Ceramic Insulating Materials

- Products of inorganic raw materials (silicates and oxides) by sintering. They comprise crystal structure embedded in a glass matrix.

Quartz porcelain raw material composition:
Kaolin - 50%, clay minerals in the form of aluminium hydrosilicates \( (\text{Al}_2\text{O}_3+2\text{SiO}_2+2\text{H}_2\text{O}) \)
Felspar – 25%, form the glass phase after sintering
Quartz – 25%

Alumina porcelain raw material composition:
Kaolin or clay – 40 to 50%
Felspar – 30%
Alumina – 30 to 20%
Manufacture Process of Porcelain

- Hard raw materials are powdered and ground wet in ball-mills to the required size distribution.
- Mixed with kaolin with 50% water content and then partially remove water through mechanical filter and intermediate storage.
- Forming cylindrical shape after vacuum extruder (12% water content). Bringing into final raw shape by turning. Further drying removes physically bound water down to ~0.5%.
- The dried sample is then coated with a ceramic suspension, the glaze, to produce a glassy smooth surface of the desired colour on firing.
- Sintering takes place at 1400°C for a period of time.

Significant shrinkage takes place during the above process.
• Major Advantages:
  Easy processability and workability of the raw material mixture before sintering
  Form various shapes
Paper

• Paper for electrotechnical purposes is primarily manufactured from wood-pulp of slowly growing northern spruce or pine.

Cellulose paper is manufactured into transformer paper with thickness of 0.05 mm to 0.08 mm, and into cable paper of 0.08 to 0.2 mm. Pressboard is made by wet pressing several thin individual layers without bonding material: it consists of 35 individual layers per mm thickness.
• The dielectric constant of cellulose at 20°C is 5.6, of paper 1.5 to 3.5 and of pressboard 4.5. The dissipation factor lies around 3 to 4 x10^{-3}, the volume resistivity in the dry state between $10^{15}$ and $10^{17} \, \Omega\text{cm}$. The volume resistivity decreases by about a factor of ten for every 1.5% of absorbed water.

• Paper is very hydroscopic and can absorb 5 to 10% water in an atmosphere of average humidity. The ageing of paper is influenced primarily by water. A good drying is of particular importance.

• The utilization of paper occurs in the form of hardboard, soft paper and pressboard.
Polymers

• Made up of chain molecules long-range connections throughout material

• In practice, mostly carbon atoms along length of the chain + various side-groups (e.g. -H, -Cl, -OH, -CH3) attached to it at regular intervals
General Characteristics

- Cheap
- Tough
- Lightweight: polyethylene density = 0.96 g cm\(^{-3}\)
- Easy to shape
- Flexible
- Resistant to chemical attack
- Thermally, electrically insulating

**BUT**

- low stiffness / strength: \( E \) (polyethylene) < 1 GPa
- limited temperature range: \( T_m \) (polyethylene) = 105°C
- high coefficient of thermal expansivity: \( a \) (polyethylene) = 150 x 10\(^{-6}\) K\(^{-1}\)
- Degrade when exposed to UV light, oxygen
Synthetic Processing

• The formation of macromolecules occurs by way of a *polymerization reaction* – molecules of low weight (e.g. monomers) combine to produce large molecules of high molecular weight (polymers).

• The reaction can take one of the followings: addition polymerization (similar groups) and condensation polymerization (dissimilar groups).
Polymerisation – three stages

Polymerisation process has three stages: initiation, propagation and termination.

In the first stage, a substance is split into two identical parts, each with an unpaired electron (free radicals). The free radical then initiates the reaction sequence by forming a bond to one of the carbon atoms in the double bond of the monomer.

The chain begins to grow--propagate, stage two--when the new free radical formed in the initiation stage reacts with another monomer to add two more carbon atoms. This process repeats over and over again to form chains containing thousands to millions carbon atoms.

It can be terminated--stage three--when any two free radicals combine, thus pairing their unpaired electrons and forming a covalent bond that links two chains together.
Polymers are long chain giant organic molecules are assembled from many smaller molecules called monomers.

Many monomers are alkenes which react by addition to their unsaturated double bonds. The formation of polyethylene from ethylene may be illustrated in the top-right graph as follows:

The electrons in the double bond are used to bond two monomer molecules together. This is represented by the red arrows moving from one molecule to the space between two molecules where a new bond is to form.

Note that in the complete polymer, all of the double bonds have been turned into single bonds. No atoms have been lost and the monomers have just been joined in the process of addition.

Polymer condensation

Polyesters such as PET (polyethylene terephthalate) are condensation polymers. The formation of a polyester follows the same procedure as in the synthesis of a simple ester. The only difference is that both the alcohol and the acid monomer units each have two functional groups - one on each end of the molecule. In this polymer, every other repeating unit is identical.

PET is made from ethylene glycol and terephthalic acid by splitting out water molecules (-H from alcohol and -OH from acid as shown in red on the graphic). The units are joined to make the ester group shown in green.

A simple representation is -[A-B-A-B-A-B]-.
Describing polymers

Basic unit = *mer*

- polyethylene
  \[
  \left( \begin{array}{c}
  \text{C} \\
  \text{C}
  \end{array} \right)_n
  \]

- polyvinyl chloride
  \[
  \left( \begin{array}{c}
  \text{C} \\
  \text{Cl}
  \end{array} \right)_n
  \]

- polystyrene
  \[
  \left( \begin{array}{c}
  \text{C} \\
  \text{C}
  \end{array} \right)_n
  =
  \left( \begin{array}{c}
  \text{C} \\
  \text{H}_6 \text{C}
  \end{array} \right)_n
  \]

Mixture $\rightarrow$ copolymers

- Alternating co-polymer
  - monomer units alternate

- Random co-polymer
  - monomer units arranged randomly

- Block co-polymer
  - blocks of homopolymer units

- Graft co-polymer
  - homopolymer chains joined
Describing polymers (cont.)

- Chain length (typically $10^3 - 10^5$ mers)
- Extent of branching

- Extent of cross-linking

- Tacticity: spatial arrangement of side-groups $\rightarrow$ isotactic, syndiotactic, atactic
Molecular weight

To characterize the distribution of polymer lengths in a sample, two parameters are defined: number average and weight average molecular weight.

- The number average (Mn) is just the sum of individual molecular weights divided by the number of polymers.
- The weight average (Mw) is proportional to the square of the molecular weight.

The weight average is always larger than the number average. The graph shows a typical distribution of polymers including the weight and number average molecular weights.

The ratio of Mw/Mn is called polydispersity index.
1 for monodisperse polymers
1.02 – 1.10 for best controlled synthetic polymers
~ 2 for step polymerisation reactions
1.5 – 20 for chain reactions
Degree of polymerisation (DP)

The *degree of polymerization* (DP) refers to the number of repeat units in the chain, and gives a measure of molecular weight. Many important properties of the final result are determined primarily from the distribution of lengths and the degree of polymerization.
Describing polymers (cont.)

Arrangement of chains

- Amorphous (random arrangement)
- Crystalline (chains aligned)
Polymer crystallinity
In practice, polymers are semi-crystalline.
Size of crystallinity and electrical breakdown of PP and HDPE

Sample thickness 1 – 0.05 mm, 2 – 0.77mm, 3- 0.80 mm
Factors influencing crystallinity

• Cooling rate
• Chain complexity and regularity
• Side group size
• Tacticity
• Cross-linking
• Branching
Factors influencing Tg

• Cooling rate
• Chain flexibility
  – Side group size
  – Cross-linking
  – Branching
  – Chain length

• Typical glass transition temperatures:
  -- Polyethylene: -90° C
  -- Polypropylene: -18° C
  -- Polystyrene: +100° C
Polymer behaviour above and below Tg

• Below Tg:
  Polymer chains “frozen” into place, only bond stretching possible. Polymer is “glassy”: stiff, strong and brittle

• Above Tg:
  Polymer chains free to move around and change shape
  > Elastomers: chain motion restricted by cross-linking
  > Semi-crystalline polymers: amorphous sections pinned by crystalline regions
  > Amorphous polymers: slight restriction on chain motion provided by entanglements, but resistance to deformation drops rapidly with temperature, until material flows

Amorphous polymers are generally used below Tg
Important polymers

• Polyethylene (PE)
  – LDPE, HDPE and XLPE
  - mainly used for high voltage cable insulation
• Polypropylene (PP)
  -- high voltage capacitor insulation
• Polyvinylchloride (PVC)
  -- low voltage cable insulation
• Polytetrafluorethylene (PTFE)
  -- high frequency applications
• Epoxy resin (EP)
  EPs are the most important hard cast type of resins employed in HV technology.
Polyethylene (PE) and XLPE

PE is a long chain polymer manufactured through the polymerisation of ethylene gas.

\[ \text{ethylene} \xrightarrow{\text{high pressure, high temperature}} [-\text{CH}_2\text{-CH}_2\text{-}]_n^- \]

At its introduction, thermoplastic PE was very popular, compared to paper insulation in power cable application because of its low cost, good electrical properties, processability, moisture and chemical resistance and low temperature flexibility.
A significant design issue with PE was that its temperature of operation was limited to 70°C. Consequently, it could not match the temperature rating of paper-insulated cables (90°C).

This problem was solved with the advent of crosslinked polyethylene (XLPE), which has the ability to match the thermal rating of paper-oil insulated cables and provide freedom from the hydraulic problems of oil-filled cables. It is possible to achieve a rated maximum conductor temperature of 90°C and a 250°C short circuit rating.

The crosslinking of LDPE with Di-cumyl Peroxide (DPC) to form XLPE was first accomplished in 1955.
Peroxide initiated crosslinking of XLPE
Research at TDHVL on XLPE Cables

220kV XLPE cable

Peeled tape

Charge dynamics

Model fitting

Extracted parameters

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<th>Trapping parameters</th>
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<th>XLPE samples from middle layer</th>
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Epoxy Resin (EP)

The chemical characteristic is the epoxy group

\[-\text{CH-CH}_2\]

\[\text{O}\]

which must be present in sufficient proportion for hardening.

Among the large number of different resins, those based on bisphenol A acquired the greatest significance.
Concepts for cast

Cast resins are compound systems consisting of resin, hardener and sometimes accelerator, plasticizer, filler and colouring material. The individual components are stable and can be stored over a certain length of time; the mixture, however, is capable of reaction. There is therefore only a limited time available for the processing of the mixture – so called pot life.
- Active resins are liquid or liquefiable resins which harden by polymerisation or addition polymerisation on their own, or with reactive agents without splitting off volatile components.

- Reactive agents are hardeners and accelerators.

- Active bulk resin is mixture of the above materials ready for processing and sometimes mixed with a filler as well.

- Resin castings are hardened substances which are produced by casting in moulds after the active bulk resin is hardened.
Processing of Epoxy Resin (EP)

Processing of EP is done by mixing and homogenising the individual components (resin, hardener, accelerator and filler) to a resin bulk capable of reaction which then cast in steel or aluminium moulds. There the hardening to EP-mouldings takes place.

Casting pieces designed for high electric stress is always carried out in vacuum to avoid cavities.

The hardening reaction is exothermic since the reaction rate is temperature dependent, removal of the heat of reaction must taken into consideration.
Pure resin suffers a reaction volume shrinkage during hardening of up to 3%; filled resins up to 0.5%. The shrinkage produces internal tension which can lead to crack formation. The large thermal expansion leads to mechanical tension at the metal/resin boundary during temperature change. This danger is counteracted by the addition of plasticizers which make the mouldings more pliable and ensure casting without crack formation. But resins with plasticizers have, in general, inferior electrical values and a poor shape retention on heating.

Filler materials serve to reduce the volume shrinkage, to increase the compressive strength, to reduce the combustibility and improve the thermal conductivity. Common filler materials, which can constitute up to 65% amount of mass of the resin bulk, are crystalline quartz powder or alumina without water of crystallization.
Application of EP-Mouldings

Dielectric properties of EP mouldings are not excellent but they are sufficiently good for the good mechanical and thermal properties to be exploited to advantage for high voltage insulation systems. The easy workability also plays an important role.

- EP mouldings act as insulation for instrument transformers and dry transformers.
Application of EP-Mouldings

- In indoor EP support insulators and EP bushings have wholly supplanted their ceramic counterparts and the support insulators for SF6 insulated installations are also usually made of EP moulding.

- Further important applications are impregnation of electrical machine insulation, insulating components in high voltage switches, fibre-reinforced plastic rods for overhead line insulators, pressed parts for mechanical supports etc.
Research at TDHVL on EP

Moulding unit for EP

Figure 1: DC flashover kit schematic diagram

Figure 1: SEM image of original epoxy sample

Figure 2: SEM image of 30-minute-fluorinated sample

Figure 3: SEM image of 60-minute-fluorinated sample
Composite Insulation: Oil-impregnated Paper Insulation

- The most important composite dielectric for HVI systems.
- Several layers of paper are used + porous nature of paper
- System can be considered as series connection of paper and oil
- Permittivity

\[ \varepsilon = \frac{\varepsilon_1 \cdot \varepsilon_2 (d_1 + d_2)}{\varepsilon_1 d_2 + \varepsilon_2 d_1} \quad d_1 + d_2 = d \]

pure oil (\(\varepsilon_1 \) and \(d_1\)) and pure paper (\(\varepsilon_2 \) and \(d_2\))
• The unknown thicknesses $d_1$ and $d_2$ are eliminated by introducing the fiducial pore volume $v$:

$$v = 1 - \frac{\gamma_p}{\gamma_z}$$

Here $\gamma_p$ is the density of the paper containing pores and $\gamma_z$ the density of pure cellulose.

• For the total impregnation, $v$ is equal to the oil volume $v_1$ and for the volume of paper $v_2 = v - v_1$. Then the permittivity of the system

$$\varepsilon = \frac{\varepsilon_1 \cdot \varepsilon_2}{\varepsilon_1 + v_1(\varepsilon_2 - \varepsilon_1)}$$
Cellulose has a density $\gamma_z = 1.55 \text{g/cm}^3$ and $\varepsilon_2 = 5.6$. With $\varepsilon_1 = 2.2$ for oil, the resultant dielectric constant is

For impregnated cable paper $\varepsilon = 3.1$

($\gamma_p = 0.75 \text{g/cm}^3$, $v_1 = 0.516$)
For impregnated capacitor paper $\varepsilon=4.0$ 
($\gamma_p=1.15\text{g/cm}^3$, $v_1=0.26$)
For impregnated pressboard $\varepsilon=4.5$ 
($\gamma_p=1.3\text{g/cm}^3$, $v_1=0.16$)
Electrical Characteristics in Oil-Impregnated Paper Systems

• Electric field distribution:
  Assuming: \( \varepsilon_1 = 2.2 \) and \( \varepsilon_2 = 5.6 \), we have
  \[
  \frac{E_1}{E_2} = \frac{\varepsilon_2}{\varepsilon_1} \approx 2.55
  \]

• The oil is electrically stressed more. Using a finely graded lamination a large number of thin oil films can be obtained, leading to a high breakdown strength of an oil-paper dielectric. Paper promotes the formation of thin oil layer, acts as a barrier to bridging impurities and ensures the mechanical stability of the insulating system.
• The short term breakdown strength of the oil-paper system can be as high as 400 kV/mm.

• Under dc operating condition for a capacitor, 100 kV/mm working stress is often used.

• Under ac operating condition, up to 20 kV/mm working stress has been achieved.

• Dissipation factor $\tan \delta = 3 \times 10^{-3}$

• Volume resistivity $\rho = 10^{15} \, \Omega \text{cm}$

• Permissible working temperature $100^\circ C$
Manufacturing Process

- Preventing formation of detrimental gas (PD)

- Moisture presence leads to degradation of paper and high dielectric loss.

- Processing:
  (i) drying -- subjecting the paper-insulated live parts in heated vacuum chambers to a vacuum of $10^{-3}$ ... $10^{-4}$ mbar and temperature of $110^\circ$C, the drying time increases quadratically with the thickness of the insulation. (ii) Impregnating – the dried paper insulation is then impregnated, in vacuum if possible, with recently refined and warm mineral oil.
Power Transformer Manufacturing Process

1) Winding Works

2) Core lamination

3) View of Core Structure (After Completion of Core Lamination)

4) Coil Insertion Works
Power Transformer Manufacturing Process

5) View of Core and Coil Assembly Works

6) Drying Works in Vacuum Vaporization Facility

7) Completion of Core & Coil Assembly

8) Factory Test
Research at TDHVL on Power Transformer Insulation

Experimental setup

A. Bridge formation under the influence of DC electric field

B. Bridge formation under the influence of AC electric field

C. Bridge formation under the influence of DC biased AC electric field

D. Bridging with paper barrier under the influence of DC electric field

Paper barrier effect