BENDING CHARACTERISTICS OF RESIN CONCRETES

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ABSTRACT
In this research work the bending characteristics of thermoset polymer concretes were analyzed. Various mixtures of resin and aggregates were considered, in view of an optimal combination. The Taguchi methodology was applied, in order to reduce the number of tests and in order to evaluate the influence of various parameters in concrete properties. This methodology is very useful for the planning of experiments.

INTRODUCTION
Polymer concrete is a kind of concrete in which a thermoset resin binds together natural aggregates, such as silica sand. Catalysts and accelerators are added up to resin before mixing with inorganic aggregates, in order to initiate the polymeric curing.

In this type of concretes, water is completely absent, as it inhibits the curing of concrete [1]. Therefore, unlike cement concretes, this is a water-free concrete.

Typical resins used in these concretes are polyester, epoxy or acrylic thermoset resins. Polyesters are the most used mainly for economic reasons.

Resin concretes have good mechanical properties, such as high compression strength, high durability in terms of fatigue and in terms of corrosion resistance. Its permeability to liquids is generally very low and its curing times are quite fast.

The industrial applications of polymer concretes are growing steadily, particularly in the area of precast concrete elements, such as façade panels [2]. The good mechanical
and corrosion properties of such concretes allow thinner cross-sections and lower cover depths in reinforced concrete, reducing transport costs and handling risks.

As Portland cement concrete, resin concretes relatively have low tensile strength, when compared to compressive strength (around 100 MPa). Therefore, brittle cracks due to tensile stresses can occur, being necessary in many cases the use of steel or frp rebars, increasing ultimate load, ductility and toughness [3-6].

The main objective of this work is to characterize the bending behaviour of polyester and epoxy concretes, and to study the influence of mixture and curing cycles in concrete characteristics.

The planning of various mixtures was achieved with a Taguchi methodology. This technique allows the analysis of the effect of several manufacturing factors [7-11]. This technique allow also to identify interactions between factors, reduction of mixture combinations, through a library of pre-set orthogonal matrices, without loss of relevant information [7-11]. To perform all possible tests with all possible mixture combinations would not be practical, either in time or cost.

**EXPERIMENTAL PROCEDURE**

**Planning of testing formulations**

To analyze the influence of various parameters in the concrete bending strength the following material factors are considered:

- Resin type;
- Resin content (%);
- Charge content in resin (%);
- Sand type;
- Curing cycle;
The variation levels, for each considered factor, are specified in table 1.
The number of all combinations between these five factors with two variation levels is 2-raised to five, or either thirty-two possible combinations. However, the proposed Taguchi method allowed the reduction of the number of combinations to test, by the use of pre-set orthogonal array with sixteen lines, which corresponded to the different formulations to test.
Using this array, not only the influence of each factor can be evaluated, but also the interactions between itself (it has fifteen degrees of freedom: five corresponding to factors and ten corresponding to its interactions).
The 16 resultant formulations are presented in table 2.

Materials characterization
A pre accelerated orthophthalic polyester resin (NESTE-S226E) was used, with 2 % (in weight) catalyst. Also it was used a low viscosity epoxy resin (EPOSIL-551), with a maximum bending strength of 70 MPa. This resin was mixed with a hardener on a 2/3 resin, 1/3 hardener ratio.
The charge incorporated in this resin was calcium carbonate. The weight percentages are related to the total weight of resin.
The foundry sand used was a siliceous one, of rather uniform particles size, with an average diameter of 245 microns. Clean sand is a locally available river sand, previously washed and well graded (0.01/1.20mm). The water content of both sands was controlled to be less than 0.1%, before being mixed with the resin.
The mixture was done mechanically, to achieve a more homogeneous material. For each formulation, nine samples were manufactured according to RILEM standards [12]. The metallic moulds are of standard type.
Experimental set-up

Samples were tested in three-point bending, after curing. An Instron universal testing machine, with a load cell of 100 kN, was used (Fig. 1). Tests were performed according to RILEM standards [13], at a rate of 1mm /min. Load-displacement curves and maximum load corresponding to the collapse bending moment, were recorded.

Testing set-up and sample geometry are defined in figure 2.

EXPERIMENTAL RESULTS

Bending tests

Table 3 presents the average failure load and failure stress for each formulation. In figure 3 it is presented the typical load-displacement curves obtained in the bending tests of concrete specimens. These particular curves are referring to concrete formulation nº 4.

The load-displacement curves for each formulation are quite similar, and the maximum loads values are also very close, which is a good indication of material behaviour prediction.

Variance analysis by the Taguchi method

In the application of the Taguchi method, the variance analysis –ANOVA- was used, in order to analyze data obtained by the chosen orthogonal matrix. ANOVA allows the testing of the significance of the effects relatively to the random error [7-11]. The analysis was performed for a significance level of 5%, or for a confidence level of 95%. The variance analysis results, for bending strength response, are shown in table 4.
The last column of table 4 represents the contributions of each factor (or interaction) to the global variance. These contributions are function of the numeric values of the effects and they indicate the level of influence in the global response, which is the bending resistance.

The numeric value of an effect (\( E_A \)), or principal effect, is not more than the difference between the average values obtained on the two levels adopted for that factor. In the calculation of each these averages, all response values where that factor interacts with the level in question are considered.

\[
E_A = A_1 - A_2 \quad \text{(I)}
\]

- where \( A_i \) represents the average value corresponding to all responses involving factor A with level “i”.

The determination of the interaction effect value between two factors (\( IE_{A*B} \)) is not so straightforward and it involves the calculus of four different average values:

\[
IE_{(A*B)} = ( A_1B_1 - A_1B_2 ) - ( A_2B_1 - A_2B_1 ) \quad \text{(II)}
\]

- where \( A_iB_j \) represents the average value corresponding to responses involving factor A with level “i” and factor B with level “j”.

**Response graphics**

Response graphics allow the evaluation of the relative importance of each factor, or interaction, in a much easier way than numeric values of effects.

For principal effects the interpretation of graphics is straightforward. Figures 4 to 8 present the response graphics of the principal effects, with 95% confidence error bars.
Each graphic point represents the average response for the factor, at a certain level. The numeric value of the effect is precisely the difference between the two points: the higher the difference, the higher the influence of the factor.

To analyze the response graphics of interaction effects, principal effects of factors must be ignored and attention must be focused in its interaction. The interaction is graphically defined by the parallelism between two straight lines: the smaller the parallelism, the bigger the interaction. The interaction effects response graphics are represented in figures 9-18, with 95% confidence error bars.

**DISCUSSION OF RESULTS**

**Variance analysis results**

From table 4, it can be concluded that resin type is the most influencing factor, followed by resin content and charge content. The interaction between this last factor and sand type also presents a significant contribution to global response.

- Resin type 49.66%
- Resin content 13.69%
- Charge content 8.33%
- Interaction Charge content * Sand type 8.43%

The remaining factors and interactions have a very small influence in the total variation. In particular, sand type and curing conditions factors, and its interactions, have been rejected for a significance level of 5%.

**Principal effects analysis**

From the analysis of the response graphics it is evident that the use of epoxy resin strongly increases bending strength, when compared to polyester resin.

For epoxy resin values are not only higher, but also more reliable, due to more uniform results [Fig.4].
Responses are also increased, at a lower level, with the use of 20% resin content, as expected and with 0% charge content [Fig. 5 and 6].

Sand type and curing treatment, isolated, have almost no influence in concrete bending strength, as one can observe from the small slope in corresponding graphics [Fig. 7 and 8].

**Interactions effects analysis**

Analyzing the interaction effects, according to figures 9-18, the following conclusions can be drawn, by interaction descending order of importance:

- **Interaction between Charge content and Sand type: (8.43%)**
  
  Foundry sand concretes are very sensitive to the incorporation of charge in resin formulation. The best mechanical results are obtained for 0% charge content. Clean sand concretes are less sensitive, and can be considered as insensitivity to variation of charge content (the two average points are coincident)[ Fig. 9 ].

  This difference in behaviour is explained by each sand particles size distribution. Foundry sand, with very fine grain size, has a large specific surface and it reacts poorly to the incorporation of more fine particles. Clean sand, with a smaller specific surface, requires less binder, and therefore the concretes made with this kind of sand and with charge, balance the lower effective resin content with a better filling of holes through the incorporation of calcium carbonate.

- **Interaction between Resin type and Charge content: (4.35%)**
  
  The incorporation of charge in polyester concretes has a rather negative influence in global response. This effect is not so pronounced in epoxy resins. An average reduction of 4% in bending strength for epoxy concrete and a 33% reduction for polyester concrete [ Fig. 10 ] exists. This phenomenon can perhaps be explained by
the higher viscosity of polyester resin and the corresponding lower wetting ability, being therefore more susceptible to the incorporation of fine particles.

- **Interaction between Resin type and Sand type: (3.82%)**

Epoxy resin concretes present better bending behaviour when manufactured with foundry sands. However, polyester concretes present better mechanical behaviour when incorporating clean sands [Fig. 11]. This can be explained by the higher capacity of epoxy resin to wet aggregates, allowing finer sands, while polyester resin, with less wetting ability, prefers aggregates with lower specific surface.

- **Interaction Resin type and Resin content: (3.14%)**

Polyester concretes are less susceptible to resin content than epoxy concretes. An increase of 17% to 20% in resin content increases response in about 56%, for polyester resin against an increase in 10% for epoxy resin [Fig. 12].

- **Interaction Resin content and Sand type: (2.17%)**

By incorporating higher resin content (20%) better results are obtained when foundry sands are used, while when smaller resin content (17%) is used, better response is obtained with clean sands [Fig. 13].

Lower resin contents require sands with lower specific surfaces, so that it may be possible to involve all material. When there is an excess of resin, this resin tends to migrate to surface, reducing homogeneity.
• *Interaction Resin content and Charge content: (1.99%)*

When 25% of charge is used in resin, global response values increase much more with the increase of resin content than with 0% charge [Fig. 14].

This reaction is due to the fact that charge incorporation corresponds to an increase in specific surface of the totality of particles.

The interaction of factors [resin content], [charge content], [resin type] and [sand type] with factor [curing treatment] have no significant influence in the global response values, as can be observed in the almost perfect parallelism of the two straight lines in corresponding response graphics [fig. 15-18].

**CONCLUSIONS**

The objective of this research was to analyze the influence of compositions and curing treatment in bending strength of polyester and epoxy concretes towards an optimal formulation.

For that purpose a number of concrete formulations with various curing treatments were manufactured and tested in bending. Load-displacement curves and failure loads were recorded.

Planning of tests and the evaluation of factor effects and its interaction effects was performed with the Taguchi method, in order to reduce the total number of formulations to be tested.

A variance analysis – ANOVA- was used for data analysis. The following conclusions can be drawn:

• The most decisive factor for bending strength is the resin type, followed by resin content and charge content.
• Curing cycle does not influence the concrete final characteristics. Seven days cure, at room temperature, is equivalent to three hours cure, at 80°C.

• The analysis of principal effects and its interactions allowed establishing the most interesting levels for each factor. The optimal combination, corresponding to the most resistant concrete was found. It is composed by:

  - Epoxy resin;
  - 20% Resin content;
  - 0% Charge content;
  - Foundry sand;

This optimal combination was really tested. It corresponds to concrete nº12, which has an average bending strength of 38 MPa. Therefore, there was no need to predict the bending strength of concrete corresponding to the optimal formulation by the Taguchi method, or to perform the confirmation test.

Obviously, this combination is not the most economical one, attending to higher cost of epoxy resin and also the resin content involved. The best relation between price and performance was presented by combination nº4. It’s similar to nº12, but with polyester resin instead epoxy resin. This formulation is almost five times cheaper, and its bending strength is only 17% smaller than the optimal combination.

A compromise solution must be sought according to specific concrete application specifications.

Based on this research, a new study accounting for an intermediate level for resin content, is sought to be helpful in the choice of that solution.
ACKNOWLEDGEMENTS

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REFERENCES


Table 1 – Factors and levels.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Resin Type</th>
<th>Charge content</th>
<th>Resin content</th>
<th>Sand type</th>
<th>Curing cycle</th>
</tr>
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<tbody>
<tr>
<td><strong>Level 1</strong></td>
<td>Polyester</td>
<td>0 %</td>
<td>17 %</td>
<td>Clean</td>
<td>7 days/23°C</td>
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<tr>
<td><strong>Level 2</strong></td>
<td>Epoxy</td>
<td>25 %</td>
<td>20 %</td>
<td>Foundry</td>
<td>3 hours./80°C</td>
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</tbody>
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Table 2 – Formulations to be tested.

<table>
<thead>
<tr>
<th>Concrete #</th>
<th>Resin type</th>
<th>Charge content (%)</th>
<th>Resin content (%)</th>
<th>Sand type</th>
<th>Curing cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Polyester</td>
<td>0</td>
<td>17</td>
<td>Clean</td>
<td>7 days/23°C</td>
</tr>
<tr>
<td>2</td>
<td>Polyester</td>
<td>0</td>
<td>17</td>
<td>Foundry</td>
<td>3 h/ 80°C</td>
</tr>
<tr>
<td>3</td>
<td>Polyester</td>
<td>0</td>
<td>20</td>
<td>Clean</td>
<td>3 h/ 80°C</td>
</tr>
<tr>
<td>4</td>
<td>Polyester</td>
<td>0</td>
<td>20</td>
<td>Foundry</td>
<td>7 days/ 23°C</td>
</tr>
<tr>
<td>5</td>
<td>Polyester</td>
<td>25</td>
<td>17</td>
<td>Clean</td>
<td>3 h/ 80°C</td>
</tr>
<tr>
<td>6</td>
<td>Polyester</td>
<td>25</td>
<td>17</td>
<td>Foundry</td>
<td>7 days/ 23°C</td>
</tr>
<tr>
<td>7</td>
<td>Polyester</td>
<td>25</td>
<td>20</td>
<td>Clean</td>
<td>7 days/ 23°C</td>
</tr>
<tr>
<td>8</td>
<td>Polyester</td>
<td>25</td>
<td>20</td>
<td>Foundry</td>
<td>3 h/ 80°C</td>
</tr>
<tr>
<td>9</td>
<td>Epoxy</td>
<td>0</td>
<td>17</td>
<td>Clean</td>
<td>3 h/ 80°C</td>
</tr>
<tr>
<td>10</td>
<td>Epoxy</td>
<td>0</td>
<td>17</td>
<td>Foundry</td>
<td>7 days/ 23°C</td>
</tr>
<tr>
<td>11</td>
<td>Epoxy</td>
<td>0</td>
<td>20</td>
<td>Clean</td>
<td>7 days/ 23°C</td>
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<tr>
<td>12</td>
<td>Epoxy</td>
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<tr>
<td>13</td>
<td>Epoxy</td>
<td>25</td>
<td>17</td>
<td>Clean</td>
<td>7 days/ 23°C</td>
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<tr>
<td>14</td>
<td>Epoxy</td>
<td>25</td>
<td>17</td>
<td>Foundry</td>
<td>3 h/ 80°C</td>
</tr>
<tr>
<td>15</td>
<td>Epoxy</td>
<td>25</td>
<td>20</td>
<td>Clean</td>
<td>3 h/ 80°C</td>
</tr>
<tr>
<td>16</td>
<td>Epoxy</td>
<td>25</td>
<td>20</td>
<td>Foundry</td>
<td>7 days/ 23°C</td>
</tr>
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</table>
Table 3 – Average failure loads and stresses.

<table>
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<th>Concrete nº</th>
<th>Average failure load (kN)</th>
<th>Average failure stress (MPa)</th>
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<tbody>
<tr>
<td>Polyester</td>
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<td></td>
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<tr>
<td>1</td>
<td>10.04</td>
<td>23.5</td>
</tr>
<tr>
<td>2</td>
<td>8.76</td>
<td>20.5</td>
</tr>
<tr>
<td>3</td>
<td>10.19</td>
<td>23.9</td>
</tr>
<tr>
<td>4</td>
<td>14.02</td>
<td>32.8</td>
</tr>
<tr>
<td>5</td>
<td>7.05</td>
<td>16.5</td>
</tr>
<tr>
<td>6</td>
<td>2.15</td>
<td>5.0</td>
</tr>
<tr>
<td>7</td>
<td>11.25</td>
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<td>8</td>
<td>8.32</td>
<td>19.5</td>
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<td>Epoxy</td>
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<td></td>
</tr>
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<td>9</td>
<td>12.79</td>
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<td>12</td>
<td>16.52</td>
<td>38.7</td>
</tr>
<tr>
<td>13</td>
<td>12.82</td>
<td>30.0</td>
</tr>
<tr>
<td>14</td>
<td>12.45</td>
<td>29.2</td>
</tr>
<tr>
<td>15</td>
<td>14.77</td>
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<td>16</td>
<td>14.91</td>
<td>34.9</td>
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Table 4 – ANOVA variance analysis.

<table>
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<th>Factors and interactions</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>F-values</th>
<th>Significance level</th>
<th>Contribution %</th>
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<td>308848754.324</td>
<td>919.133</td>
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<td>49.66</td>
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<td>% de Charge</td>
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<td>52092015.415</td>
<td>155.026</td>
<td>0.0001</td>
<td>8.33</td>
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<td>% Resin</td>
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<td>85382646.521</td>
<td>254.098</td>
<td>0.0001</td>
<td>13.69</td>
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<tr>
<td>Sand type</td>
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<td>314706.548</td>
<td>0.937</td>
<td>0.3404</td>
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<tr>
<td>Post-cure</td>
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<td>1186241.505</td>
<td>3.530</td>
<td>0.0694</td>
<td>0.14</td>
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<td>Resin * % of Charge</td>
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<td>27367979.979</td>
<td>81.447</td>
<td>0.0001</td>
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<td>24047207.405</td>
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<td>Resin * Curing temperature</td>
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<td>2954330.259</td>
<td>8.792</td>
<td>0.0057</td>
<td>0.42</td>
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<td>% of Charge * % Resin</td>
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<td>12723477.521</td>
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<td>% of Charge * Sand type</td>
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<td>52713912.209</td>
<td>156.876</td>
<td>0.0001</td>
<td>8.43</td>
</tr>
<tr>
<td>% of Charge * Curing temperature</td>
<td>1</td>
<td>5173855.167</td>
<td>15.397</td>
<td>0.0004</td>
<td>0.78</td>
</tr>
<tr>
<td>% Resin * Sand type</td>
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<td>13817761.187</td>
<td>41.122</td>
<td>0.0001</td>
<td>2.17</td>
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<td>621249508.628</td>
<td>100.00</td>
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Fig.1 – Bending test of resin concrete.

Fig.2 – Test scheme and sample geometry.

Fig.3 – Load-displacement curves (formulation nº4)

Fig.4 – Effect of “Resin type”.

Fig.5 – Effect of “Resin content”.

Fig.6 – Effect of “Charge content”.

Fig.7 – Effect of “Sand type”.

Fig.8 – Effect of “Curing cycle”

Fig.9 – Effect of interaction “Charge content * Sand type”.

Fig.10 – Effect of interaction “Resin type * Charge content”.

Fig.11 – Effect of interaction “Resin type * Sand type”.

Fig.12 – Effect of interaction “Resin type * Resin content”.

Fig.13 - Effect of interaction “Resin content * Sand type”.

Fig.14 - Effect of interaction “Charge content * Resin content”.

Fig.15 - Effect of interaction “Resin content * Curing cycle”.

Fig.16 - Effect of interaction “Charge content * Curing cycle”.

Fig.17 - Effect of interaction “Resin type * Curing cycle”.

Fig.18 - Effect of interaction “Sand type * Curing cycle”.
Figure 3.

Figure 4
Figure 5.

Figure 6.
Figure 7.

Figure 8.
Figure 9.

![Graph showing load (N) vs. sand condition (Foundry vs. Clean) with data points for 25% and 0% charge.]

Figure 10.

![Graph showing load (N) vs. percentage charge (25% vs. 0%) with data points for Epoxy and Polyester.]

LOAD (N)
**Figure 11.**

**Figure 12.**
Figure 13.

Figure 14.
Figure 15.

Figure 16.
Figure 17.

Figure 18.