CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

'God made man from clay' is a claim by some enthusiastic ceramists and is the first science reported in Genesis (Grimshaw 1971). The discovery of ceramics is one of the man's earliest scientific achievements. The early history of man has been traced mainly through ceramics. The ceramic ware are the evidences available to reveal the ancient civilization and are today complementary to the metals and polymers. The research in clay based ceramics is continuing till date and will continue for ever to exploit the natural resources for the comforts of humans.

The word ceramics is derived from the Greek word 'keramos', which literally, means earthen. So ceramics is defined in a general sense as materials and articles made from naturally occurring earth. In recent years, the development of a wide range of articles from different raw materials other than clay necessitates the requirement of modified definition for ceramics. Hence ceramics is suitably defined as 'the art and science of making and using solid articles which have as their essential component, and are composed in large part of, inorganic non-metallic materials' (Kingery et al 1976). This definition includes not only materials such as pottery, porcelain, refractories, structural clay products, abrasives, porcelain enamels, cements, and glass but also non-metallic magnetic materials, ferro electrics, single crystals, glass-ceramics and a variety of other products which were not in existence until a few years ago and many do not exist to day.

Ceramics can be divided into traditional ceramics and technical or advanced ceramics. Many of the raw natural materials used in the ancient civilizations are still
utilized today and form the basis of a sizable segment of the ceramic industry. These ceramic products are often referred to as traditional ceramics (Richerson 1992). Traditional ceramics are clay based ceramics which include bricks, tiles, pottery etc. The clay, quartz and feldspar are the primary raw materials used for their production. Steatite and silica bricks representing non-clay products are also included in this classification. The traditional ceramics also include refractory products as well as spark plugs and cover certain oxide ceramics. Traditional ceramics are classified by Budnikov (1964) in his book ‘The technology of ceramics’ as:

1. Structural products (heavy clay products),
2. Refractories,
3. Fine ceramics.

During the past 50 years scientists and engineers have acquired better understanding of ceramic materials and their processing and have found that naturally occurring minerals can be refined and/or new compositions can be derived to achieve unique properties. These new ceramics are known as either technical or advanced ceramics. Technical ceramics require high purity synthetic raw materials and hence possess better mechanical, electrical, optical and magnetic properties. They are employed in critical structural applications, which require high strength, hardness, chemical inertness, refractoriness, thermal shock and wear resistance. In spite of their high strength, ceramics are brittle, basically due to the strong bonds present in their atomic structure (Barsoum 1997). Table 1.1 summarises some of the applications of traditional and technical ceramics (Richerson 1992). Figure 1.1 shows the major differences in processing sequences of traditional and advanced ceramics (McColm 1995).

Production of advanced ceramics involves more processing steps and in each step a large number of parameters can be varied. Also, the use of synthetic raw materials of specific characteristics is an important difference with respect to traditional ceramics, where the natural raw materials are used. Advanced ceramics are
Advanced Ceramics

1. Chemically prepared powders
2. Precipitation
3. Spray dry
4. Freeze dry
5. Vapor quench
6. Carbothermic
7. Sol-gel
8. Organo-metallic

Traditional Ceramics

1. Natural raw minerals
2. Clay
3. Silica
4. Feldspar

Figure 1.1 Processing sequences of traditional and advanced ceramics
(McColm1995)
typically produced on a small scale, with expensive raw materials to achieve improved properties and consistent quality. The higher input costs are more than compensated by value based products of reproducibility, reliability and consequent high yield.

Common ceramic raw materials are listed in Table 1.2 (Reed 1989). Traditional ceramic products are made out of clay and naturally occurring raw materials through easy beneficiation and simple shaping methods. They are dried and fired in a conventional flame kilns like down draft kilns and tunnel kilns. Most of the traditional ceramic products are sent to the market as-fired products without any polishing. Since the present work is based on clays and different alumina sources such as reactive alumina, gibbsite and boehmite, a brief account of these raw materials is given.

Table 1.1 Applications of traditional and technical ceramics (Richerson 1992)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Group</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Traditional Ceramics</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Whiteware</td>
<td>Dishes, plumbing, enamels, tiles</td>
</tr>
<tr>
<td>2.</td>
<td>Heavy clay products</td>
<td>Sewer pipe, brick, pottery, sewage treatment components</td>
</tr>
<tr>
<td>3.</td>
<td>Refractories</td>
<td>Brick, castables, cements crucibles, molds</td>
</tr>
<tr>
<td>4.</td>
<td>Construction</td>
<td>Brick, block, plaster, concrete, tile, glass, fiberglass</td>
</tr>
<tr>
<td>5.</td>
<td>Abrasive products</td>
<td>Grinding wheels, abrasives, milling media, sandblast nozzles</td>
</tr>
<tr>
<td>6.</td>
<td>Glass</td>
<td>Too numerous to list</td>
</tr>
</tbody>
</table>
(b) **Technical Ceramics**

1. **Electronics**
   - Heating elements, dielectrics, substrates, semiconductors, insulators, transducers, lasers, igniters

2. **Aerospace and automotive**
   - Re-entry, radomes, turbine components, heat exchangers, emission control

3. **Medical**
   - Prosthetics, controls, orthodontic brackets

4. **High-temperature structural**
   - Kiln furniture, braze fixture, advanced refractories

5. **Nuclear**
   - Fuels, controls

6. **Technical**
   - Laboratory ware

7. **Miscellaneous**
   - Cutting tools, wear-resistant components, armor, magnets, glass ceramics, single crystals, fiber optics

Table 1.2  **Common ceramic raw materials (Reed 1989)**

<table>
<thead>
<tr>
<th>Category</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Crude materials</td>
<td>Shales, stoneware clay, tile clay, crude bauxite, crude kyanite, natural ball clay bentonite</td>
</tr>
<tr>
<td>2. Industrial minerals</td>
<td>Ball clay kaolin, bentononite, pyrophyllite, talc, feldspar, glass sand, bauxite, zircon and rutile</td>
</tr>
<tr>
<td>3. Industrial inorganic chemicals</td>
<td>Calcined alumina (Bayer process), calcined magnesia, fused alumina, fused magnesia, silicon carbide, soda ash, barium carbonate, titania, calcined titanates, iron oxide, calcined ferrite, calcined stabilized zirconia, zirconia pigments, calcined zircon pigments.</td>
</tr>
</tbody>
</table>
1.2 CLAY

The most abundant, ubiquitous, and accessible material on the earth’s crust is clay. Clay is concisely defined as a fine grained rock which, when suitably crushed and pulverized, becomes plastic when wet, leather hard when dried and on firing is converted to a permanent rock like mass.

The clay technically referred as kaolin. The name is a corruption of the Chinese Kao-liang meaning ‘high ridge’ a local designation for the area where a white china clay was found (Singer and Singer 1963). This term kaolin is world wide accepted and still in use (Rado 1988).

1.2.1 Formation of clays

Kaolin is the product of the breakdown of the mineral feldspar or of similar meta-stable alumino-silicate minerals that were formed under high temperature conditions as components of various kinds of igneous and metamorphic rocks. The conversion of feldspar to kaolin has been explained by many theories, namely (i) the igneous emanation theory, ii) the surface weathering theory and iii) hydrolysis theory. In the above theories, the hydrolysis theory is widely accepted and in which, the three major reactions are taking place, (1) hydrolysis, (2) desilicisation and (3) hydration.

\[ \text{KAlSi}_2\text{O}_8 + \text{H}_2\text{O} \rightarrow \text{HAiSi}_3\text{O}_5 + \text{KOH} \quad \text{(Hydralysis)} \]

\[ \text{HAlSi}_3\text{O}_8 \rightarrow \text{HAiSiO}_4 + 2\text{SiO}_2 \quad \text{(Desilicisation)} \]

\[ 2\text{HAiSiO}_4 + \text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 + 2\text{SiO}_2 + 2\text{H}_2\text{O} \quad \text{(Hydration)} \]

The clay minerals may remain insitu or be transported and deposited elsewhere. In the first case, the product is termed as residual and in the second case it is
known as sedimentary. These two terms are normally denoted by primary and secondary.

1.2.2 Structure of clay

There are three main groups of clay minerals, the kaolinite, montmorillonite and illites. The simplest clay mineral group is the kaolinite group. The kaolinite group includes kaolin, dickite, nacrite, anauxite, halloysite and livesite. Among them, the most important is kaolin, since it is the principal constituent of china clay, ball clay, fire clay and many brick clays. The other kaolinite minerals are rare in occurrence and usage. The kaolin has the chemical formula $\text{Al}_2\text{O}_3\cdot2\text{SiO}_2\cdot2\text{H}_2\text{O}$.

All the kaolin minerals have the same basic structural feature. They consist of a layer of Si-O atoms, referred to as the silica, or tetrahedral layer, joined by common oxygen atoms to a similar layer of Al-O atoms, called gibbsite or octahedral layer. The side elevation of the structure of kaolin is shown in Figure 1.2. (a) (Grimshaw 1971). The lowest plane in the layer contains the oxygen atoms linking adjacent silicon atoms in the sheet above and then comes a layer of close packed anions with a hydroxyl unit $(\text{OH})^-$ at the centre of six oxygen atoms. The next layer is aluminium atoms, above which are a sheet of close-packed hydroxyl ions. As hydroxyl units are similar in size to oxygen atoms and all anions are relatively much larger than the cations, the layer structure can be imagined ideally as a close-packed system of spheres. The top elevation of the kaolin layer is shown in Figure 1.2. (b). The position of aluminium atoms can be clearly seen in the figure. Pask and Tomisia (1991) explained the kaolin as a layer lattice mineral in which the layers are held together by strong attractive forces, by Van der Waals bonding. The shape of the resulting crystal is mostly submicroscopic hexagonal platelets reflecting the atomic structure of the mineral.
Figure 1.2  The diagrammatical structure of a Kaolin layer. A. Side elevation, B. Top elevation.
1.2.3 Clay sources in Tamilnadu

Clays are found in many locations in Tamilnadu and most of them are not fully mapped and characterized. Large clay deposits are available in Neyveli and Panruti from Cuddalore district and Udayarpalayam from Ariyalur district. These clays are taken for systematic investigations. Neyveli lignite mines are located at Neyveli, in Cuddalore district of Tamilnadu. The clay beds are available under the lignite seams about 70-130 meters from the ground level. The thickness of the clay beds varies from 1.5 to 2 meters. According to geological survey, the deposit extends through out an area of sixteen square kilometer and the total quantity of clay available has been estimated to about forty million tones. The reserves are very much encouraging and it is sufficient to meet the present and future demands. The Panruti and Udayarpalayam mines are still not quantified.

1.3 ALUMINA SOURCES

Bauxite is the basic naturally occurring raw material for the production of alumina. The term ‘bauxite’ does not refer to a specific mineral but to rocks consisting chiefly of the hydrated aluminium oxides, gibbsite, boehmite and diaspore. Gibbsite is colorless to pale brown in thin section, feebly pleochroic, commonly occur as tiny tabular crystals, showing pseudo hexagonal outline (Das Poddar and Charudhuri 1994).

Reactive alumina is produced from bauxite ore by Bayer’s process. To remove the common impurities such as SiO₂, Fe₂O₃ and TiO₂, the Bayer’s process is commonly employed. The process is applicable to bauxite ores with low silica and iron impurities, and having gibbsite and boehmite as the primary alumina bearing phases.
Dry and fine powder of bauxite is digested with a solution of sodium hydroxide and sodium carbonate in presence of a flocculent. Lime is added to caustic soda and serves as a filter aid. In an autoclave under a pressure of 40 to 50 MPa at about 145°C, aluminium oxide dissolves into the solution as sodium aluminate and is separated from the insoluble oxides of iron, titania, carbonated lime and other impurities (known as 'red mud') by filtration. The concentrated solution after cooling to about 50–60°C, is seeded with fine crystals of alumina trihydrate. Alumina trihydrate is precipitated from supersaturated solution. It is washed and calcined to form α-alumina. The spent liquid containing mainly NaOH is evaporated and reused for digestion of a fresh charge. The particle size, size distribution, purity, morphology and yield of α-alumina will vary with the processing conditions.

Boehmite is synthesized from aluminium alkoxides, Al(OR)₃. Aluminium hydroxide sols can be prepared from various aluminium compounds. Aluminium iso-propoxide is used as a starting material for the preparation of boehmite. (Sathyakumar 2000)

1.3.1 Structure of alumina

α-Al₂O₃ is the stable form of alumina and the crystallographic data are summarised in Table 1.3. The hexagonal structural cell is most commonly used to describe α-Al₂O₃, even though the crystal is actually rhombohedral (Lee and Rainforth 1994).

Table 1.3 Crystallographic information for α-Al₂O₃

<table>
<thead>
<tr>
<th>Crystal system</th>
<th>Space group</th>
<th>Lattice Parameters</th>
<th>JCPDS Card No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhombohedral</td>
<td>R3c</td>
<td>a 4.7589 b -- c 12.991</td>
<td>10-173</td>
</tr>
</tbody>
</table>
The crystal structure is often described as having $O_2^-$ anions in an approximately hexagonal close packed arrangement with $Al^{3+}$ cations occupying two-thirds of the octahedral interstices. The empty sites of the cation sub lattice are used to define the corners of the unit cell (Figure 1.3). The use of these sites to define the cell means that there is a $30^\circ$ rotation of the $a$-axis about the $c$-axis when compared to an hcp system, so that the close-packed planes in the anion sub lattice lie along $(10\bar{1}0)$, where as in hcp system, the close-packed direction lies along $(1\bar{1}20)$.

1.4 PROCESSING OF CERAMICS

Ceramics can be fabricated by a variety of methods, some of which have their origin in early civilizations. In most cases, the fabrication process starts from a bulk quantity of powder obtained from commercial sources. The characteristics of the powder depend strongly on the method of preparation and these characteristics in turn influence the subsequent processing of the ceramics (Rahaman 1995).

The general ceramic processing steps are given in Figure 1.1 for traditional and advanced ceramics. The ceramic processing usually starts with one or more ceramic materials, liquids and special additives. The common ceramic raw materials are listed in Table 1.2 (Reed 1989). The naturally occurring materials are normally beneficiated first to remove impurities and are brought to required consistency (Rado 1988). Different operations such as crushing, milling, washing, chemical dissolving, settling, flotation, magnetic separation, dispersion, mixing, classification, de-airing filtration and spray drying are performed to achieve consistency of the starting material. The advanced ceramic raw materials are obtained either by chemical processing of minerals or synthesized directly from other precursor materials. The availability of fine homogeneous powders is important in fabrication of advanced ceramics.
Figure 1.3 Crystal structure of $\alpha$-alumina

(Lee and Rainforth, 1994)
1.4.1 Powder processing

The conventional powder preparation method involves grinding of coarse starting materials using different mills to reduce the particles to the desired size and followed by the intensive mixing of the different raw materials. Particle size distribution is important and the consolidation or shaping technique is selected based on this characteristics. The objective of the consolidation is to achieve maximum particle packing and uniformity so that minimum shrinkage and retained porosity will result during densification. In order to achieve maximum packing density, the particle size distribution is important. In the present investigation, a planetary ball mill has been used for milling and subsequent mixing. The non-conventional powder preparation methods are classified as (Richerson 1992), 1. Precipitation, 2. Liquid mix (Pechini process), 3. Spray roasting, 4. Freeze drying, 5. Hot kerosene drying, 6. Plasma, 7. Combustion synthesis, 8. Laser method, 9. Sol-gel and 10. hydrothermal technique.

1.4.2 Ceramic shaping process

Shaping techniques in ceramics are very numerous. However all the ceramic shaping techniques can be fitted into three basic types (Mostetzky 1982).

1. Plastic shaping
2. Slip casting
3. Pressing

Plastic shaping includes, for example, throwing, jolleying & jiggering, hand moulding, extrusion and injection moulding. Casting includes Plaster mould casting and advanced casting techniques like vacuum casting, pneumatic casting, etc. And other techniques like hot pressing and hot iso static pressing are commonly used for advanced ceramic processing. Using hot pressing the sintered density equal to theoretical value can be obtained when optimum conditions (5 MPa & 1500°C for 30 minutes) are used (Mazdiyansi and Brown 1972). Rotary forging (Boccaccini et al
1999) and hot forging (Ohashi and Ida 2000) are the latest techniques for the fabrication of dense mullite at much lower temperature (1350-1400°C). Among the different shaping processes discussed above, uniaxial pressing and extrusion techniques have been chosen for the present investigation as the shaping route, and are explained below.

1.4.3 Pressing

Pressing is accomplished by placing the powder into a die and applying pressure to achieve compaction. Two categories of pressing are commonly used, (1) Uniaxial and (2) Isostatic. Uniaxial pressing is used to shape the simple geometric products like tiles, bricks, pellets and bars etc. Uniaxial pressing involves the compaction of powder into a rigid die by applying pressure along a single axial direction through a rigid punch. Most uniaxial presses are either mechanical or hydraulic. Figure 1.4 shows schematically the pressing sequence of a typical uniaxial press. The punch positions in the die body at different stages of the pressing operation are predetermined to contain the correct volume to achieve the required green dimensions after compaction. The feed shoe is then moved into position and the cavity is filled with powder and the upper punch is moved down to precompress the powder. The upper and lower punches then simultaneously compress the powder and finally compact is ejected out. The motion of the punches at different stages of operation is shown by an arrow in the Figure 1.4. The various problems encountered in uniaxial pressing are (1) improper density or size, (2) die wear, (3) cracking (4) density variation. These problems are minimized in isostatic pressing in which pressure is applied in all the directions.

1.4.4 Extrusion

Extrusion is a plastic forming method which has been extensively used for fabrication of rods, tubes, honeycomb structures and channels. The extrusion process
Figure 1.4 Sequence of Die pressing operations.
consists of forcing a high viscous, cohesive, plastic mixture of ceramic powder and additives through a die of desired shape. The feed material is pre-compacted in the compaction chamber and the air/gas entrapped is removed prior to pushing through a tapered die. The plasticized mixture is then forced under high pressure through the die. The resulting long strands of extruded ceramic bodies of constant cross section are supported in trays and cut to the desired length prior to drying and firing.

1.4.5 Stages involved in extrusion

The following are the major stages involved in the process of extrusion.

1. Selection and tailoring of the powder for the process.
2. Mixing the powder with a suitable binder
3. Production of homogeneous, granular powder-binder system.
4. Forming the part by forcing the mixture through the die of desired shape.
5. Processing of the formed part to remove the binder.
6. Densification of the compact by high temperature sintering.
7. Post sintering processing if required.

An extruder is a machine that forces the material through a die by applying pressure. There are two basic types, (1) piston type and (2) screw type. Figure 1.5 shows the schematic diagram of piston type extruder. The piston extruder is very simple in construction and consists of a barrel, a piston and a die. It is inherently a batch process. A limited amount of mixing occurs in the extruder. This occurs mainly during the reduction of the extrudate from the barrel section to the die section.

1.4.6 Sintering

Sintering is a process in which the physical bond between the particles is converted into chemical bond, leading to the formation of an internal structure known as microstructure by the action of temperature or temperature and pressure. Sintering
Figure 1.5 Diagram of Piston Extruder (Richerson, 1992).
is the final step in the fabrication of ceramic products involving the motion of atoms through diffusion, viscous flow, evaporation, and condensation. Sintering removes the pores that are accompanied by shrinkage to form a dense structure. There are three stages in the sintering process. During the initial stage of sintering, neck growth occurs along the contact region between adjacent particles with the simultaneous development of particle boundaries between particles with change in pore shape without affecting pore volume and grain size. In intermediate stage of sintering, the pores become more spherical and smaller in size. The pore elimination sets in and grain growth starts. In the final stage of sintering, the elimination of closed pores and grain growth take place due to mass transfer. This results in shrinkage equivalent to the amount of porosity reduction. Thus ceramics are densified by sintering at elevated temperature to produce a solid with a major reduction in porosity. In certain cases, pore free ceramics have been prepared by careful control of such process parameters such as chemical compositions and sintering conditions.

1.4.7 Reaction sintering

A suitable way to avoid the problems involved with densification of mullite powder compacts is reaction sintering of alumina and silica reactants because it allows a high degree of densification prior to mullitisation. A further advantage of reaction sintering is the low cost for processing mullite ceramics (Aksay et al 1991; Somiya and Hirata 1991; Bartsch et al 1999). Reaction sintering of mullite is possible with the admixtures of $\text{Al}_2\text{O}_3$ and $\text{SiO}_2$ powders and the admixtures of clays and bauxite. The temperature and the rates of mullite formation depend on the characteristics of the starting materials such as the chemical purity, particle size and surface chemistry of the particles (Rana et al 1982; Rodrigo and Boch 1985; Boch et al 1990a, b; Ebadzadeh 2000).

Fine crystalline mullite powder compacts require high temperatures ($\geq 1600^\circ\text{C}$) to achieve high sinter density. This is due to the low inter diffusion rates of aluminium
and silicon ions. Boch et al (1990b) and Kansaki et al (1990) have reported that a close compositional and microstructural control is necessary to maximize the sintering behaviour of mullite. Hence, the sintering of stoichiometric mullite is very difficult, often necessitating pressure assisted sintering like hot pressing, hot isostatic pressing to achieve a higher densification. Yamagishi et al (1990a; 1990b) have reported that improvement in the densification of mullite to 96% of T.D. is achieved by the addition of X-phase sialon. Co, Ni and Cu have been successfully incorporated in mullite through solid state reaction sintering to improve the catalytic activity of mullite (Mazza et al 2000).

1.5 MULLITE MATRIX COMPOSITES

Various mullite based composites have been extensively investigated in recent years in order to enhance the mechanical properties of mullite ceramics. Great attention has been paid to toughen the mullite matrix composites by the addition of ZrO₂ particles, fibers and/or whiskers. Prochazka and Klug (1983) prepared mullite-ZrO₂ composites by the conventional mixing of fused mullite and ZrO₂ powders in an attrition mill. Samples were fired at 1610°C. Compared with pure mullite, the addition of ZrO₂ was effective in enhancing densification and retarding grain growth of mullite and gave favorable improvement on the mechanical properties. Mizuno et al (1988) prepared mullite-ZrO₂ composites by the sol-gel method using mullite and ZrO₂ sol as starting materials. The density reached nearly 100% by firing at 1550°C. This temperature was lower than that of the conventional mixing method. Mullite-ZrO₂ composites have been developed from metal organics for special applications by microwave assisted sintering (Ravi et al 1998). Scheppokat (1998) have developed Mullite-ZrO₂ composites by reaction sintering with negligible shrinkage (0.1%).

Various kinds of continuous fibers, whiskers, platelets and particles have been used to reinforce mullite matrices. Most of them aim at enhancing the mechanical properties of mullite. Some mullite matrix composites were developed to improve the
low-temperature sinterability and special physical properties, such as thermal expansion and dielectric constant for possible application as substrate materials for electronic packaging. SiC fibers and carbon fibers were used to prepare fiber-reinforced-mullite composites (Cornie et al 1986). Hirata et al (1991) prepared Si₃N₄ whisker-reinforced mullite and mullite whisker-reinforced mullite composites by a colloidal process. Mullite/mullite composites with whisker like grains having very high aspect ratios obtained by adding AlF₃ in to mullite precursor and sintered 1580°C show high fracture toughness of 3 MPam⁰.₅ (Meng et al 1998).

1.6 OBJECTIVE OF THE PRESENT WORK

Plastic aluminus clays are abundantly available in Tamilnadu. However, at present the utilisation of these clays is very minimal due to lack of detailed characterisation of these clays. The present thesis work aims,

1) To investigate the green and fired characteristics of the clays obtained from three different locations in Tamilnadu (Udayarpalayam, Panruti and Neyveli) to assess their potential use as the ceramic raw material.

2) To study the mullite formation of the above clays with the addition of TiO₂, MgO and Y₂O₃ (2, 4 and 6 wt %) sintered at different temperatures (1200 - 1400°C).

3) To study the mullitisation behavior of uncalcined clays and calcined (1400°C) clays from Neyveli, Panruti and Udayarpalayam and three different alumina sources, (reactive alumina, gibbsite and boehmite) to produce stoichiometric mullite.

4) To develop dense mullite products using Neyveli clay and reactive alumina. The effect of MgO and Yttria (1.0 to 5.0 wt %), as sinter
additives and partial substitution of reactive alumina by boehmite (1.0 to 7.0 wt %) is also investigated.

5) To develop bench scale technology to utilize Neyveli clay for value added artifacts like, porous mullite based membrane support, dense mullite tube, electronic substrate and tubes for high temperature roller hearth kiln.