CORRELATION BETWEEN THE STANDARD, RHEOLOGICAL AND TECHNOLOGICAL PARAMETERS IN CLUPACK EXTENSIBLE PAPER MANUFACTURING

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This paper is part of a more ample study, aimed at establishing some rheological characteristics, besides the standard ones, for a better knowledge of the Clupack extensible papers, according with their behaviour in subsequent converting and utilization. Clupack extensible papers, manufactured at different times, were subjected to standard and rheological tests (utilizing the stress - strain and direct/ reverse creep curves), on simultaneously recording the main technological parameters. Based on the standard and rheological characteristics and on the processing parameters the simple and multiple correlations between the above mentioned factors have been determined (r being between 0.7 - 0.9). Thus, the optimum processing conditions could be established on considering paper’s rheological characteristics.

**KEY WORDS:** Clupack extensible paper; rheological characteristics; standard characteristics; simple and multiple correlations

**INTRODUCTION**

The paper analyzes the results of the investigations performed both at laboratory and industrial scale, in view of a better characterization of Clupack extensible sack papers, and also for an improved behaviour during their processing and/or utilization.

The possible existence of a “structure-properties” correlation is also considered, according to its physico-mechanical and rheological characteristics.\(^1\)\(^2\)

Also, in a previous study, the observation was made that, under similar conditions of paper’s obtainment, the rheological characteristics have a higher variation domain, which means that they are more sensible than those observed for the same product by the parameters determined under standard conditions.\(^3\)

Based on the above observations, the present study is meant at establishing - by means of their rheological characteristics and correlations with the technological parameters of fabrication - the optimum conditions for them asking of this paper grades, closely dependent on the requirements from the requirements of utilizers.
EXPERIMENTAL PART

Investigation stages

The investigations were performed in two stages, as follows:

a) Study of the influence of kraft pulp, as a raw material in the manufacturing of Clupack extensible sack papers, especially for establishing the conditions of stock’s preparation and the role of screening and beating processes.

b) Establishment of the influence of the main factors involved in the manufacturing of Clupack extensible paper and its optimization both by means of the main technological parameters and of the rheological characteristics essential in this process.

This involved monitoring - for two years - of both the technological factors and the standard physico-mechanical and rheological characteristics of the products considered.

Working Conditions

In a first series of investigations, kraft pulp resulted from the current fabrication for Clupack extensible sack paper at “AMBRO” Co. Suceava, taken over both prior to and after screening, was employed.

The characteristics of this pulp are given in Table 1.

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooking method</td>
<td>Sulfate</td>
</tr>
<tr>
<td>Küng number</td>
<td>71</td>
</tr>
<tr>
<td>Initial beating degree, ° SR</td>
<td>16</td>
</tr>
<tr>
<td>Yield of washing, g / L NaOH - initial</td>
<td>0.288</td>
</tr>
<tr>
<td>- end</td>
<td>0.104</td>
</tr>
</tbody>
</table>

The latter step of investigations was performed on the fabrication line of Clupack extensible sack paper, on the paper machine - Nr.2. from “AMBRO” Co. Suceava.

The manufacturing process was monitored parameters i.e. its technological parameters, the main standard and rheological characteristics of this grade of paper.

The standard tests on the papers considered for the study have been performed in the conditions established by the norms in force.4

The tests of tensile stress and determination of the mechanical work were developed on a Tira-Test device on which the stress-strain curves could be plotted under determined conditions of strain rates.
Paper’s rheological characteristics have been established both from the curves plotted on the Tira-Test device and from those resulted from direct and reverse creep tests performed on an device built in our laboratory.

As already discussed in a previous study, on longitudinal direction, the stress-strain curve for extensible paper evidences three distinct domains, as follows: the elastic domain (I) for stresses lower than 20-25 of the breaking load, the visco-elastic domain (II), manifested at stresses lower than 40 % of the breaking load, and the plastic domain (III), with two distinct regions: one characterized by a significant increase of deformation for low variation of the stretching stress (IIIa) - considered as the domain in which breaking of the microcreep from the structure of extensible papers occurs predominantly, and a region in which deformations increase more slowly with stretching IIIb - occurring at an stress threshold of the breaking load higher than 70 %.

All these domains also act transversally, although to a lower extent.

Consequently, according to the rheological model adopted, the main rheological parameters selected for these papers, have been the following:

- the components of deformation: $\varepsilon_I$, $\varepsilon_{v.e.}$, $\varepsilon_{pl.}$, $\varepsilon_0$;
- the module of elasticity: $E_1$ and $E_2$;
- viscosities: $\eta_1$ and $\eta_2$;
- the stress jump in the demicrocreeping domain: $\Delta \sigma_{IIIa}$;
- mechanical work in the demicrocreeping domain: $L_{IIIa}$;
- percent value of the work consumed during demicrocreeping versus total mechanical work: $\phi = \frac{L_{IIIa}}{L_t} \times 100$;
- rate at which the leap of stress occurs in the field of demicrocreeping domain: $\Omega = \frac{\Delta \sigma_{IIIa}}{\Delta t_{IIIa}}$.

The creep curves, partially involved in the determination of these parameters, have been developed for 15 min. for a stress of 60 % of the paper’s breaking stress. Consequently, once these tests are performed below the above-mentioned threshold limit of 70 %, the Burger rheological model has been employed in the first phase.

Over the whole domain of paper stretching most suitable was found the modified Burger model, which contains, besides other elements, also:

- a stress limitator, for values higher than 70 % of the breaking load’s value;
- the $\eta_3$ - damper, indicating the remanent deformations in this last domain of stretching with

$$\sigma > 0.70 \sigma_R.$$  

**Influence of Kraft pulp’s screening and beating**

Initially, the sheets obtained from both screened and unscreened pulp, with a constant basis weight of 70 g/m², have been subjected to tests for the determination of the physico-
mechanical and rheological characteristics. The results obtained are presented graphically in Figure 1.

Fig.1.- Physico-mechanical and rheological characteristics of screened kraft pulp (S), versus the unscreened (N) one

According to the presented diagrams, the classical physico-mechanical characteristics ($S_R$, $\varepsilon_R$, and $L_{mech}$) of the papers obtained from the same pulp and for initial beating degree, are found as lower for the screened pulp; this may be explained by the fact that during screening of pulp prior to its refining, besides the coarse material, fines, known as playing an important role in the development of the physico-mechanical characteristics are also rejected.

As to the evolution of the rheological parameters, they are different in the two stages of stock’s preparation, as follows: the fact that the modulus of elasticity $E_1$ and viscosity $\eta_1$ are higher for screened pulp indicates the increasing tendency of the relaxation time ($t_{rel}$) and, therefore, of paper’s stiffness.

Decrease of parameters $E_2$ and $\eta_2$ for screened pulps shows that differences appear, too, at the level of the visco-elastic properties: reduction of the retardation time ($t_{ret}$) and, consequently, of the delayed elastic deformations.

Through refining, in time, modification of the kraft-pulp and, implicitly, of the corresponding papers characteristics occurs.
Modification of the stress-strain curves, as a function of duration and, respectively, the refining time in a Yokro mill, are illustrated in Figure 2.

Fig.2.- The stress-strain curves of kraft pulp, for various beating degrees
1-defibrising (16 °SR); 2-17 °SR; 3-32 °SR; 4- 45 °SR; 5-23 °SR

Figures 3 a and b plot the evolutions of breaking load ($S_R$), deformation ($\varepsilon_R$) and mechanical work ($L_{\text{mech.}}$) as a function of the beating degree.

Diagrams 3 c, d and e plot the variations of some rheological parameters - i.e., module of elasticity ($E_1$ and $E_2$), viscosity values ($\eta_1$ and $\eta_2$) and the components of deformation ($\varepsilon_i$; $\varepsilon_{\text{v.e.}}$; $\varepsilon_{\text{pl.}}$; $\varepsilon_0$) as a function of refining.

From the viewpoint of the rheological characteristics' evolution, refining - inducing a decrease of $t_{\text{ret.}}$ - causes paper’s stiffness. At the same time, maintaining of $t_{\text{ret.}}$ relatively constant induces no essential modifications in the value of the delayed deformation’s components, with the increase of the refining degree.

Based on the above results, the conclusion may be drawn that, for having a pulp suitable for the fabrication of Clupack extensible paper, it should be screened - as much as possible - without the elimination of the fines.

Refining should be developed up to the optimum domain of 30 °SR, when both the physico-mechanical and the rheological parameters obtain maximum values, suitable for the manufacturing of such papers.
Fig.4.- Evolution of the physical, mechanical and rheological characteristics as a function of the beating degree

a)- evolution of mechanical characteristics \((S_r, \varepsilon_r, \varepsilon)\) as a function of the beating degree
b)- evolution of \(L_{\text{mech}}\) as a function of the beating degree
c)- evolution of modulus \(E_1\) and \(E_2\) as a function of the beating degree.
d)- evolution of viscosities \(\eta_1\) and \(\eta_2\) as a function of the beating degree.
e)- evolution of deformations as a function of the beating degree.
Optimization and pre-establishment of the technological parameters by the utilization of certain rheological parameters

The study has involved monitoring - for two years - of the technological parameters, standard physico-mechanical and non-conventional rheological characteristics.

The data obtained on both conventional and rheological characteristics for the microcreeped paper obtained on the paper machine No.3 at “AMBRO” Co – Suceava, are listed in Table 2.

TABLE 2
Physico-mechanical and rheological characteristics of the industrially produced papers taken into study

At the same time, the values of the main technological parameters involved in the process have been recorded during stock preparation, stock inlet, forming - dewatering, pressing, drying, micro-creeping (on Clupack device) and calendering of paper.

Part of the parameters considered are given in Table 3.

TABLE 3
Some technological parameters considered for this study

For checking the applicability of Burger’s model - considered for the rheological characterization of these papers (over a stress domain of up to 70 % of the breaking load value) - Figure 4 presents comparatively the direct creep curve obtained experimentally and the one resulted from the equation of creep valid for this model.

![Theoretical creep curve for the Burger model (2) and the experimentally obtained one(1) for Clupack extensible paper](image-url)
A very good agreement is observed, the error recorded between the two curves being of only 0.533%.

Attainment of the objectives of the present study involved initially establishment of the correlation equations and, respectively, correlation coefficients between:

a - the physico-mechanical characteristics and technological parameters of fabrication

(Table 4)

TABLE 4
Main physico-mechanical and rheological paper characteristics

b - technological parameters and rheological characteristics of paper (Table 5)

TABLE 5
Technological parameters and rheological paper characteristics

c - rheological and physico-mechanical characteristics (Table 6)

TABLE 6
Rheological and physico-mechanical characteristics

Analysis of the data from Tables 4 - 6 evidences that between most of the parameters and the characteristics of the paper investigated in the study, a very good correlation exists, the multiple regression coefficients varying between 0.66 - 0.99 (particular cases: r = 0.5 - 0.55).

Also, the observations made in a previous study³, namely that the rheological parameters considered for the characterization of such papers define more exactly the behaviour and the main (standard) physico-mechanical characteristics of such materials (see Table 6), have been now fully confirmed.

Another conclusion of the study is that the paper’s rheological characteristics may anticipate the conditions and main parameters of manufacturing, in operations of refining stock inlet forming-dewatering, micro-creeping and, especially the rate differences between the final dryer groups, a domain known as very sensible and influencing decisively the characteristics of the obtained papers (see Fig. 3). All the above observations have been confirmed by the relations given in Table 5 and by those recorded experimentally and listed in Table 7.

TABLE 7
Technological parameters calculated with the correlation equation
Having all these in view, the assertion may be made that, in spite of the high number of factors of influence, acting simultaneously in such a complex technological process, very useful correlations may be established between them and the physico-mechanical and, respectively, rheological characteristics of the produced paper.

Based on this observation, it was concluded that such correlations may be also useful for the pre-establishment of the technological conditions for the manufacturing of paper with required characteristics.

Indeed, such a hypothesis is once more found as valid, as seen in the scheme given in Figure 5.

Fig.5.- Diagram for the calculation of the pre-established conditions of fabrication

The above situation to the manufacturing of Clupack extensible paper with the following breaking characteristics:

- load \( (S_R) \) 88 N
- elongation \( (\varepsilon_R) \) 5 %
- mechanical work \( (W_{\text{mech.}}) \) 0.4 N*m

The correlation equations between the technological parameters and the paper’s characteristics having been previously established through modelling and preliminary tests, on observing that:

- The imposed physico-mechanical parameters are significantly correlated (0.75 - 0.95) with seven of the basic rheological characteristics of paper (see the right part of the diagram), in a high correlation ratio (0.70 - 0.80) too, with the four rheological parameters suggested by us (see the left side of the diagram).

- On further following the line of correlations (the right and, respectively, left part of the diagram), one may observe that, by means of the rheological characteristics, under significant correlation conditions (0.7 - 0.9), the main technological parameters of manufacturing pre-established through calculation, should be kept within the following limits:

  - evacuation consistency from refining \( 4.7 - 5.0 \% \);
  - final beating degree \( 30^\circ \) SR;
  - stock inlet consistency \( 0.32 \% \);
  - pressure at the micro-creeping Clupack \( 19.3 \cdot 10^5 \) N/m²

According to such conditions, the result of the calculations will be a Clupack extensible paper with \( S_R = 80-89 \) N, i.e. very close to the initially imposed value. More than that, such technological conditions are known as optimum for the manufacturing of such papers.

CONCLUSIONS
1. The necessity of considering carefully paper’s rheological characteristics for the evaluation of both the fibrous material’s quality and the resulting paper has been confirmed.

2. Physico-mechanical and rheological tests applied to kraft pulp showed that screening of the fibrous material prior to refining should avoid - possibly, through fractionation - elimination of the fines. The optimum beating degree should range between 30 - 35 ° SR.

3. It was also shown that, in conditions of industrial-scale manufacturing, establishment of certain correlations between the processing ( technological) parameters and the paper’s physico-mechanical and rheological characteristics should be considered.

4. The rheological characteristics permit not only a more correct characterization of paper’s behaviour under various stresses and/or utilizations, but also pre-establishment, through calculations, of the optimum papermaking conditions.

In this way, the possibilities of a correct evaluation of paper’s quality and also programming and maintaining of a product within the imposed limits, are much extended.

REFERENCES

3 Em. Poppel, C. Malutan, N.Orleschi and M.Puiu, Cellulose Chem. Technol, in print
4 * * * Trademark Information, Clupack Inc., July 1993
6 Em. Poppel, Applied Rheology, 12, 269 (1996)
TABLE 2
The physico-mechanical and rheological characteristics of the industrially produced papers taken into study

<table>
<thead>
<tr>
<th>Experimental series</th>
<th>CONVENTIONAL</th>
<th>NEW MECHANICAL - RHEOLOGICAL VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S&lt;sub&gt;r&lt;/sub&gt;, kgf</td>
<td>ε&lt;sub&gt;r&lt;/sub&gt;, %</td>
</tr>
<tr>
<td>6.02.'94 sh.II</td>
<td>9.03</td>
<td>8.8</td>
</tr>
<tr>
<td>7.02.'94 sh.II</td>
<td>8.8</td>
<td>5.0</td>
</tr>
<tr>
<td>7.02.'94 sh.III</td>
<td>9.0</td>
<td>6.1</td>
</tr>
<tr>
<td>22.03.'94</td>
<td>7.64</td>
<td>10.35</td>
</tr>
<tr>
<td>T7/30.06.'95</td>
<td>3.89</td>
<td>5.78</td>
</tr>
<tr>
<td>T8/30.06.'95</td>
<td>4.08</td>
<td>7.23</td>
</tr>
<tr>
<td>T9/30.06.'95</td>
<td>4.36</td>
<td>6.57</td>
</tr>
<tr>
<td>T4/3.07.'95</td>
<td>6.9</td>
<td>7.63</td>
</tr>
<tr>
<td>T5/3.07.'95</td>
<td>6.18</td>
<td>6.85</td>
</tr>
<tr>
<td>T6/3.07.'95</td>
<td>5.97</td>
<td>7.89</td>
</tr>
</tbody>
</table>

where:
\[ \Delta \sigma_{III} = \sigma_{III, f} - \sigma_{III, I} \]
\[ \Omega = \frac{\Delta \sigma_{III} - \sigma_{III, I}}{L_{IIIa}} \]
\[ \Phi = \frac{L_{IIIa}}{L_{IIIa, mech}} \times 100 \]
### TABLE 3

Technological parameters considered for this study

<table>
<thead>
<tr>
<th>Experimental series</th>
<th>Refining Series</th>
<th>Inlet</th>
<th>Drying Section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>c, %</td>
<td>BD, %</td>
<td>c, %</td>
</tr>
<tr>
<td>6.02.'94 sh.II</td>
<td>4.8</td>
<td>33</td>
<td>0.3</td>
</tr>
<tr>
<td>7.02.'94 sh.II</td>
<td>5.12</td>
<td>32</td>
<td>0.34</td>
</tr>
<tr>
<td>7.02.'94 sh.III</td>
<td>5.42</td>
<td>30</td>
<td>0.35</td>
</tr>
<tr>
<td>22.03.'94</td>
<td>4.7</td>
<td>24</td>
<td>0.3</td>
</tr>
<tr>
<td>T7/30.06.'95</td>
<td>4.86</td>
<td>21</td>
<td>0.33</td>
</tr>
<tr>
<td>T8/30.06.'95</td>
<td>4.86</td>
<td>21</td>
<td>0.33</td>
</tr>
<tr>
<td>T9/30.06.'95</td>
<td>4.86</td>
<td>21</td>
<td>0.33</td>
</tr>
<tr>
<td>T4/3.07.'95</td>
<td>4.54</td>
<td>22</td>
<td>0.40</td>
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<td>T5/3.07.'95</td>
<td>4.54</td>
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<tr>
<td>T6/3.07.'95</td>
<td>4.54</td>
<td>22</td>
<td>0.40</td>
</tr>
</tbody>
</table>

### TABLE 4

Main physico-mechanical and rheological paper characteristics

<table>
<thead>
<tr>
<th>Correlation equations</th>
<th>Correlation ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Sr = -2.1668 - 1.1796 * c_{R, output} + 0.435 * BD_{output} + 10.493 * c_{inlet} )</td>
<td>( r = 0.83 )</td>
</tr>
<tr>
<td>( L_{mech} = 0.784 - 0.395 * W_{j-s} )</td>
<td>( r = 0.51 )</td>
</tr>
<tr>
<td>( L_{mech} = 0.494 - 0.262 * W_{gu4-gk} )</td>
<td>( r = 0.5 )</td>
</tr>
<tr>
<td>( c_r = 7.68 - 2.18 * W_{gu4-gk} )</td>
<td>( r = 0.66 )</td>
</tr>
<tr>
<td>Correlation equations</td>
<td>Correlation ratio</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>( c_{\text{R, output}} = 0.246.10^{-3} \times E_1 + 0.1018.10^{-3} \times E_2 - 0.2225.10^{-6} \times \eta_1 - 0.4958.10^{-4} \times \eta_2 + 0.60098 \times \varepsilon_{\text{eli}} - 0.3347 \times \varepsilon_{\text{pl}} + 6.8094 \times \varepsilon_{\text{vel}} - 0.339 \times \varepsilon_0 )</td>
<td>( r = 0.92 )</td>
</tr>
<tr>
<td>( \eta_2^- ) ( \text{BD}<em>{\text{output}} = 3.78.10^{-3} \times E_1 + 9.695.10^{-3} \times E_2 + 0.6935.10^{-6} \times \eta_1 - 3.0658.10^{-4} \times \eta_2^- - 2.865 \times \varepsilon</em>{\text{eli}} + 0.4115 \times \varepsilon_{\text{pl}} + 29.663 \times \varepsilon_{\text{vel}} - 0.66 \times \varepsilon_0 )</td>
<td>( r = 0.94 )</td>
</tr>
<tr>
<td>( \eta_2^- ) ( \text{c}<em>{\text{inlet}} = 0.1467.10^{-3} \times E_1 + 0.0276.10^{-3} \times E_2 - 0.00835.10^{-6} \times \eta_1 - 0.0242.10^{-4} \times \eta_2^- - 0.0973 \times \varepsilon</em>{\text{eli}} + 0.0812 \times \varepsilon_{\text{pl}} + 0.5148 \times \varepsilon_{\text{vel}} + 0.0337 \times \varepsilon_0 )</td>
<td>( r = 0.90 )</td>
</tr>
<tr>
<td>( W_{j-s} = 1.955 - 1.474.10^{-3} \times E_1 )</td>
<td>( r = 0.88 )</td>
</tr>
<tr>
<td>( W_{\text{gu-gk}} = 1.8497 - 2.222.10^{-3} \times E_1 )</td>
<td>( r = 0.90 )</td>
</tr>
<tr>
<td>( \text{Pkc} = 22.99 - 0.335.10^{-6} \times \eta_1 )</td>
<td>( r = 0.75 )</td>
</tr>
<tr>
<td>( W_{\text{gk-gu5}} = -7.2796 + 0.52.10^{-3} \times E_1 )</td>
<td>( r = 0.85 )</td>
</tr>
<tr>
<td>( W_{\text{gu5-gu6}} = 0.3828 - 0.312.10^{-3} \times E_1 )</td>
<td>( r = 0.91 )</td>
</tr>
<tr>
<td>( W_{\text{gu6-gu7}} = -0.0836 + 0.1406.10^{-3} \times E_1 )</td>
<td>( r = 0.90 )</td>
</tr>
<tr>
<td>( W_{\text{gu7-gu8}} = -0.4587 + 0.583.10^{-3} \times E_1 )</td>
<td>( r = 0.89 )</td>
</tr>
<tr>
<td>( c_{\text{R, output}} = 5.5807 - 0.0204 \times \Delta \sigma_{\text{III a}} + 0.7277 \times L_{\text{mech.III a}} - 0.0104 \times \Phi + 0.0225 \times \Omega )</td>
<td>( r = 0.72 )</td>
</tr>
<tr>
<td>( \text{BD}<em>{\text{output}} = 29.626 + 0.074 \times \Delta \sigma</em>{\text{III a}} - 27.13 \times L_{\text{mech.III a}} - 0.144 \times \Phi + 1.323 \times \Omega )</td>
<td>( r = 0.89 )</td>
</tr>
<tr>
<td>( \text{c}<em>{\text{inlet}} = 0.3009 + 0.0039 \times \Delta \sigma</em>{\text{III a}} - 0.23 \times L_{\text{mech.III a}} + 4.775.10^{-5} \times \Phi - 0.0017 \times \Omega )</td>
<td>( r = 0.70 )</td>
</tr>
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</table>
### TABLE 6
Rheological and physico-mechanical characteristics

<table>
<thead>
<tr>
<th>Correlation equations</th>
<th>Correlation ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_1 = 502.167 + 110.569 \cdot S_r - 60.157 \cdot \varepsilon_r + 113.104 \cdot L_{mech} )</td>
<td>( r = 0.93 )</td>
</tr>
<tr>
<td>( E_2 = 200.164 \cdot S_r + 17.78 \cdot \varepsilon_r + 215.513 \cdot L_{mech} )</td>
<td>( r = 0.94 )</td>
</tr>
<tr>
<td>( \eta_1 = 3.178 \cdot 10^6 + 1.09 \cdot 10^6 \cdot S_r - 0.2677 \cdot 10^6 \cdot \varepsilon_r - 1.125 \cdot 10^6 \cdot L_{mech} )</td>
<td>( r = 0.81 )</td>
</tr>
<tr>
<td>( \eta_2 = 2466.134 \cdot \varepsilon_r + 1187.304 \cdot L_{mech} )</td>
<td>( r = 0.83 )</td>
</tr>
<tr>
<td>( \varepsilon_{eli} = 0.0105 \cdot S_r + 0.3007 \cdot \varepsilon_r + 2.328 \cdot L_{mech} )</td>
<td>( r = 0.98 )</td>
</tr>
<tr>
<td>( \varepsilon_{vel} = 0.0137 \cdot S_r + 0.0426 \cdot \varepsilon_r + 0.3598 \cdot L_{mech} )</td>
<td>( r = 0.99 )</td>
</tr>
<tr>
<td>( \varepsilon_0 = 0.038 \cdot S_r + 0.0804 \cdot \varepsilon_r + 1.0577 \cdot L_{mech} )</td>
<td>( r = 0.99 )</td>
</tr>
<tr>
<td>( \varepsilon_{pl} = -6.489 + 2.693 \cdot \varepsilon_r - 0.1726 \cdot \varepsilon_r^2 )</td>
<td>( r = 0.55 )</td>
</tr>
<tr>
<td>( \Delta \sigma_{III a} = -1.1695 \cdot S_r + 1.2409 \cdot \varepsilon_r + 55.2824 \cdot L_{mech} )</td>
<td>( r = 0.94 )</td>
</tr>
<tr>
<td>( L_{mech , III a} = 0.0074 - 0.00345 \cdot S_r + 0.00968 \cdot \varepsilon_r + 0.3136 \cdot L_{mech} )</td>
<td>( r = 0.98 )</td>
</tr>
<tr>
<td>( \Phi = 0.3475 \cdot S_r + 4.1977 \cdot \varepsilon_r + 34.0643 \cdot L_{mech} )</td>
<td>( r = 0.98 )</td>
</tr>
<tr>
<td>( \Omega = -5.029 + 1.389 \cdot S_r + 0.11 \cdot \varepsilon_r - 2.995 \cdot L_{mech} )</td>
<td>( r = 0.94 )</td>
</tr>
</tbody>
</table>

### TABLE 7
Technological parameters calculated with the correlation equation

<table>
<thead>
<tr>
<th>Experimental series</th>
<th>REFINING</th>
<th>INLET</th>
<th>DRYING SECTION</th>
</tr>
</thead>
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