

NANO TECHNOLOGY BASED ON THE KNOWLEDGE OF TRADITIONAL CERAMICS AND CLAYS

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Nano technology is regarded as a very new and advanced technology. Therefore technologies of traditional ceramics and clays may be thought that they have no relations with the nano technology because the origins of these technologies are very old. However the technologies have intimate relations with the nano technology. Nano scale phenomena act important rolls in those old technologies. In this paper, technologies of traditional ceramics and clays are considered from a view point of the nano technology through our research history.

1. INTRODUCTION

Nowadays, nano technology is becoming one of the most widely used terms in scientific and technological research and development. The impression of the term “Nano Technology” is very new and advanced, therefore many people may fell the nano technology is not related to the technologies of “Traditional Ceramics” and “Clays” since the origin of these technologies are very old. However, from our standpoint, the old traditional ceramics and clays technologies actually have strong relations with the nano technology. One example is that the sizes of natural clay particles themselves are nano scale. Another example is that many phenomena occurred on the particle surface during ceramics forming or sintering is nano scale. Nano-technologies have been used for the production of traditional ceramics without considering that the technologies of traditional ceramics are related to the nano-technologies because the origins of technology have been given by the nature.

Figure 1 shows the relations of our works on ceramics and clays. The center part of our work is “Clay Science”, especially as a meaning of thinking base, because clay is one of most important raw materials for the production of traditional ceramics. Our research work was started in the field of clay science and the work field has been spread to application fields such as ceramic forming, self humidity control materials and so on as show in Fig. 1.

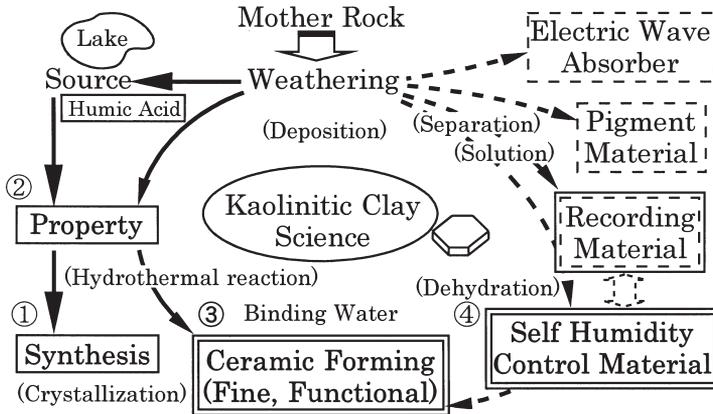


FIGURE 1 - Relations of research works on traditional ceramics and clays.

In this paper, four topics “Synthesis of Artificial Clay”, “Property of Clay”, “Ceramic Forming Technology” and “Self Humidity Control Material” will be considered from a view point of “Nano Technology”.

2. SYNTHESIS OF KAOLINITE

Kaolinite is one of clay minerals widely used as a raw material for the production of traditional ceramics. We have a massive deposit of high quality kaolinitic clay at Seto-region in Japan. The deposit is very large scale, but the exhaust of clay resource was prospected because of mass production of potteries at Seto-region some decades ago. Under such situation, a development project of artificial clay, namely the research on synthesis of kaolinite, was started. The project had been performed under the leadership of National Industrial Research Institute of Nagoya (NIRIN, present: AIST Chubu) in corporation with eight prefectural institutes and Research Association for Artificial Clay which consist of six private companies. The project scheme was as follows,

- (1) Synthesis technology of artificial clay
 - a: Development of hydrothermal technology for synthetic kaolinite
 - b: Development of treatment technology for artificial clay
- (2) Application technology for artificial clay
 - c: Evaluation of properties
 - d: Application of artificial clay for ceramics

The results of kaolinite synthesis are summarized in Fig. 2. Various kinds of starting materials were used as shown in the figure. It was found that the

appropriate synthesis conditions depended on the raw materials and obtained kaolinites showed various morphologies. It was also recognized that the hydrothermal treatment has another effects on kaolinite synthesis, particularly deironation. Purity of the product is improved by this effect.

The formation process of kaolinite was investigated by NMR. The estimated kaolinite formation process is schematically illustrated in Fig. 3. Q^4 (tect-silicate) and Q^2 (cyclo-silicate) were observed in the calcium-aluminum-silicate amorphous raw materials. Under the hydrothermal

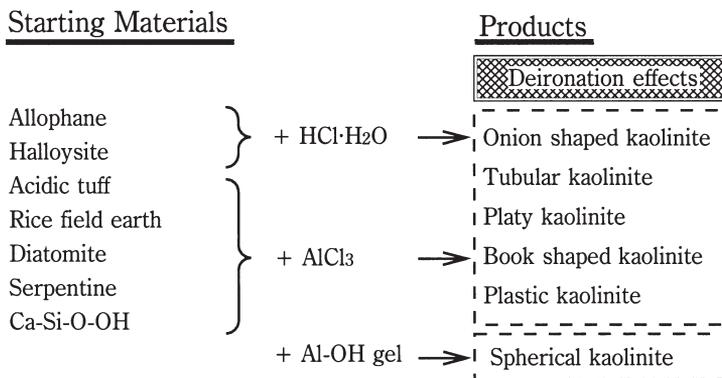


FIGURE 2 - Results of research on kaolinite synthesis for 1977-1993 in GIRIN under hydrothermal condition ($pH = 7$, $P_{H_2O} = 100atm$, $T = 300\text{ }^\circ C$, $t = 60days$).

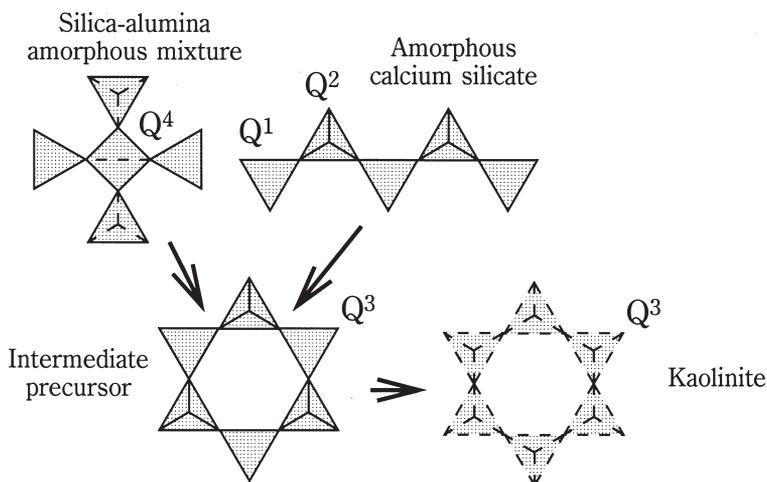


FIGURE 3 - Estimated formation process of kaolinite by ESR measurement.

conditions, hydration, dissolution, and precipitation of kaolinite occur. Then, an intermediate precursor is formed and kaolinite is precipitated.

Figure 4 shows TEM photographs of (a) synthesized kaolinite and (b) natural kaolinite. Synthesized kaolinite has been produced commercially by TOYO DENKA KOGYO (Kochi, Japan) using Ca-Si-O-OH as the starting material. As seen in the photographs, synthesized kaolinite consist of rather fine and uniform particles though natural kaolinite includes larger particles over $1\mu\text{m}$. The size of most synthesized kaolinite particles are submicron order, i.e. nano meter order.

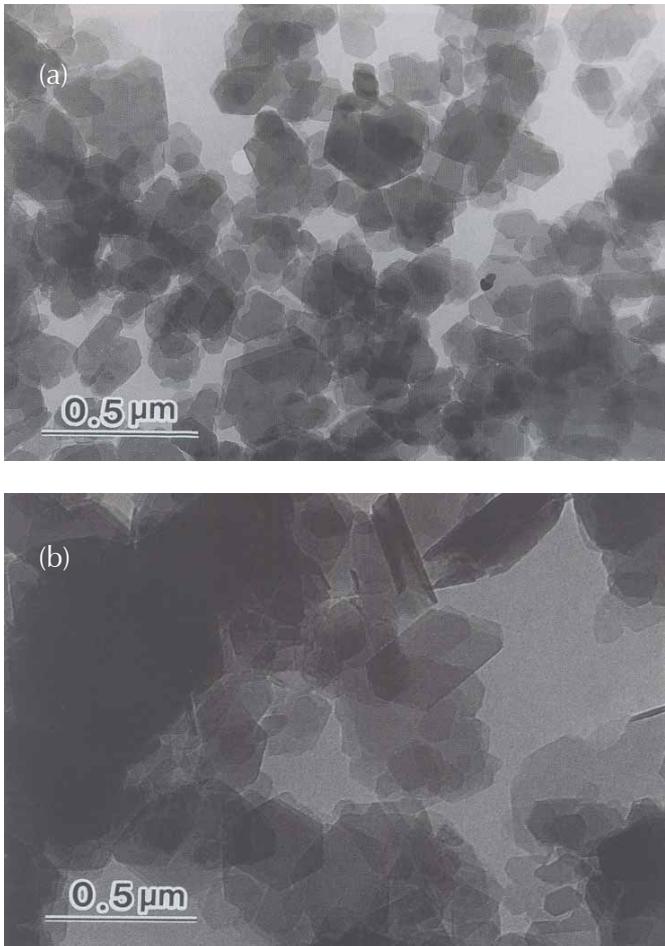


FIGURE 4 - TEM photographs of (a) synthesized kaolinite and (b) natural kaolinite.

3. PROPERTIES OF CLAYS

It is important to know the properties of clays for producing ceramic products. Wet forming processes such as wet pressing, extrusion, slip casting and so on are widely applied in ceramic forming processes. In these processes, it is important to know phenomena occurred on the solid particle surface, especially the particle-water interaction behaviors. Figure 5 schematically shows the main factors of kaolinite synthesis and the main factors necessary for surface treatment and wet forming. The key technologies terms are surface charge, cluster and rheology. Properties of synthesized kaolinite and natural clays are examined in this point of view.

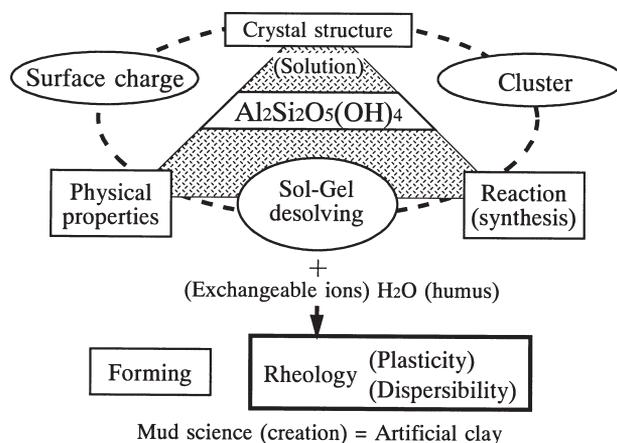


FIGURE 5 - Main factors of kaolinite synthesis and main factors necessary for surface treatment and wet forming.

The basic structure of kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) has entwined SiO_4 tetrahedral sheets and $\text{Al}(\text{OH})_6$ octahedral sheets forming a 1:1 layer with shared vertex oxygen. As all the OH bases in the octahedral sheets cannot share all the oxygen in the tetrahedral sheets, they remain both inside and outside the layer. Refinement of the arrangement and location of the protons within this layer has not been completed to date.

There is strong demand for a common scale to evaluate the degree of crystallization of kaolinite, and many proposals have been made. The Hinckley Index is most commonly used. Plate-shaped kaolinite shows considerable relationship between the origin and the Hinckley Index. Kaolinite resulting from high-temperature, high-pressure water (hydrothermal condition) usually has a high Hinckley Index (≥ 1.0), while that of weathering origin is normally low (≤ 0.5).

Figure 6 indicates each specimen's molar relationship between ignition loss and SiO_2 and Al_2O_3 components (theoretical value of kaolinite: $\text{SiO}_2/\text{Al}_2\text{O}_3=2$). The result shows that artificial clay is closer to the theoretical value than natural clay powders. As natural clay powders contain humus, quartz and other substances, they deviate from the theoretical values. Fig. 6 also indicates the relationship between the refining degree to eliminate SiO_2 (quartz) and the elutriation classification (horizontal axis). The ignition loss (vertical axis) is proportional to the sum of organic substances and kaolinite.

Figure 7 shows the content of Fe_2O_3 and TiO_2 – the least desirable components for high quality porcelain and electro-ceramics. In this respect, synthesized kaolinite has better quality than natural clays. As mentioned before, low impurity level of Fe_2O_3 and TiO_2 in synthesized kaolinite may be achieved under the hydrothermal treatment.

Figure 8 shows the relationship between ignition loss and surface area (S) of natural clays and synthesized kaolinite. S was determined by the BET method. The result shows that S of synthesized kaolinite is larger than those of natural clays. This result is agreed with the TEM observation result shown in Fig. 4.

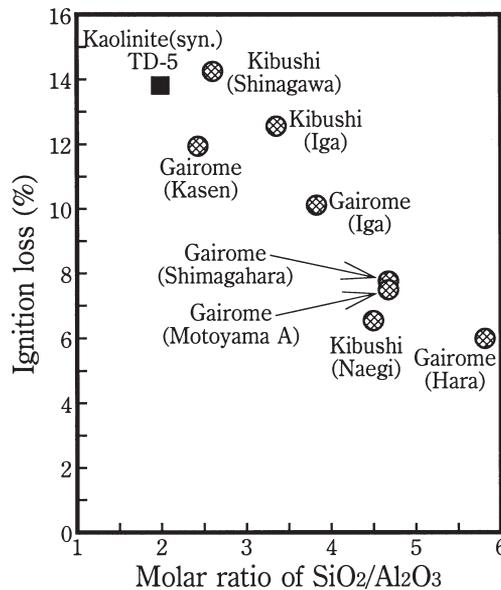


FIGURE 6 - Relation between ignition loss and the molar ratio of $\text{SiO}_2/\text{Al}_2\text{O}_3$ of natural clays and synthesized kaolinite.

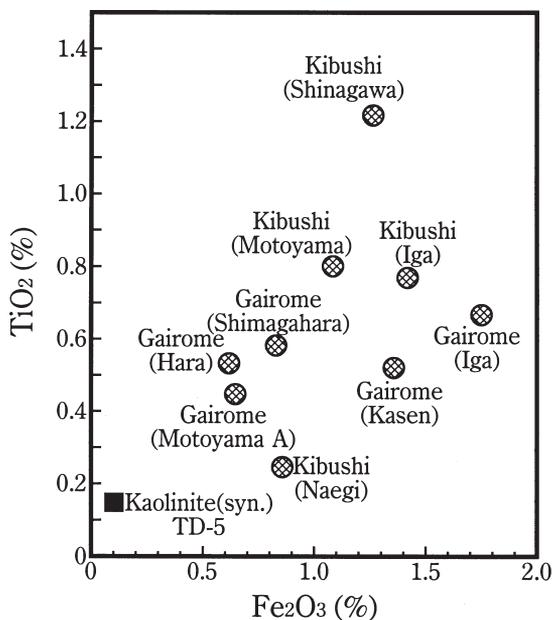


FIGURE 7 - Concentrations of TiO_2 and Fe_2O_3 impurities in natural clays and synthesized kaolinite.

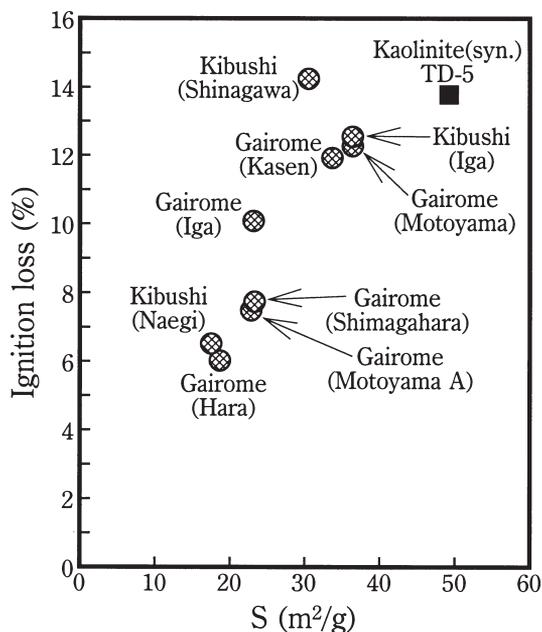


FIGURE 8 - Relationship between ignition loss and surface area (S) of natural clays and synthesized kaolinite.

Figure 9 shows the relationship between cation exchange capacity (CEC) per specific surface area and water film thickness. A linear relationship is observed. Japanese clays fall into one category. Synthesized kaolinite is also in this category. In contrast, Kanpaku kaolin, of hydrothermal origin, and Georgia kaolin, which has undergone a longer period of diagenesis than Japanese kaolin, have characteristics that deviated significantly from this trend. Synthesized kaolinite comprise almost 90% kaolinite and does not coexist with humus. These characteristics make synthesized kaolinite exceptional in comparison with natural clays. Usually the clay showing high plasticity has large CEC per specific surface area and ignition loss. Synthesized kaolinite has large CEC and ignition loss, therefore it may show high plasticity.

It is important to know the conditions of water on the surface of solid particles for wet forming of ceramics, developing a self humidity controllable material and so on. Differential Scanning Calorimeter (DSC) method is a useful technique to determine the restricted water on the solid surface and the free water in the inter particles pores. The restricted water is determined by calculating the difference between the measured water amount by the heat of fusion and the one by the heat of vaporization. Figure 10 shows a typical DSC curve. This datum was obtained for Suzhou-Kaolin. The DSC curve was

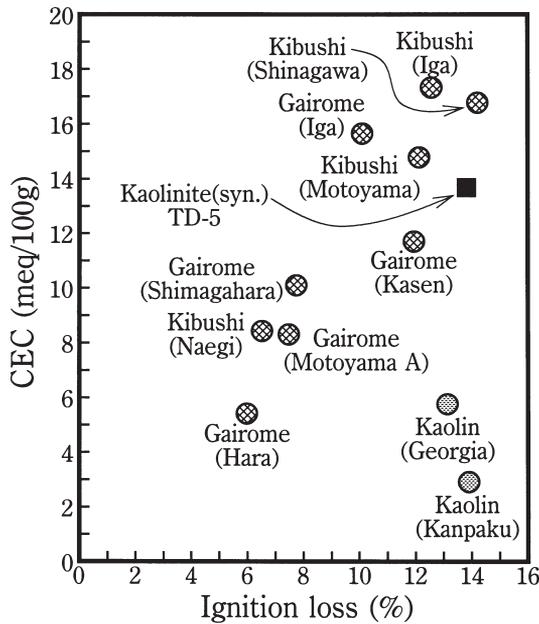


FIGURE 9 - Relationship between Cation Exchange Capacity (CEC) and ignition loss for natural clays and artificial clay.

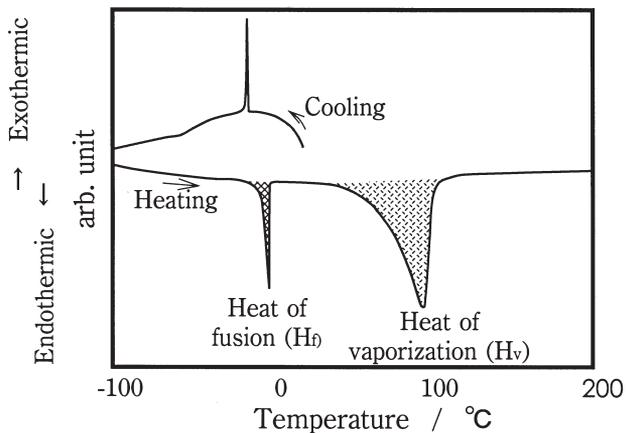


FIGURE 10 - Typical DSC curves measured during cooling and heating.

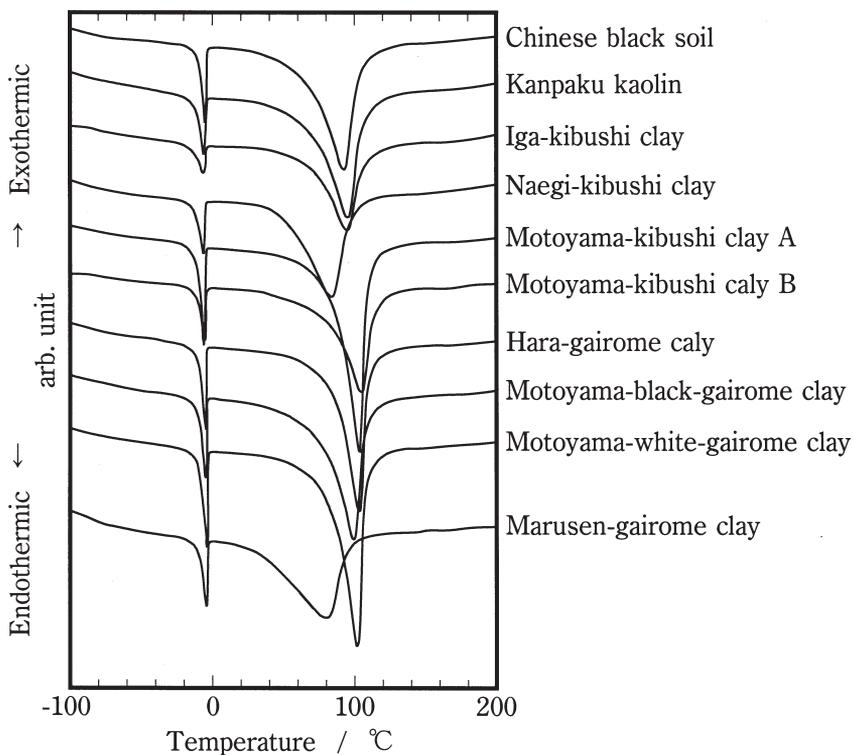


FIGURE 11 - DSC curves of various clay samples.

measured between the liquid nitrogen temperature and 200 °C. A rapid exothermic peak is observed on the cooling stage, at where the excess water is froze under over cooling condition. Around 0 °C, a sharp endothermic peak of fusion appears and a broad endothermic peak of vaporization appears over 0 °C on the heating stage. Two endothermic peaks on the heating stage of DSC curve are used for calculating the amount of restricted water, that is, unfrozen water. The amount of unfrozen water is calculated by next equation.

$$W_{UF} = H_v/Q_v - H_f/Q_f \quad (1)$$

Where, W_{UF} is amount of unfrozen water (mg/mg), H_v is measured heat of vaporization (mJ/mg), H_f is measured heat of fusion (mJ/mg), Q_v is evaporation heat of water (2258.9mJ/mg) and Q_f is the melting heat of water (333.9mJ/mg).

Figure 11 shows the DSC curves of various natural clay samples. All samples shows clear tow peaks around 0°C and 100°C, respectively correspond to the heat of fusion and the heat of vaporization, but the magnitude of the pesks are different with each other. It means that the amount of unfrozen water on the sample surface must be depending on the behavior of the sample surface. From these DSC curves, the amount of unfrozen water on sample surfaces is obtained, and then the thickness of unfrozen water film (DSC water film thickness) is calculated by the next equation.

$$\text{DSC water film thickness} = W_{UF} / S \quad (2)$$

We also evaluated the plasticity of clay green bodies by the Pfefferkorn method. This method was originally developed to evaluate the characteristic of soil on the field of civil engineering. Figure 12 shows an outline of Pfefferkorn method and how to calculate the values. A green body, 33mm in diameter and 40mm in height, is placed at the center. A steel plate is dropped from the high of 185mm. We obtain the relationship between the water content and the deformation ratio. Empirically, the green body is appropriated for the ROKURO-forming, that shows the ratio of 3.3. Then, the Plasticity Index (PI) can be determined as water content. We defined the water content difference between 40 °C and 100 °C as Water Retentivity (WR), and the ratio of WR to PI as Characteristic Value (CV) of plasticity.

Figure 13 shows the relationship between WR water film thickness (film thickness of bounding water, denoted by D_B) and DSC water film thickness (film thickness of unfrozen water, denoted by D_{UF}) for various kinds of natural clays and artificial clays. D_B and D_{UF} values of as synthesized artificial clays (synthesized kaolinite) depend on the starting raw materials as indicated by symbols (a) and (b). Artificial clay synthesized from Q⁴ raw material, i.e. Al-Si-O-OH, showed higher values of D_B and D_{UF} . D_B and D_{UF} of the artificial clay are increased by the calcium ion-exchange or by the organic surface

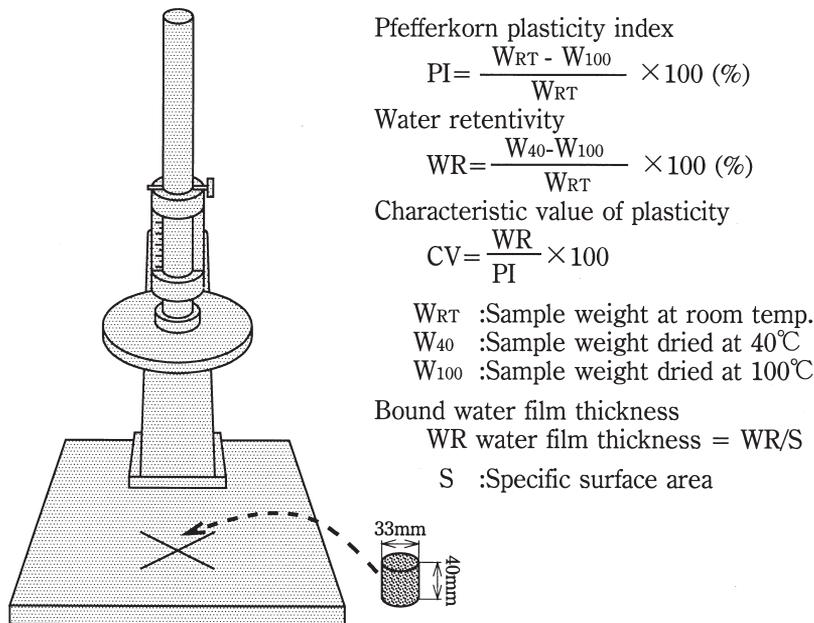


FIGURE 12 - Outline of Pfefferkorn method and how to calculate the values.

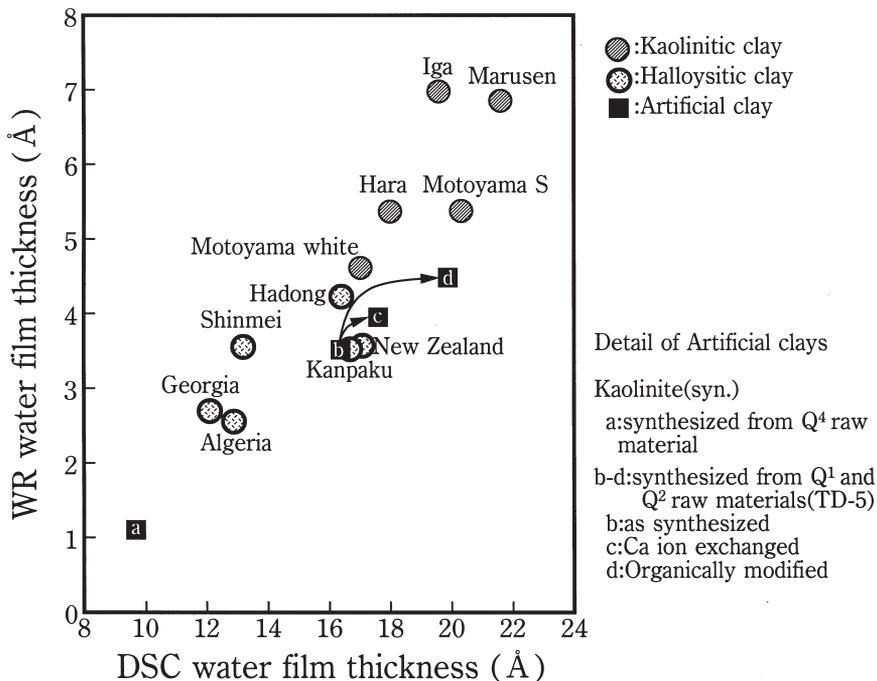


FIGURE 13 - Relationship between WR water film thickness and DSC water film thickness.

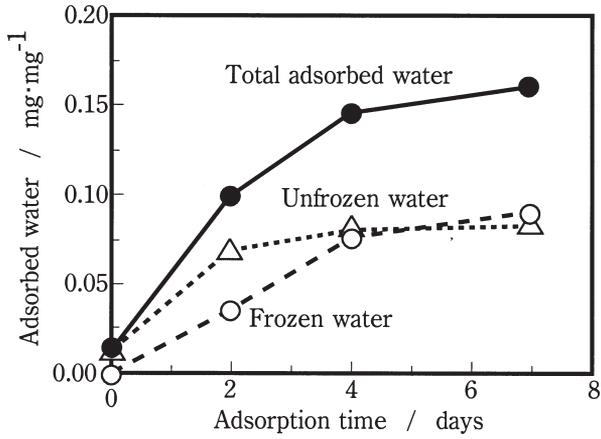


FIGURE 14 - Relationship between normalized amount of adsorbed water and adsorption time for Shidare-kibushi clay sample.

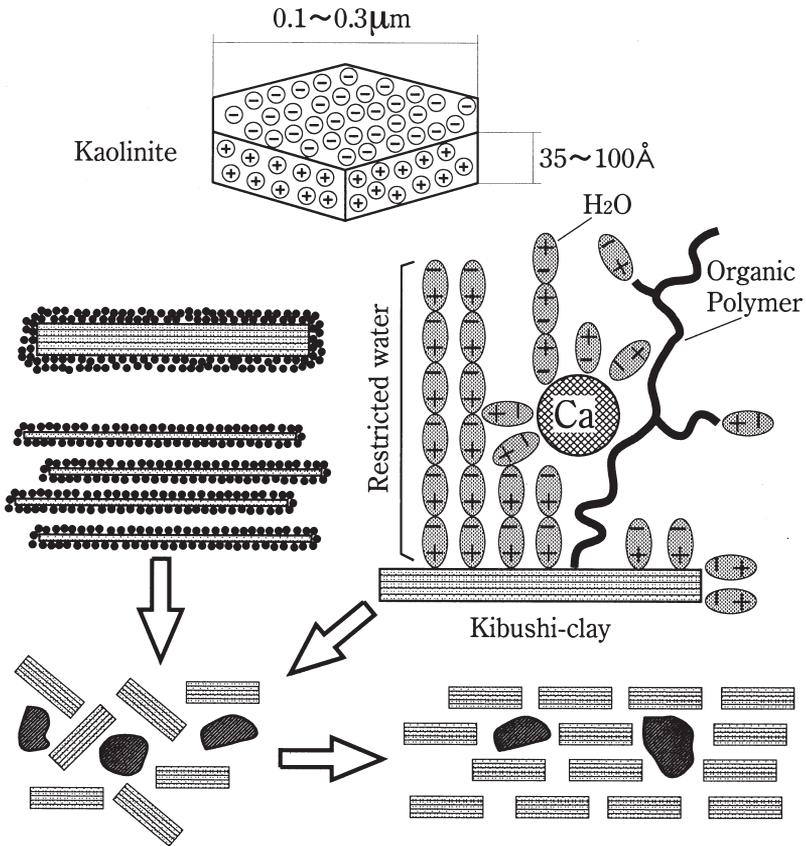


FIGURE 15 - Schematic model of restricted water on surface of Kibushi-clay particle.

modification with organic matter as indicated by symbols (c) and (d). The plasticity of artificial clay can be improved as well as that of natural clay showing high-plasticity by these treatments.

Figure 14 shows a typical result of relationship between the amount of adsorbed water and the adsorption time measured by the DSC method. This is a result of Shidare-kibushi clay. As shown in the figure, the amount of unfrozen water and total water increase with the time and the amount of unfrozen water is saturated around 4 days. The thickness of unfrozen water on the surface of Kibushi-clay particle was calculated to be from 21 to 23 angstroms, i.e. from 2.1 to 2.3 nm. The value is equivalent to 7 layers of water molecules. The value was larger than that for alumina on which the value was 2 layers.

A model of restricted (unfrozen) water on the Kibushi-clay particle is schematically illustrated in Fig. 15. It is thought that water molecules near the surface are more strongly restricted, that is named as unfrozen water, on the clay particle surface than the free water. The thickness of unfrozen water, i.e. DSC water film thickness, is depended on the behaviors of clay particle surfaces and clay which have thicker film shows higher plasticity. From this perspective, artificial clay may have enough plasticity.

4. SLIP CASTING OF FINE CERAMICS

Our research field was extended to application fields of ceramics using the fruits from the fundamental researches of clay. First, we tried to develop wet forming technologies of fine ceramics. Figure 16 shows the development flow of the wet forming technologies, e.g. slip casting, for fine ceramics based on the knowledge of clay science. Fine ceramics powders such as alumina, zirconia, silicon nitride, silicon carbide and so on were evaluated by methods used for evaluating natural clays and synthesized kaolinite. Usually, as received fine ceramics powders do not have enough formability. As mentioned above, the thickness of unfrozen water on the surface of as received alumina particle was only 2 layers though that of plastic natural clay was 7 layers. Therefore, it was thought that research on surface modification technologies for fine ceramics powders are necessary for wet forming.

Water glass (concentrated solution of Na_2O and SiO_2) is widely used as a dispersant in the slip casting of traditional ceramics. In the field of electronics, i.e. in the production of semiconductors, sodium is one of avoidance elements; therefore it is necessary to find sodium free forming additives for fine ceramics. Figure 17 shows the concept of developing forming additive for fine ceramics performed as a collaborative research of NIRIN and Nikken-kasei Co., Ltd. (Shizuoka, Japan). As shown in Fig. 17, attempts had been done to change Na to NH_4 in surfactant molecules. Attempt to change the surfactant from

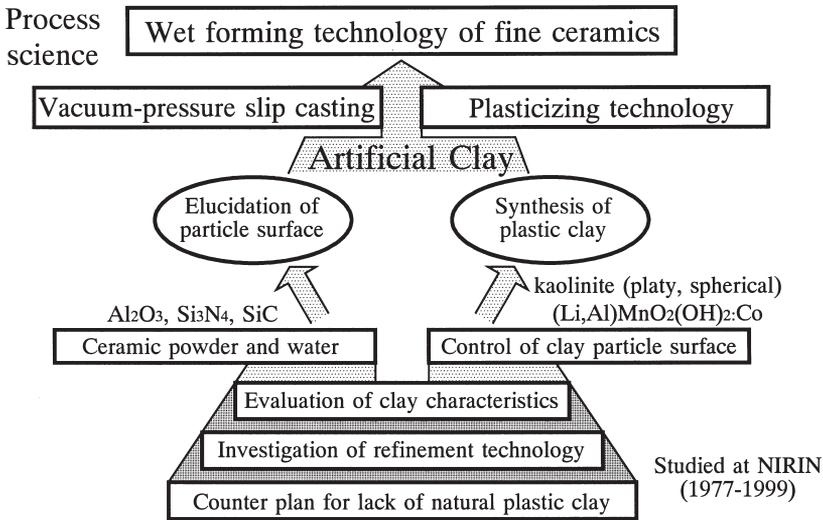


FIGURE 16 - Development flow of wet forming technologies at NIRIN.

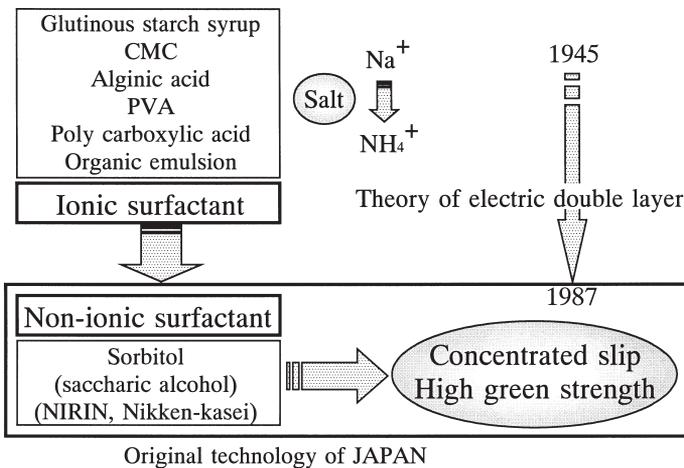


FIGURE 17 - Concept of developing forming additive for fine ceramics.

inorganic materials, i.e. water glass, to organic materials also had been done. Another attempt was to change from ionic surfactant to non-ionic surfactant. We developed Solbitol (a kind of saccharic alcohol) as a surfactant for fine ceramic forming. Basically, Solbitol is a kind of binder for ceramic forming, but it also has ability as a dispersant for ceramic slurry. High solid concentration slurry can be obtained by using Solbitol and obtained green body has high strength.

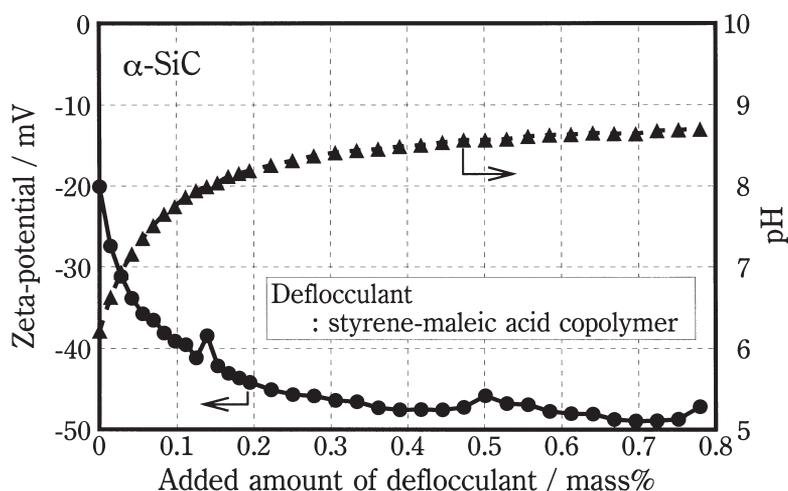


FIGURE 18 - Zeta-potential and pH change of α -SiC with addition of polymer type deflocculant.

Organic polymer type surfactants are used for preparing fine ceramic slurry. If too much surfactant is added to ceramic particle slurry, the surfactant may act as a condensation assistant for ceramic particles. Therefore it is important to know an optimum amount of surfactant addition for preparing ceramic slurry. Zeta-potential measurement was done for this purpose. Figure 18 shows Zeta-potential and pH change of α -SiC with addition of polymer type deflocculant (surfactant), styrene-maleic acid copolymer. Zeta-potential decrease with the increase of deflocculant and the zeta-potential is saturated around 0.3 mass% addition of deflocculant. The point of inflection in Zeta-potential vs. added amount of deflocculant curve is thought to be a point where whole SiC particle surface is covered by one layer of deflocculant. The optimum amount of deflocculant addition can be determined by this way. It was also confirmed that slurry with optimum deflocculant addition has low viscosity. pH vs. added amount of deflocculant curve shows opposite tendency of Zeta-potential. pH increases with the increase of added amount of deflocculant and saturate around 0.3 mass% addition.

Alumina is the most common fine ceramics material. High purity and fine alumina raw powder was developed by TAIMEI Chemical Co., Ltd. by using a research result of NIRIN. Similarly, platy alumina powder was developed by YKK Corporation by using research results of NIRIN on clay and hydrothermal synthesis. For these fine alumina powders, research on green body forming technology had been performed at NIRIN. Flow of research on development of fine alumina powders and its applications preformed at NIRIN

is shown in Fig. 19. For example, suitable particle surface modification technologies and forming technologies such as the vacuum-pressure slip casting were developed in this study.

These studies have been done using knowledge obtained on the study of clay, especially from a view point of nano scale. Studies from the view point of nano scale not only useful on the study of ceramic forming but also useful for the nano technology.

5. SELF HUMIDITY CONTROL MATERIALS

Japan is one of the high humidity countries in the world which belong in a monsoon climate. The climate of Japan is high humidity, especially in the rainy season, that is, June and July. As well known, Japanese traditional houses were made of wood, soil and paper. These materials have humidity controllability and the houses are air-opened. Japanese have been lived comfortably in traditional Japanese houses.

Materials used in Modern houses built in Japan after the World War II have been changed and the houses have become air-tight to enjoy more comfortable house life. There are other reasons such as Japanese life have been westernized, cost consumption, energy consumption and so on. Nowadays, almost all of houses newly build in Japan are modern air-tight houses. We need electric air conditioners for the humidity control to live comfortably in such air-tight houses.

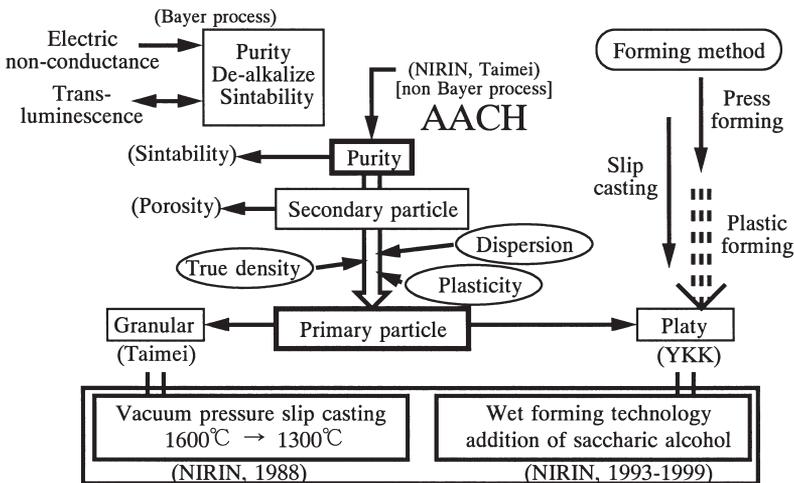


FIGURE 19 - Flow of research on development of fine alumina powders and its applications.

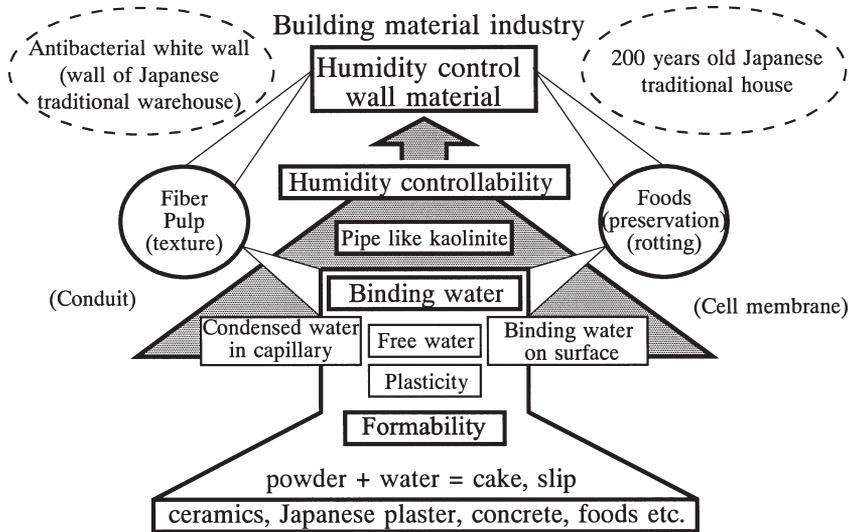


FIGURE 20 - Background technologies for developing self humidity controllable materials.

The energy consumption and the sick-house syndrome are reduced by using self humidity controllable materials as the inside wall materials of the modern air-tight houses. As the basic investigations for such purpose, we have been contributing the DSC measurement, the nano meter size pore diameter distribution measurement, the water vapor adsorption-desorption measurement and so on for candidate materials of self humidity control materials such as natural clays, allophane and mesoporous silica. Figure 20 shows the background technologies for developing self humidity controllable materials.

Figure 21 shows the climatographs of cities in Japan and the growth regions of normal molds and xerophytic molds. The most part of Japan belongs to the temperate zone. Asahikawa, a north city in Hokkaido, belongs to the subarctic zone and Naha, a south city in Okinawa, belongs to the subtropics zone. As seen in the figure, the climate of Japanese cities are very humid even at Asahikawa, a city belong to the subarctic zone. As shown in the figure, all climatographs are overlapped with the growth regions of molds both normal type and xerophytic type. Therefore, humidity control is needed not only to get a comfortable house life, but also to prevent the molds growth on house walls.

Figure 22 shows schematic illustrations of the traditional Japanese soil based wall and the modern air-tight wall. The traditional Japanese wall is made of bamboo, rice straw, sand, clay and Japanese mortar as shown in the left

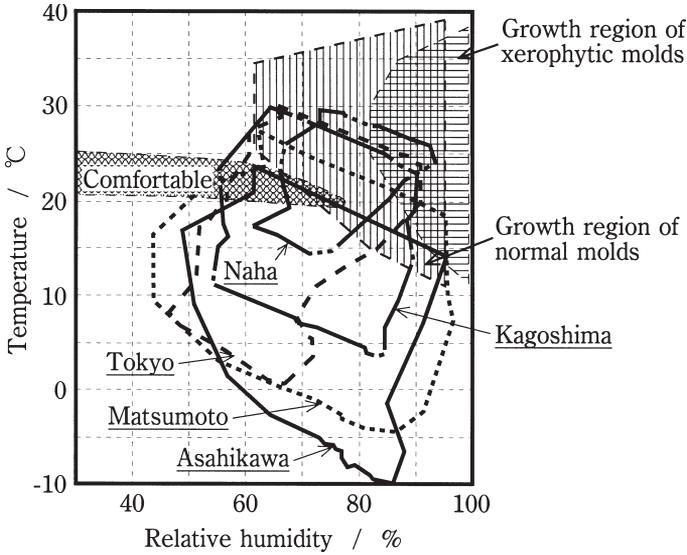


FIGURE 21 - Climatographs of cities in Japan and growth region of molds.

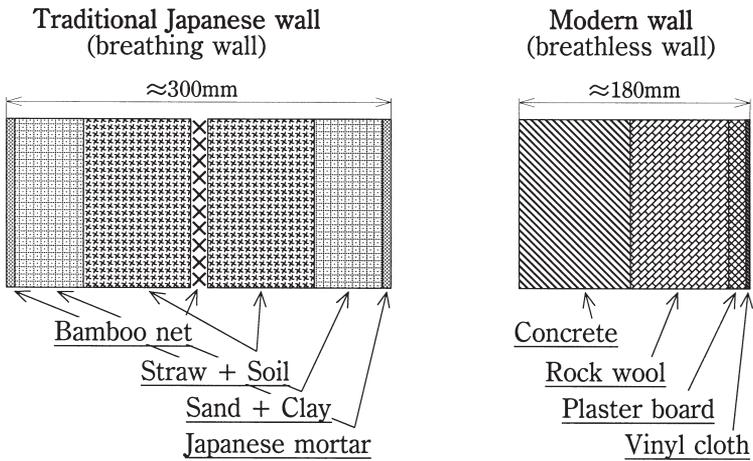


FIGURE 22 - Schematic illustrations of traditional Japanese soil based wall and modern air-tight wall.

side of the figure. We investigate an old Japanese house wall and cleared that the surface part, the Japanese mortar has highest humidity controllability than other materials used in the wall. All materials used in the Japanese traditional wall are water-attracting and water vapor can move through the wall. By

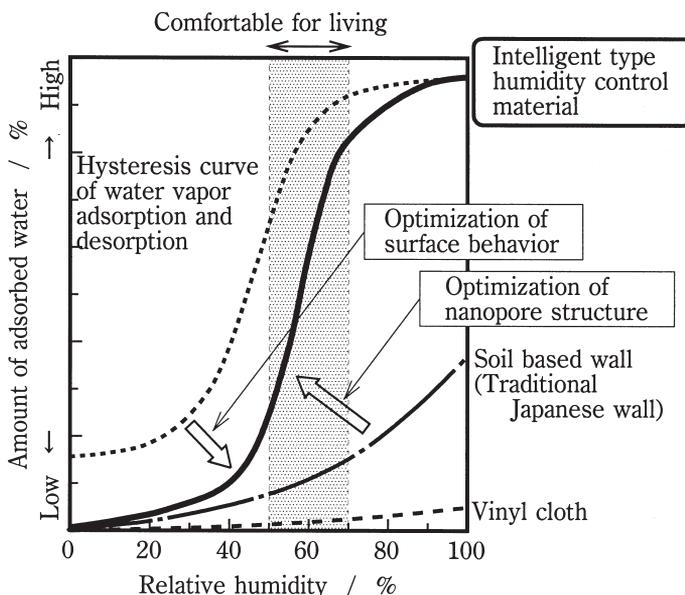


FIGURE 23 - Target behavior of self humidity control material.

helping these abilities of the wall Japanese live comfortably in Japanese traditional houses even during the rainy season. The structure of wall in the Japanese modern houses is consist of concrete, rock wool, plaster board and vinyl cloth as shown in the right side of the figure. The wall is air-tight and any water vapor can't move through the wall. Therefore, it is difficult to live comfortably in the Japanese modern houses without electric air conditioners.

Figure 23 shows the relationship between the amount of adsorbed water and the relative humidity for the wall materials. The soil based wall, traditional Japanese wall, has rather high humidity controllability though vinyl cloth has almost no humidity controllability. The aim of developing a high humidity controllable wall material is to replace the surface material on the modern wall by a self humidity controllable one.

The ability of the soil based wall is not enough to use for such purpose as shown in the figure. Some materials have high ability to adsorb water but those materials adsorb rather high amount of water in the low humidity condition as showed by the dotted line in the figure. The objective material must have a high gradient at the region of humidity from 50 to 70% as shown by the solid line as shown in Fig. 23. Therefore the approaches to develop self humidity control materials were decided to optimize the nano pore structure of the soil based wall materials.

Clay samples usually show clear two peaks in DSC curves as shown in Figures 10 and 11. When a DSC measurement was done for the elutriation product of Kanuma-soil at cooling stage, a unique profile was obtained as shown in Fig. 24. DSC curves for both the raw Kanuma-soil and for the heat treated one at 300°C are shown in the figure. Both curves show broad profile as peaks of the heat of freezing. The elutriation product of Kanuma-soil mainly consists of allophane, therefore the DSC curves are recognized as the curves of allophane. It is thought from the profiles that there are steep for weak restricts states of water on the solid surfaces. It is also thought that the reason may be since the difference of pore size. The model of single allophane unit is illustrated in Fig. 25.

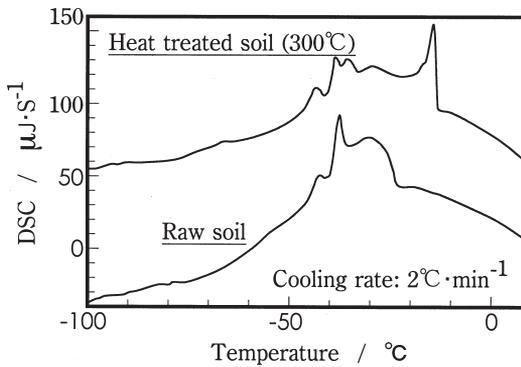


FIGURE 24 - DSC profiles for elutriation products of Kanuma-soil (allophane). Measured after adsorption in saturated water vapor at 15°C for 6 days.

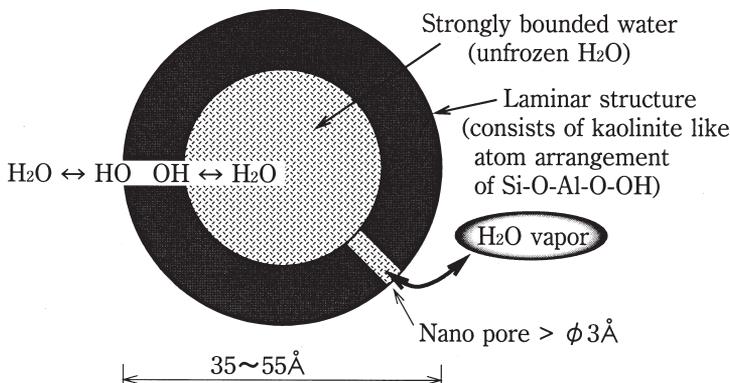


FIGURE 25 - Model of single allophane unit.

The size of single allophane unit is very small, from 35 to 55 angstroms (3.5 to 5.5 nm), and it has nano pore at the surface where water vapors can transport between inside and outside of allophane. Detailed properties of allophane were explained in elsewhere.

Target behavior of the self humidity control materials is having a steep gradient at the comfortable humidity range in the amount of adsorbed water-humidity relation as shown in Fig. 23. It is necessary to have large amount of nano pores for such purpose as mentioned above.

The adsorption phenomenon in nano pores is explained by the Kelvin's capillary condensation theory. Kelvin radius (r), radius of capillary which has ability to condensate the water vapor, is expressed as follows.

$$r = r_0 + t = \frac{2\gamma M \cdot \cos\theta}{\rho RT \cdot \ln(P/P_0)} \quad (3)$$

Where, r_0 is the radius of capillary, t is the thickness of multi-layered adsorbed molecules, γ is the surface tension of liquid, M is the molecular weight of liquid, θ is the contact angle, ρ is the density of liquid, R is the gas constant, T is the absolute temperature and P/P_0 is the relative pressure of gas. Plot for the water vapor is shown in Fig. 26. As shown in the figure, $r = 31$ angstroms and $r = 16$ angstroms are correspond to the Kelvin radius at relative humidity of 70 and 50%, respectively.

It is obvious that a material which has large volume of nano pores adsorb much water vapor. Figure 27 shows the pore size distribution measurement result of the elutriation products of Kanuma-soil (allophane). As seen in the figure, allophane has a large amount of nano pores of radius size range from

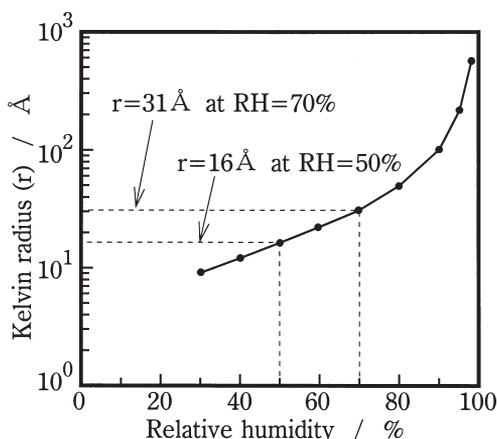


FIGURE 26 - Relationship between capillary radius and relative humidity.

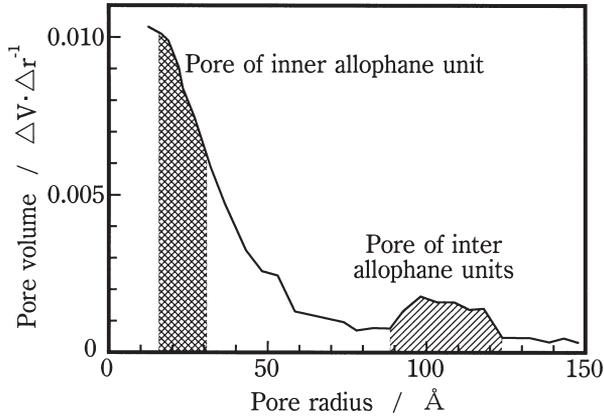


FIGURE 27 - Pore size distribution of elutriation products of Kanuma-soil (allophane).

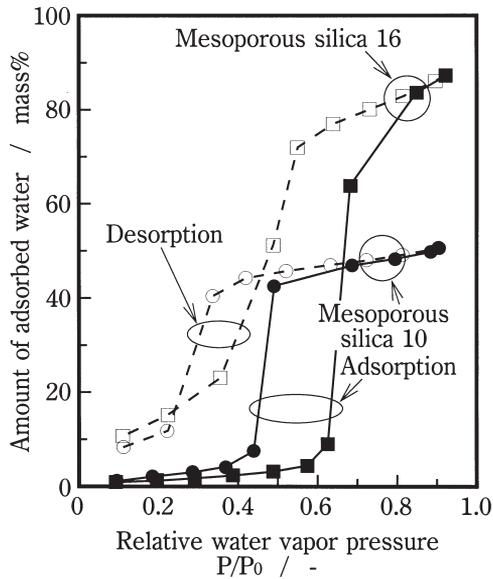


FIGURE 28 - Relationship between amount of adsorbed water and the relative water vapor pressure.

16 to 31 angstroms (1.6 to 3.1nm).

Based on the concept above mentioned, a self humidity control material using allophane for inner walls of houses was developed. The material is commercially selling as tile in Japan and it has excellent ability of humidity control.

To substantiate the humidity controllability of nano pores, adsorption-desorption behaviors of mesoporous silica samples were measured. The mixture of silica gel and liquid crystal as template was heat treated to remove the wax, and then the mesoporous silica was obtained. Figure 28 shows the relationship between the amount of adsorbed water and the relative water vapor pressure measured for mesoporous silica samples. The value of relative water vapor pressure is related to the value of relative humidity. The adsorption and desorption curves show hysteresis, but the shapes are similar with the target behavior shown in Fig. 23. It is obvious that a self humidity control material is achieved by using nano pore materials from above results.

As explained here, technology of the self humidity control material is based on the control technology of nano pore in the ceramic materials. The knowledge must be helpful for the new and advanced nano technology.

6. CONCLUSIONS

Technology of traditional ceramics and clays, which origin is very old, was considered from a view point of the nano technology in this paper. These technologies are strongly related to nano scale phenomena. The knowledge of traditional ceramics and clays must be helpful for research and development on the new and advanced nano technology.

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Discussion

W. Rieger: For the artificial alumina (Taimei), you presented impressive figures on strength you obtained for products made by slip casting. Can you tell us if you obtain the same high strength for parts made by other techniques of manufactures (Injection Molding, Axial and Isostatic Pressing, Extrusion and others)? Is the high strength related to the slip casting process?

Y. Shibasaki: We obtained the bending strength of 800MPa by HIP (Hot Isostatic Pressing) of slip cast Taimei alumina green body 10 years ago. Now, the maximum strength was improved up to 1.5GPa HIP treatment. Unfortunately, we did not try another techniques such as Injection molding or Extrusion. However, we think the high strength is due to the behavior of Taimei's high purity alumina powder, and high strength part can be obtained regardless of forming methods. The strength of parts made by slip casting is almost same with ones obtained by other techniques, by which high strength parts are obtained. Therefore the most important advantage of slip casting is easiness of processing, for example the easiness of forming complicated shape parts.