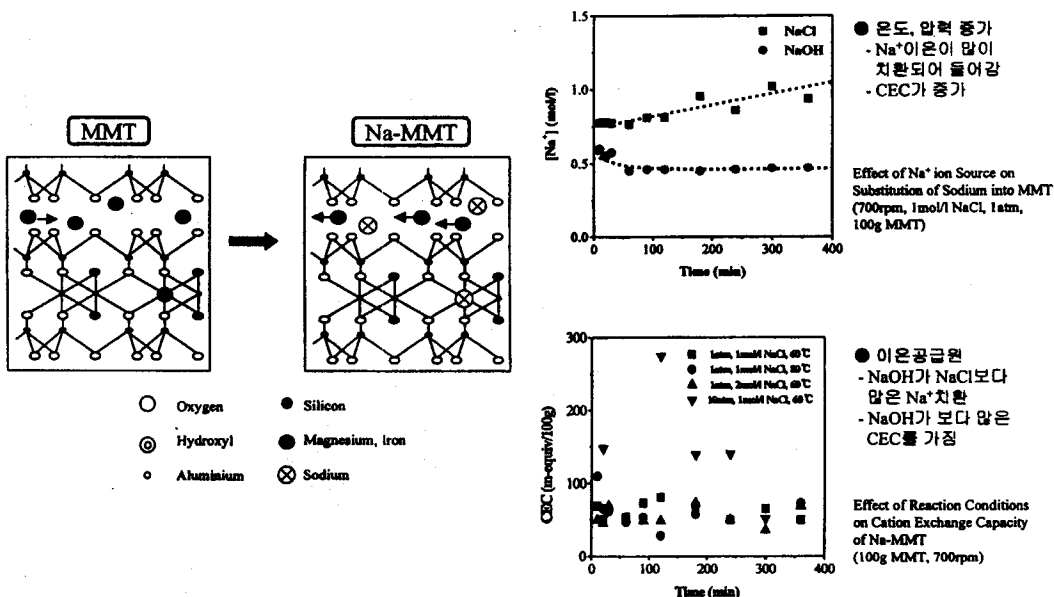
Polymer Hybrids Research Center, KIST

Intercalants in use

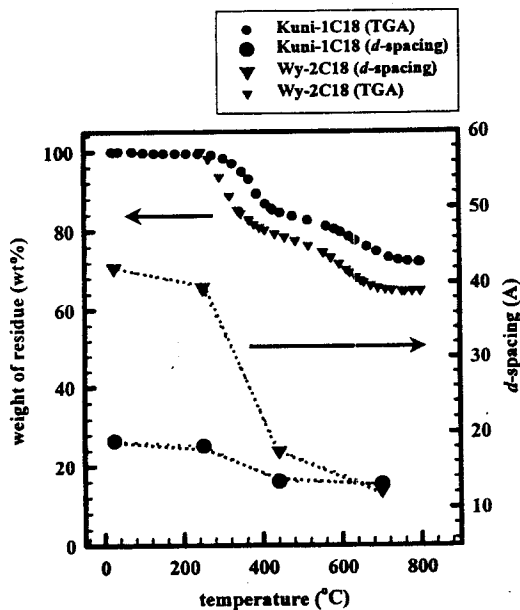
Chemical formula	Nomenclature	Melting point (°C)	Reference
$\text{CH}_3\text{N}^+\text{H}_3\text{Cl}^-$	Methylamine hydrochloride	228	1
$\text{CH}_3(\text{CH}_2)_2\text{NH}_2$	Propyl amine	-83	2
$\text{CH}_3(\text{CH}_2)_3\text{NH}_2$	Butyl amine	-50	3,4
$\text{CH}_3(\text{CH}_2)_4\text{NH}_2$	Octyl amine	-3	3,4
$\text{CH}_3(\text{CH}_2)_6\text{NH}_2$	Decyl amine	13	4
$\text{CH}_3(\text{CH}_2)_8\text{NH}_2$	Dodecyl amine	30	3,4
$\text{CH}_3(\text{CH}_2)_{10}\text{NH}_2$	Hexadecyl amine	46	3,4
$\text{CH}_3(\text{CH}_2)_{12}\text{NH}_2$	Octadecyl(or Stearyl) amine	57	3,4,5
$\text{HOOC}(\text{CH}_2)_6\text{NH}_2$	6-Aminohexanoic acid	205	6
$\text{HOOC}(\text{CH}_2)_{11}\text{NH}_2$	12-Aminododecanoic acid	186	6,7
$(\text{CH}_3)_4\text{N}^+\text{Cl}^-$	Tetramethyl ammonium chloride	>300	1
$\text{CH}_3(\text{CH}_2)_8\text{NH}(\text{CH}_3)$	N-Methyl octadecyl amine	45	1
$\text{CH}_3(\text{CH}_2)_{10}\text{N}^+(\text{CH}_3)_2\text{Br}^-$	Octadecyl trimethyl ammonium bromide	-	4
$\text{CH}_3(\text{CH}_2)_{11}\text{N}^+(\text{CH}_3)_2\text{Br}^-$	Dodecyl trimethyl ammonium bromide	246	1
$(\text{CH}_3(\text{CH}_2)_8)_2\text{N}^+(\text{CH}_3)\text{Br}^-$	Diocadecyl dimethyl ammonium bromide	-	1,8-10
$\text{CH}_3(\text{CH}_2)_{10}\text{N}^+(\text{C}_6\text{H}_5)(\text{CH}_3)_2\text{Br}^-$	Dimethyl benzyl octadecyl ammonium bromide	-	10
$\text{CH}_3(\text{CH}_2)_{10}\text{N}^+(\text{HOCH}_2\text{CH}_2)_2\text{CH}_2\text{Cl}^-$	bis(2-hydroxyethyl) methyl octadecyl ammonium chloride	-	10-12
$\text{CH}_3(\text{CH}_2)_{10}\text{CH}_2(\text{C}_6\text{H}_4\text{N}^+)\text{Br}^-$	1-Hexadecylpyridium bromide	69	13
$\text{H}_2\text{N}(\text{CH}_2)_6\text{NH}_2$	1,6-Hexamethylene diamine	44	6
$\text{H}_2\text{N}(\text{CH}_2)_{12}\text{NH}_2$	1,12-Dodecane diamine	70	6

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Synthesis of Na-MMT



The space arrangement of intercalant in OLS



the weight loss from TGA
&
the trend of *d-spacing* reduction
by thermal degradation



intra-gallery substitution of
intercalants
&
trans-conformation for 2C₁₈

Polymer Hybrids Research Center, KIST

Internal structure of OLS's agglomerate

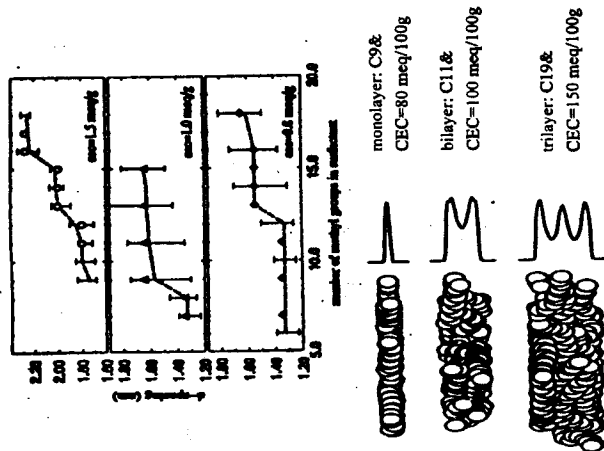


Figure. Effects of CEC-value and the chain length of intercalants on *d-spacing*: (a) XRD (dashed line) and simulation results (symbol); (b) snap shots and concentration profiles from simulation results.

Polymer Hybrids Research Center, KIST

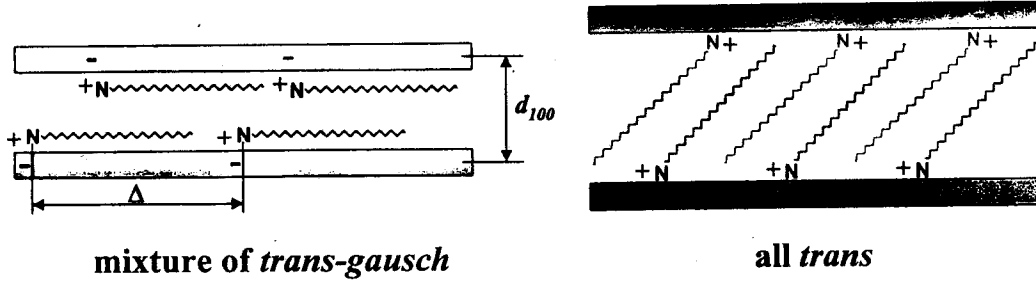
Factors governing the gallery height change in _____
organically modified layered silicates (OLS)

$$d_{100} \sim f(\Delta/n, \delta)$$

Δ ($\sim f(\text{CEC})$) : charge distribution

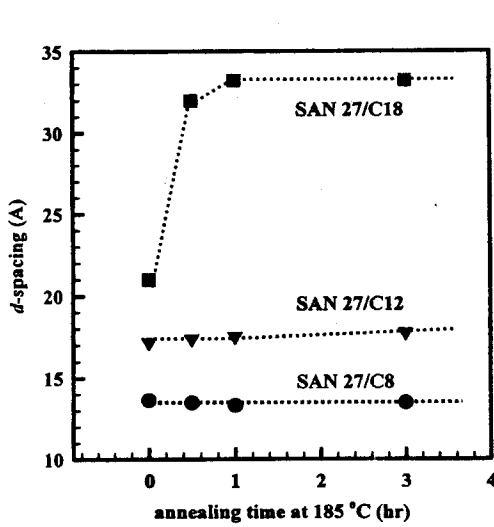
n : geometric factor such as the length/number of chain

δ : specific interactions between clays or clay and organics



Polymer Hybrids Research Center, KIST

The effect of length of intercalant in OLS -

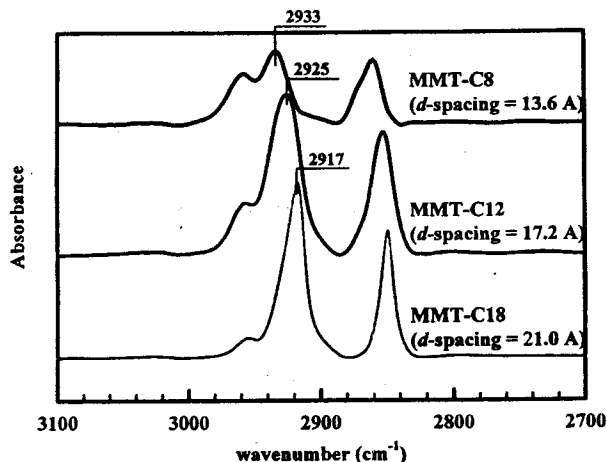


the length of intercalant ↑
 ↓
 empty space for polymer diffusion ↑
 ↓
 noticeable increase of *d*-spacing
 ↓
 existence of critical *d*-spacing
 for matrix diffusion

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Conformation change of intercalant in OLS

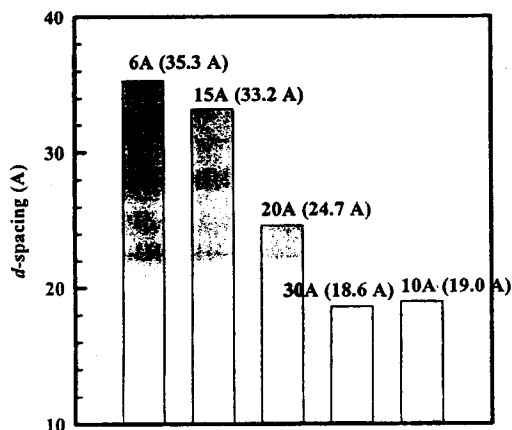
asymmetric CH_2 stretching mode, $\nu_{\text{as}}(\text{CH}_2)$:
 in *gausch* state $\sim 2930 \text{ cm}^{-1}$ for all-*trans* ordered state $\sim 2917 \text{ cm}^{-1}$



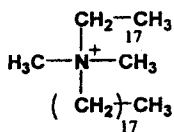
the length of alkyl chain ↑
 ↓
 spatial restriction ↑
 ↓
 more ordered conformation
 (*gausch* → *trans*)
 &
 d_{100} increase

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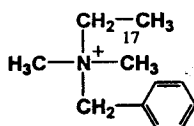
Modified layered silicates



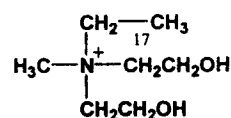
CEC ↑
 or
 the number of alkyl chain ↑
 of intercalant
 or
 crystallinity ↑
 ↓
 d_{100} -spacing ↑



6A (CEC = 140 meq/100 g)
 15A (CEC = 125 meq/100 g)
 20A (CEC = 95 meq/100 g)



10A (CEC = 125 meq/100 g)



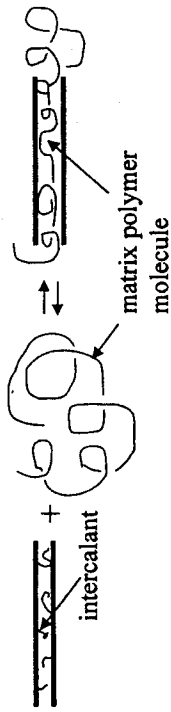
30A (CEC = 95 meq/100 g)

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Thermodynamics of melt intercalation

$$\Delta G = \Delta H - T\Delta S$$

Case 1. No Interaction between Clay and Intercalant

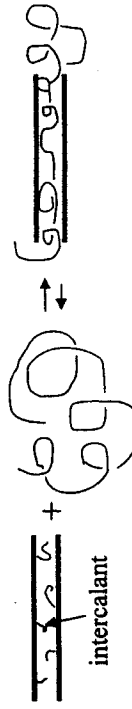


A. $\chi_{ep} < 0$ & $\chi_{ip} = 0$
 $\Delta H_{ep} < 0$, $\Delta H_{ip} = 0$, and $T\Delta S < 0$
 $\Rightarrow \Delta H_{ep} < T\Delta S < 0$ for Intercalation of Polymer Chain

B. $\chi_{ep} = 0$ & $\chi_{ip} < 0$
 $\Delta H_{ep} = 0$, $\Delta H_{ip} = 0$, and $T\Delta S < 0$
 $\Rightarrow \Delta G > 0$ No-Intercalation of Polymer Chain

C. $\chi_{ep} < 0$ & $\chi_{ip} < 0$
 $\Delta H_{ep} < 0$, $\Delta H_{ip} = 0$, and $T\Delta S < 0$
 $\Rightarrow \Delta H_{ep} < T\Delta S < 0$ for Intercalation of Polymer Chain

Case 2. Strong Interaction between Clay and Intercalant



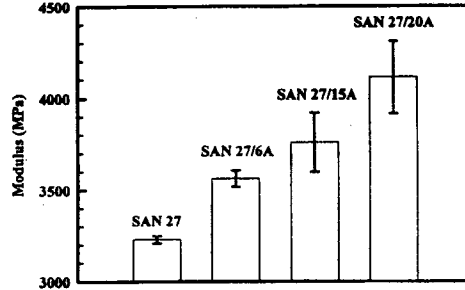
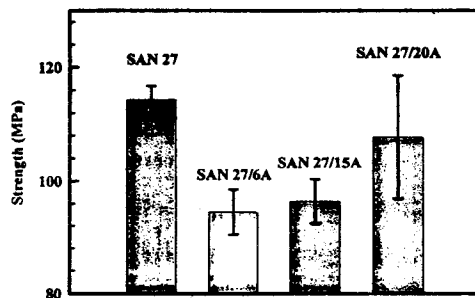
$\chi_{ep} < 0$ & $\chi_{ip} < 0$
 $\Delta H_{ep} < 0$, $\Delta H_{ip} < 0$, and $T\Delta S < 0$
 All of ΔH_{ep} , ΔH_{ip} , and $T\Delta S$ must be considered.

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Mechanical properties of extruded nanocomposites

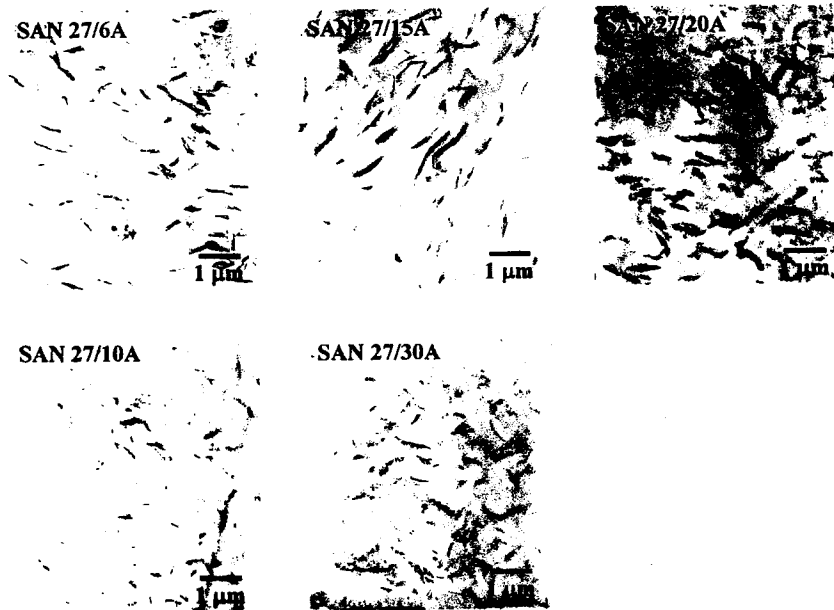
mechanical properties of composite

$\sim f(\Delta d, \text{ amount of exfoliation})$



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TEM microphotographs of extruded nanocomposites



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Future researches

- To evaluate the dominant factors to control the intercalation/exfoliation mechanisms for polar matrix system
- To design/synthesis the optimum intercalating agents
- Development of exfoliated polar matrix nano-composite by suppression of “glue effect”
- Development of interlayer-force-controlled MMT
- Development of exfoliated non-polar nanocomposites

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