# SELECTION METHOD OF ENVIRONMENTALLY FRIENDLY MATERIALS FOR POWER EQUIPMENT BASED ON FUZZY PERFORMANCE SUMMATION

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## *Abstract*

*In the past the selection and evaluation of materials were based solely upon the design requirements, but in recent years the environment issues have become more important and it is now necessary to consider their contribution at a much earlier stage in the selection procedure. As there are numerous materials available some methodical means is now necessary to reduce the number to a manageable size. This paper presents a new selection procedure based upon a Fuzzy Performance Summation in order to choose suitable insulating materials for power equipment. A materials selection model is proposed based on the intrinsic character of the properties and their relationship with the design requirements. The data was processed by quantitative analysis and by comparing the numerical values suitable materials chosen.*

**Key words:** Material Selection, Fuzzy Performance Summation, Insulation, Environmentally Friendly

## 1 INTRODUCTION

Material selection in the design of a particular product is becoming a much more complex issue. It is not only dependant upon the basic functional performance of the product, but now its impact on the environment and its overall cost to produce, maintain and dispose of at the end of its life cycle. If a principle known as the Analytical Hierarchy Process (AHP) is applied to this problem, it can separate these various factors into their individual components, place them in an order of priority and relate their dependency upon one another. This is best shown by the illustration given in Figure 1 representing the Eco-index in order to achieve a product design, which satisfies these three basic criteria of functional performance, cost and environment.

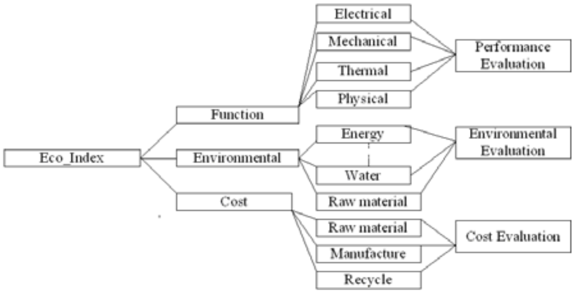

**Figure 1: The Process of Analytical Hierarchy for the selection of Environmentally Friendly Materials**

It is not the intention to address the issues of the environment and cost, which will have been published elsewhere but for this paper to present the methodology for the selection of suitable materials based upon the functional performance only. A case study to demonstrate this methodology is the replacement of an existing material used in a tie rod (Figure 2), which is part of a pole mounted switch used by the AREVA T&D medium voltage business.

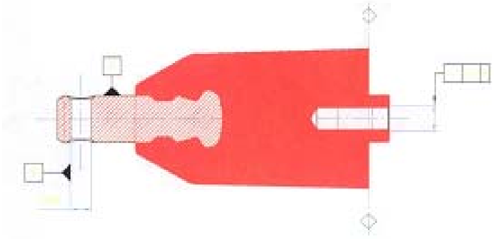

**Figure 2: Tie rod of a pole mounted switch**

## 2 MATERIALS SELECTION AND EVALUATION

### 2.1 Mathematic Basis

Suppose there are M candidate materials, each with N properties. This can be represented by an N × M matrix [X]:

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1M} \\ x_{21} & x_{22} & \dots & x_{2M} \\ . & . & & . \\ x_{N1} & x_{N2} & \dots & x_{NM} \end{bmatrix}$$

The elements of the matrix are $X_{ij}$ where $X_{ij}$ is property i of material j. The M materials are termed the *candidate set* and the N properties form the *factor set.*

The chosen material must have properties that match with the design requirements. Each property is assigned a different weight, depending on its importance to the design’s success. The set of weights can be expressed as $W=\{w_1, w_2, \dots, w_N\}$.

The relation between the component and the candidate materials is defined by the *relative function,* R.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \dots & r_{2m} \\ . & . & & . \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}$$

The elements of the matrix are $r_{ij}$, where $r_{ij}$ is the relative value of property i when material j is the candidate material.

Once the candidate set, the factor set and the relative set have been defined the material data can be processed.

### 2.2 Weight Set

The allocation of appropriate weightings for each property is important. In the example of the tie rod many experts were asked to assign weight values of 1, 3 or 5 to each property.

Their decisions were based on the design requirements and their personal experience.

The weight values signify:
Weight = 5: most important
Weight = 3: important
Weight = 1: least important

Once the opinions of all the experts had been collected a weighting was given to each property. These values were then used for the analysis.

The weightings used for the tie rod are given in table 1.

| Properties | Weight | Properties | Weight |
|---|---|---|---|
| Tensile strength | 5 | Glass transition Tg | 3 |
| Tensile modules | 5 | Thermal conductivity | 3 |
| Flexural strength | 5 | Liner expansion | 3 |
| Compressive strength | 5 | Deflection T | 3 |
| Impact strength | 5 | Dielectric strength | 5 |
| Insulation resistance | 3 | Permittivity | 5 |
| Loss tangent | 5 | Water absorption | 3 |
| Density | 1 | | |

**Table 1 Weighting of each property**

### 2.3 Relative Function

The choice of relative function can affect the evaluation greatly so the function must be chosen with care. This paper presents a new method used to establish the relative function. This is based on the design requirements of the components and the material data sheet values.

After investigating many materials three principles emerged as the basis of the relative function:

**1. Property Distribution -** By plotting the cumulative distribution against property value for a large number of materials it is possible to determine a functional description of the distribution. Most properties are seen to have either a linear or a logarithmic distribution. For example, Figure 3 shows the distribution curve for tensile strength showing a logarithmic relationship.

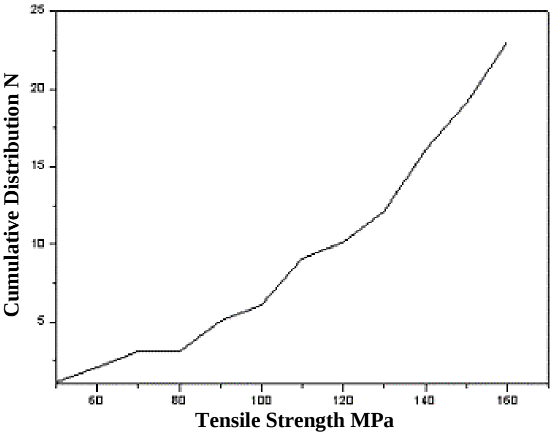

**Figure 3: Distribution of tensile strength property**

**2. Benchmark -** This is the optimum value of the material property determined from the design requirements.

**3. Boundary Value -** This is the minimum value below which the candidate material would be unsuitable.

For the tensile strength property we find

1. The distribution is logarithmic
2. The benchmark value is 75 MPa
3. The boundary value is 50 MPa

The relative function, R, is then defined by

$$R = k_1 \times \ln\left(\frac{ex}{b}\right) + k_2$$

where x is the property value
b is the benchmark value
$k_1$ and $k_2$ are coefficients still to be determined
e is the base for natural logs =2.71828

It is now assumed that when the material property fits the benchmark exactly then the relative function takes the value 3. If the property is equal to the boundary value then the function takes the value 0. These limits are used to determine the two coefficients, $k_1$ and $k_2$. These principles are illustrated in Figure 4.

Substituting the values R = 3 when B = 75 and R = 0 when b = 50 gives the two coefficients:

$k_1 = 7.5$ and $k_2 = -4.5$. Thus the relative function for the tensile strength is

$$R = 7.5 \times \ln\left(\frac{2.71828x}{75}\right) - 4.5$$

Based on this formula it is now possible to calculate the relative factor for each material's tensile strength.

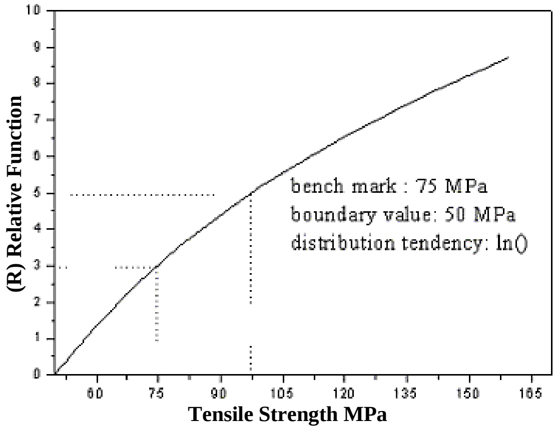

Figure 4: Principle of ranking for tensile strength

For the permittivity the distribution is linear, the benchmark value is 4.5 and the boundary value is 5.5. The linear relative function is given by

$$R = k_1 x + k_2$$

Applying the limiting cases, R=3 when x=4.5 and R=0 when x=5.5 gives coefficient values $k_1$=-3 and $k_2$ =16.5.

$$R = -3x + 16.5$$

The principle of ranking for permittivity is illustrated in Figure 5.

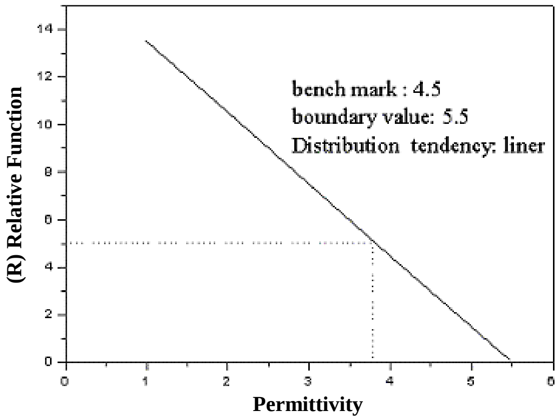

Figure 5: Principle of ranking for permittivity

For the loss tangent the distribution follows a $\log_{10}$ function as shown in Figure 6. The benchmark value is 0.01 and the boundary value is 0.1. Application of the limiting values gives coefficients $k_1$ = 3 and $k_2$ = -3. Thus the relative function is given by

$$R = 3\mathrm{Log}_{10}(1/x) - 3$$

In this way the relative function can be calculated for all properties for all materials. If the value of R is higher than 5 then that property must be much better than required by the design and the value is reset to 5. Table 2 shows the relative functions for all the properties to be considered when selecting the materials.

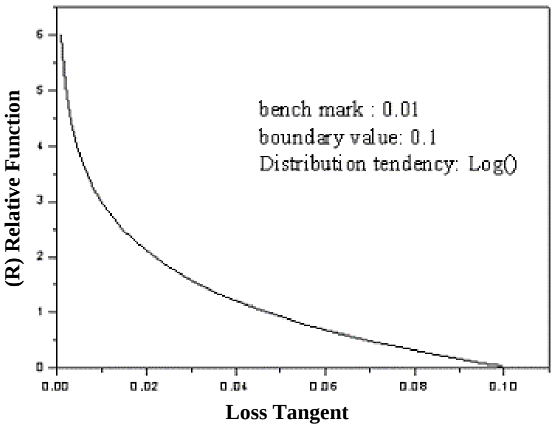

Figure 6: Principle of ranking for Loss Tangent

| Properties | | Principle of Ranking | | | |
|---|---|---|---|---|---|
| | Unit | Bench Mark | Boundary Value | Distribution | Relative Function |
| Mechanical | | | | | |
| Tensile strength | MPa | 75 | 50 | Ln() | R=7.5×Ln (0.036×x)-4.5 |
| Tensile modulus | GPa | 9.5 | 3 | Ln() | R=2.6×Ln (2.718×x/9.5)+0.4 |
| Flexural strength | MPa | 110 | 60 | Ln() | R=5×Ln (2.71828x/110)-2 |
| Compressive strength | MPa | 135 | 70 | Ln() | R=4.61×Ln (2.71828x/135)-1.61 |
| Impact strength Notch | kJ/m$^2$ | 7 | 4 | Ln() | R=5.34×Ln (2.71828x/7)-2.34 |
| Thermal | | | | | |
| Glass transition Tg | $^o$C | 100 | 80 | Liner | R=0.15x-12 |
| Thermal conductivity | W/mK | 0.8 | 0.2 | Liner | R=5x-1 |
| Liner expansion | $10^{-5}$ 1/K | 3.5 | 10 | Liner | R=-0.46x+4.6 |
| Deflection Temp.1.8MPa | $^o$C | 120 | 100 | Liner | R=0.15x-15 |
| Electrical | | | | | |
| Insulation resistance | Ω.cm | 1.00E+14 | 1.0E+9 | Log() | R=0.6Log(x)-5.4 |
| Loss tangent 1kHz | | 0.01 | 0.1 | Log() | R=3×Log(1/x)-3 |
| Permittivity 1kHz | | 3.5 | 5.5 | Liner | R=-3×x+16.5 |
| Dielectric strength | kV/mm | 18 | 10 | Ln() | R=5Ln(2.718x/18)-2 |
| Physical | | | | | |
| Density | kg/cm$^2$ | 1.75 | 3 | Liner | R=-2.4x+7.2 |
| Water absorption | % | 0.1 | 0.4 | Liner | R=-10x+4 |

Table 2: Principle of ranking for properties

## 2.4 Evaluation Method

Once the weights and relative functions have been compiled they can be multiplied up in a linear system

$$Z = (w_1, w_2 w_3 \cdots w_n) \cdot \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ . & . & & . \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}$$

$$= (z_1, z_2, z_3 \cdots z_m)$$

$$z_j = \sum_{i-1}^{n} w_i \cdot r_{ij} (j = 1,2,\cdots m)$$

Sometimes it is not possible to find all the data sheet information from material manufacturers. When this occurs, it is not possible to establish a consistent factor set. It has been found that the best way to overcome data deficiencies is to set the weight to zero for any property values where the default value is still set (i.e. where a data value has not been provided).

Thus the weighting technique is able to apply the relative importance of different properties and to overcome the difficulties of missing data.

$$Z = \frac{\sum_{i=1}^{n} W_i R_i}{\sum W_i} \qquad \ldots\ldots\ldots\ldots (1)$$

Thus an overall value for each material, known as the weighted average (Z) was calculated.

## 3 SELECTION AND EVALUATION FOR ENVIRONMENTALLY FRIENDLY MATERIALS

### 3.1 Functional Selection

The manufacturer's technical data for typically five different thermoplastic materials is shown below in Table 3. These are known to have good dimensional stability, excellent electrical performance and can be fabricated easily.

| Properties | | Materials | | | | |
|---|---|---|---|---|---|---|
| | Unit | PC | PBT | PAA | PPS | PET |
| **Mechanical** | | | | | | |
| Tensile strength | MPa | 61 | 149 | 235 | 195 | 172 |
| Tensile modulus | GPa | 5.0 | 10.4 | 20.0 | 14.7 | 17.0 |
| Flexural strength | MPa | 91 | 217 | 360 | 285 | - |
| Compressive strength | MPa | - | - | - | - | - |
| **Thermal** | | | | | | |
| Impact strength Notch | $kJ/m^2$ | 76 | 10.4 | - | 10 | 10 |
| Glass transition Tg | $^oC$ | - | - | - | 90 | - |
| Thermal conductivity | W/mK | - | - | - | - | - |
| Liner expansion | $10^{-5}$ 1/K | 7 | 9.1 | 1.5 | 6.2 | |
| Deflection Temp. 1.8MPa | $^oC$ | 133 | 208 | 230 | 270 | 240 |
| **Electrical** | | | | | | |
| Insulation resistance | Ω.cm | E13 | 2.70E +14 | 2.0E +15 | E+13 | E+15 |
| Loss tangent 1kHz | - | 0.009 | 0.0024 | 0.017 | 0.0002 | 0.017 |
| 1kHz Permittivity | - | 3 | 4.1 | 4.6 | 4 | 4.1 |
| Dielectric strength | kV/mm | 30 | 24 | 28 | 28 | - |
| **Physical** | | | | | | |
| Density | $kg/cm^2$ | 1.2 | 1.6 | 1.65 | 1.65 | 1.79 |
| Water absorption | % | 0.2 | 0.07 | 0.16 | 0.02 | 0.11 |

**Table 3: Data sheet of five thermoplastic materials**

Applying this technical data to the formulae outlined in Table 2 (last column) enabled a relative value to be calculated for each property given in Table 4. If the Relative value was higher than 5, the value was set at 5.

Since the weightings and relative values are now known the summation of all of these values for each material was then calculated using formula 1.

| Properties | | Relative Values ($R_I$) | | | | | |
|---|---|---|---|---|---|---|---|
| | Unit | PC | PBT | PAA | PPS | PET | |
| **Mechanical** | | | | | | | $W_I$ |
| Tensile strength | MPa | 1.45 | 5.00 | 5.00 | 5.00 | 5.00 | 5 |
| Tensile modulus | GPa | 0.00 | 3.24 | 4.94 | 4.14 | 4.51 | 5 |
| Flexural strength | MPa | 2.05 | 5.00 | 5.00 | 5.00 | default | 5 |
| Compressive strength | MPa | default | default | default | default | default | 5 |
| Impact strength Notch | $kJ/m^2$ | 5.00 | 5.00 | default | 4.90 | 4.90 | 5 |
| **Thermal** | | | | | | | |
| Glass transition Tg | $^oC$ | default | default | default | 1.50 | default | 3 |
| Thermal conductivity | W/mK | default | default | default | default | default | 3 |
| Liner expansion | $10^{-5}$ 1/K | 1.38 | 0.41 | 3.91 | 1.75 | default | 3 |
| Deflection T1.8MPa | $^oC$ | 4.95 | 5.00 | 5.00 | 5.00 | 5.00 | 3 |
| **Electrical** | | | | | | | |
| Insulation resistance | Ω.cm | 2.40 | 3.26 | 3.78 | 2.40 | 3.60 | 3 |
| Loss tangent 1kHz | - | 3.14 | 4.86 | 2.31 | 5.00 | 2.31 | 5 |
| 1kHz Permittivity | - | 5.00 | 4.20 | 2.70 | 4.50 | 4.20 | 5 |
| Dielectric strength | kV/mm | 5.00 | 4.44 | 5.00 | 5.00 | default | 5 |
| **Physical** | | | | | | | |
| Density | $kg/cm^2$ | 4.32 | 3.36 | 3.24 | 3.24 | 2.90 | 1 |
| Water absorption | % | 2.00 | 3.30 | 2.40 | 3.80 | 2.90 | 3 |
| Weighted Average (Z) | | **3.01** | **4.12** | **4.03** | **4.20** | **4.05** | |

**Table 4: Calculating the weighted average of 5 dfferent thermoplastic materials**

When these particular properties were considered, then PPS has the highest value, which indicates that this material fulfills the functional requirements of the tie rod better than any of the other thermoplastics.

### 3.2 Environmental and Cost Evaluation

Those materials that exhibited higher weighted average values for their functional performance were then examined further for their effect on the environment. Elimination of certain candidates was achieved by applying the basic principles of the:

- 3R system (Reuse, Recycle and Reduce).
- avoidance of heavily filled composites, which are environmentally worse as they consume more energy and are more expensive to recycle.
- selection of materials without flame retardant additives.
- exclusion of materials that are forbidden by legislation.

Further selection of preferred materials was determined using a software tool known as the Environmental Information and Management Explorer (E.I.M.E.) which applies a quantitative analysis procedure (Ref 1).

After the application of these two methods the preferred candidates were then further reduced in number by an examination of their economic viability in terms of raw materials and fabrication route.

## 4 CONCLUSION

It has been demonstrated that a modified Fuzzy performance summation is an objective and effective method in the material evaluation and selection of alternative materials for existing designs. It has the advantages of:

- an accurate quantitative technique applying greater emphasis to certain properties.
- a way to reduce errors brought about by the omission of technical data from the manufacturers.

## REFERENCES

(1) CODDE 11-17 rue HAMELIN-78753 Paris.
www. Codde.fr

E.I.M.E.-This was jointly developed by ADEME (French Environmental Agency) with the assistance of a number of French electrical companies particularly AREVA T&D Ltd.

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