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THERMAL BEHAVIOUR OF PAPER SHEETS STRENGTH

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ABSTRACT

The effect of heating wood and bagasse paper sheets between 100 and 220 ° C for different intervals, on their physical and mechanical properties was investigated. Heating up to 160 ° C for 0.25 h enhances sheet properties, but above that temperature, the properties deteriorated. The activation energy from the kinetics of paper strength loss between 180 and 220 ° C was calculated for wood and bagasse paper samples. The differences between these values was discussed on the basis of the chemical composition of the paper pulp. The effect of thermal treatment on the folding endurance and burst factor of the sheets were also investigated.

INTRODUCTION

The mechanical behaviour of the fibres can be significantly altered by physical and/or chemical pretreatments. Indeed, the effect of heat on the cellulosic fibres is exceedingly complex, and produces chemical and structural changes resulting, eventually, at higher temperatures, in a deterioration in the mechanical properties. The extent of these changes depends on numerous factors, e.g., temperature, time, and other heating conditions [1]. A paper sheet is considered as a network structure consisting of cellulosic fibres with other non-cellulosic materials, so a thermal treatment has an effect on the fibres, which are randomly arranged, in addition to its effect on the non-cellulosic materials, and the resultant determines the properties of the sheet. Veith [2] was one of the first to show that decomposition occurs even at temperatures as low as 70 ° C. At higher temperatures, the exothermic reactions can become uncontrollably rapid, leading to self-ignition. Much research has been carried out on this effect, and the results depend on the experimental conditions and the raw material used.

The aim of the present work is to investigate the influence of heat on the breaking length, folding endurance, and the burst factor of paper sheets produced from wood and bagasse pulp, and to estimate the activation energy from the kinetics of strength loss.

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EXPERIMENTAL

Pulp preparation and analysis

In this work unbleached bagasse pulp from Edfu mill, Egypt was bleached using the conventional three stage method, also commercial bleached birch (*Betula verrucosa*) sulfate pulp was used. The pulps possess the following specifications

	α-Cellulose % [3]	Lignin % [4]	Pentosans % [5]
Bagasse pulp	69.3	1.5	24.5
Wood pulp	85.5	0.0	6.7

Paper sheets preparation

Bleached bagasse and wood pulps were beaten, separately, till 35 ° SR in a Jokro-mill beater then paper sheets were made according to the Swedish Standard method (S.C.A.).

Thermal treatments

Paper sheets from wood and bagasse pulps were placed in a previously heated oven at 100, 120, 140, 160, 180, 200, 210 and 220 °C for different intervals, then the sheets were cooled down to room temperature. The strength properties of the heated sheets were determined [6].

All data recorded are the average of six measurements.

RESULTS AND DISCUSSION

The effect of thermal treatments on the physical and mechanical properties of paper sheets produced from wood and bagasse pulps between 100 and 220 °C for different periods was shown in Figs. 1–4.

Breaking length

Figures 1a and 2a illustrate the effect of heating on the breaking length of paper sheets produced from wood and bagasse pulps, respectively. From these figures it is clear that the breaking length of the heated sheets increases with increasing time and temperature of heating until 140 °C. This may be attributed to the increase of the intensity of cross-linking between the fibres, also an increasing temperature produce a softening to the hemicellulose (6.7% in wood pulp and 24.5% in bagasse pulp) which enhances the adhesive

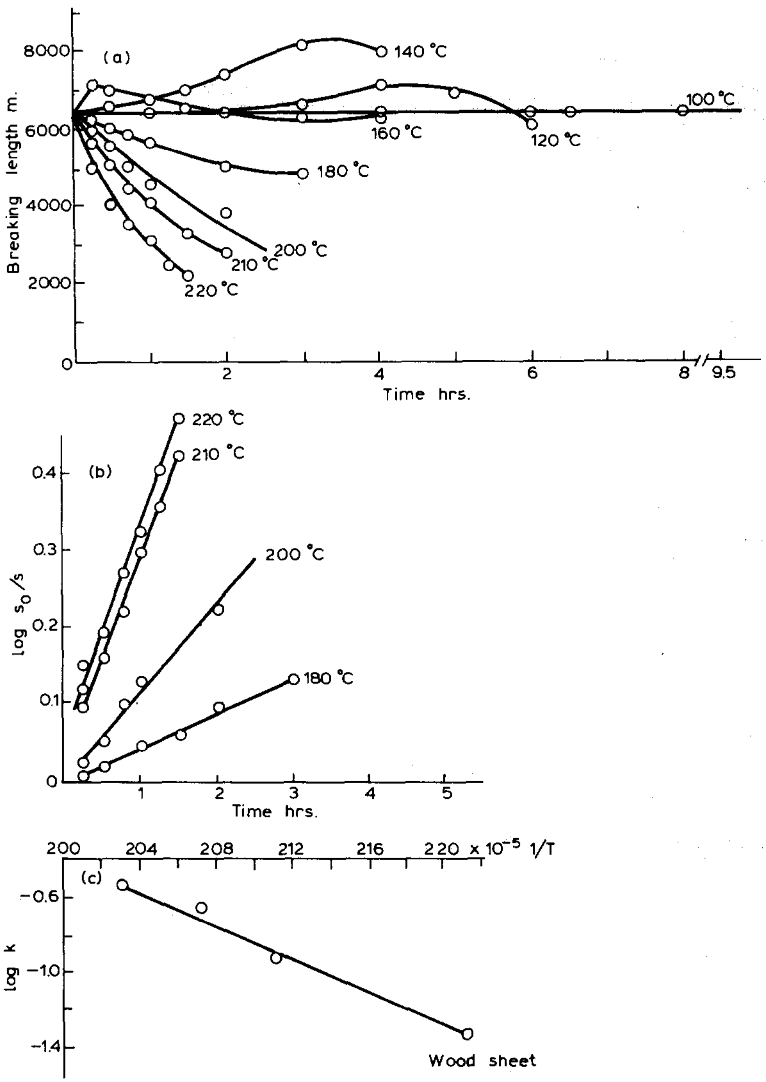

Fig. 1. (a) Plot of breaking length of wood pulp sheet vs. time of heating; (b) plot of log S_0/S vs. heating time; (c) Arrhenius plot for log k vs. $1/T$.

forces between the fibres. It is clear, also that the percentage increase in the breaking length of bagasse pulp paper sheets is higher than that in case of wood pulp sheets, this may be due to the high percentage of pentosans in case of bagasse and also to the presence of a small amount of lignin.

The breaking length of wood and bagasse paper sheets heated at 160 °C reaches its maximum after 0.25 h heating, then it decreases with increasing time of heating. It appears that a higher degree of cross-linking intensity was attained at this stage; however, it was found that the degree of polymerisation decreased when the fibres were heated at 160 °C for more than 15 min

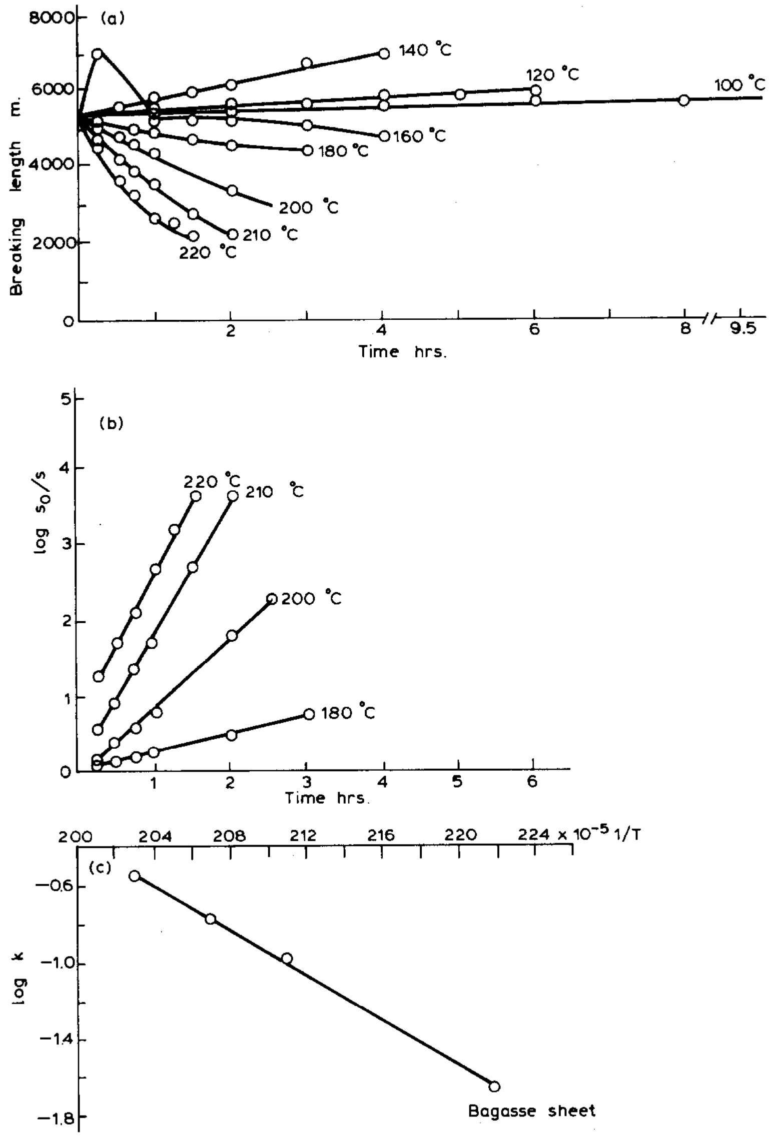

Fig. 2. (a) Plot of breaking length of bagasse sheet vs. time of heating; (b) plot of log S_0/S vs. heating time; (c) Arrhenius plot for log k vs. $1/T$.

[7]. Also, the hardening of hemicellulose decreases its character as an adhesive to the fibres.

On increasing the temperature to above 160 °C, i.e., 180, 200, 210 and 220 °C, the breaking length of both samples decreases with increasing heating time. The percentage decrease in the breaking length increases with increased temperature, see Figs. 1a and 2a.

From the above discussion, heating at 160 °C for 0.25 h may be consid-

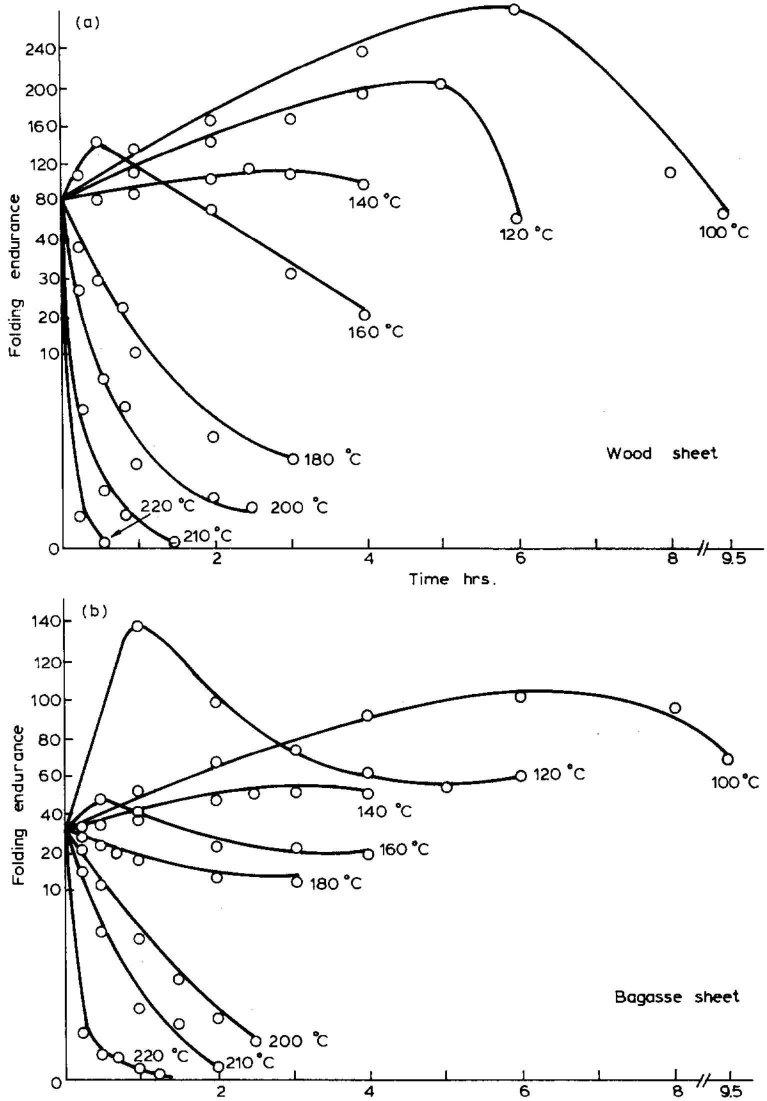

Fig. 3. Relation between folding endurance and time of heating for (a) wood pulp sheet; (b) for bagasse.

ered as a method to improve the breaking length of wood-pulp paper sheets (improved by about 19%) and bagasse-pulp paper (increased by about 28%). Unfortunately, the degree of whiteness was deteriorated.

Kinetics of breaking-length (strength) loss of paper sheets

The first-order reaction is expressed as follows

$$-\mathrm{d}c/\mathrm{d}t = kc$$

where c is the concentration of the reactant, t is the time and k the rate

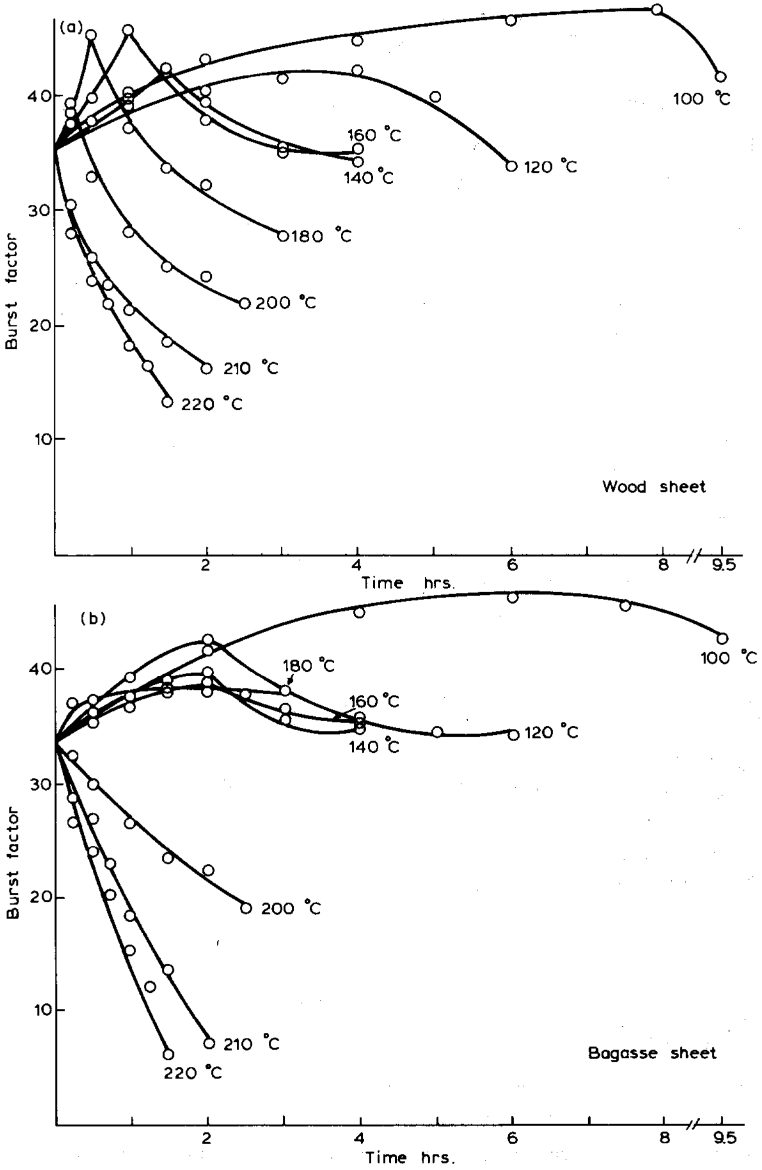

Fig. 4. Relation between burst factor and time of heating for (a) wood pulp sheet; (b) bagasse sheet.

constant of the reaction. If the concentration is replaced by the observed strength, S, of the paper sheets then

$$d(S_0 - S)/dt = k[S_0 - (S_0 - S)] = kS.$$

Where S_0 is the original strength. By derivation of the above equation [8], a plot of log S_0/S vs. t should be a straight line. Indeed, Figs. 1b and 2b illustrate the linearity of the above equation, except near the origin due to the evaporation of water and low molecular substances.

Such plots indicate that the loss in strength due to the thermal treatments of paper sheets, produced from wood and bagasse pulp, between 180 and 220 °C is a first order reaction. The slope of these plots determine k the rate constant. The activation energy of both samples was calculated by applying the Arrhenius equation [9]. A plot of log k vs. $1/T$ for both samples gave straight lines, see Figs. 1c and 2c, with a slope equal to $-E_a/2.303R$ (where E_a is the activation energy, and R is the gas constant). It was found that E_a values are 89.3 and 126.8 kJ for wood and bagasse paper sheets, respectively. It should be noted that the E_a values calculated from the kinetics of paper strength loss are the resultant of several factors as well as the energy of the bonds which are responsible for the strength in the original fibre structure, covalent and/or hydrogen bonds, e.g., adhesive forces due to the presence of hemicellulose and lignin, also the forces originated from the "net-like structure bonding" which formed during paper sheet production must be considered. As the bagasse sample possessed a high hemicellulose and lignin content, the activation energy was found to be higher than those obtained from wood pulp sheets.

Folding endurance

Figures 3a and 3b, illustrate that the folding endurance of wood and bagasse paper sheets increases with increasing heating temperature up to 140 °C, it is also clear that the maximum increase of the folding endurance of both samples decreases with increasing time and temperature of heating. At 160 °C the folding endurance of wood and bagasse sheets increases after 0.5 h heating, then it decreases with increasing heating period. On heating at 180, 200, 210 and 220 °C the folding endurance decreases with increasing heating time. The increase of folding endurance of heated wood pulp sheets at a lower temperature is higher than in case of bagasse pulp sheets, this may be attributed to the high α-cellulose and low hemicellulose ratio in wood pulp. On the contrary, the increase in the folding endurance of bagasse sheets, heated at the same temperature, is lower than wood pulp due to the hardening effect of the hemicellulose at higher temperatures.

Burst factor

The influence of the thermal treatment on the burst factor of sheets produced from wood and bagasse pulps is illustrated in Figs. 4a and b, respectively. The behaviour of both samples was found to be similar to those obtained in the case of folding endurance. Samples with a high α-cellulose content produce high burst factor, this may be related to the high intensity of cross-linking. It should be noted that the amount of lignin, which acts as a cementing material to enhance the burst factor, can be taken into consideration.

Summing up the above results, the heating of sheet samples up to 160 °C for 0.25 h improves the physical and mechanical properties. Activation energy values calculated from the kinetics of the strength loss, showed that the chemical composition plays an important role for determining strength properties. Other properties, the burst factor and the folding endurance were also affected by the heat treatment.

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