Measurement of Water Penetration and Swelling in a Multilayered Sheet

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SUMMARY

This paper reports on experimental measurement of water penetration into a multilayered linerboard sheet. A rig previously used to study drying characteristics of paper, has been modified to measure water penetration due to wetting. Measurements of water uptake into two to three layers of laboratory formed hand sheets were made at 2.5 second intervals following surface wetting. Simultaneously, the swelling of each layer due to progressive wetting has also been measured. Two types of laboratory formed sheets, directionally and randomly oriented sheets, have been investigated and the water uptake and swelling characteristics of each type of sheet is reported.

INTRODUCTION

The work reported here was undertaken as part of a study on dimensional stability of linerboards as it might impact ink-jet printing on a corrugator. A linerboard printed with water based inks, will experience a temporary moisture gradient through the thickness of the linerboard sheet. This moisture change in the liner may result in twist or warp of the final combined board, once the printed liner is combined with the single facer web to form a corrugated board.

When a multilayered linerboard sheet is wetted on one side, several important changes occur within the sheet structure. Firstly, the water starts to penetrate into the thickness of the sheet causing a moisture gradient through the thickness of the sheet. Due to this wetting, dried in stresses in the sheet are released, to different extents, varying through the sheet, depending on the amount of wetting in different layers. The Z-direction moisture profile created due to wetting causes the layers to expand differentially and the mechanical properties such as bending stiffness to change through the thickness of the sheet. If the sheet is free to move, these changes are manifested as a dynamic curl response, immediately following wetting. If however, the sheet is restrained while wetting, release of dried in stresses and softening of the different layers through the thickness still occurs but these changes will only become manifest after the liner is released from the tension, as it settles back to an equilibrium moisture content during drying. In previous work we showed that wetting and drying under tension increases the tendency of the linerboard sample to settle into a twisted shape *(1)*. In order to understand the behaviour of a multilayer sheet when wetted on one side, such as in the case when a print pattern is applied to one surface, it is necessary to understand the dynamic behaviour of the top and subsequent layers. The experimental work undertaken in this paper addresses this issue.

Water penetration into the sheet was measured by modification of a rig designed to measure drying characteristics. In the past, this unit had been used to measure the z-direction moisture transport and shrinkage profile in the drying of paper *(2, 3)*. The principle of operation of this unit is to measure the impedance between pairs of copper mesh electrodes embedded between sheet layers and to use this data to measure the change in moisture content in each layer with time. A number of researchers have previously used impedance measurements to estimate the moisture content of paper. A good introduction to the impedance method of moisture content estimation is given in an earlier publication *(4)*.The copper meshes, used as electrodes to measure the moisture content, are also used as targets for eddy current measurements of displacement and thus swelling of each layer can be simultaneously measured with the moisture content.

This paper details work to calibrate the output from the experimental rig with laboratory made test sheets, and to understand the relationship between moisture uptake and swelling behaviour in multi layer sheets. The effect of random and directional formation has been investigated and the moisture uptake and swelling characteristics of each layer is reported.

EXPERIMENTAL

Experimental rig for measuring moisture content and swelling

The drying rig at Australian Pulp and Paper Institute, has been previously used to measure the z-direction moisture transport and shrinkage profile during the drying of paper *(2, 3)*. The basis of the apparatus is that impedance is measured between pairs of copper mesh electrodes embedded at different depths within the sheet. Impedance, the resistance that a circuit presents to an alternating current, includes inductive resistance and capacitive resistance. The capacitive resistance is related to the dielectric constant of paper and this in turn is known to depend heavily on the moisture content of the paper *(5)*. Thus, the measured impedance is indicative of the changes in moisture content of the sheet material between the electrode pairs.

The copper mesh electrodes used for impedance measurements are also used as displacement targets to simultaneously measure the swelling of the paper sheet due

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to wetting. Displacement (swelling) measurement is based on the measurement of eddy currents generated in the targets. This technique being non-contact, is suitable for the measurement of small displacements encountered in the shrinkage/swelling of a paper sheet and is sensitive to measure changes in displacement of under a micron. Eddy current sensors are mounted at the base of the rig. In the modified experimental rig, the paper layers swell when wetted, causing the copper mesh targets to move apart while the eddy current voltage is continuously measured. There is a very good linear relationship between the eddy current voltage and the actual displacement of the target.

The dual purpose copper mesh targets, 25.4 microns thick and of 50% openness (Figure 1) were chosen for displacement measurements, based on the success of previous studies in providing accurate results *(2, 6)*. The area of the target chosen must be small enough to minimize moisture flow disturbance but large enough for accurate measurements of displacement *(6)*. A 2x2cm square target/electrode size was selected, to satisfy these requirements and this proved to be effective for this application *(2)*. For impedance measurements the copper mesh electrodes are connected through a 2mm wide tail.

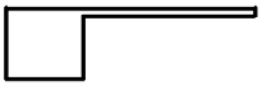

Figure 1 a) Diagram of the copper mesh with the tail attached for impedance measurements

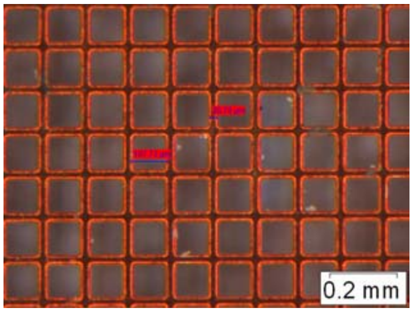

Figure 1 b) Open structure of the copper mesh

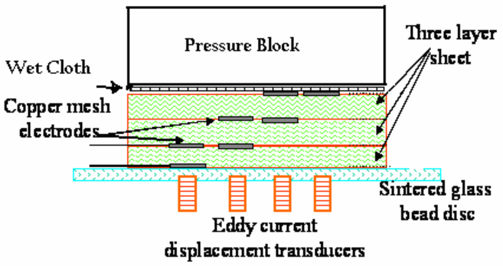

Figure 2 a) Schematic of the test unit (modified from *(3)*, not to scale)

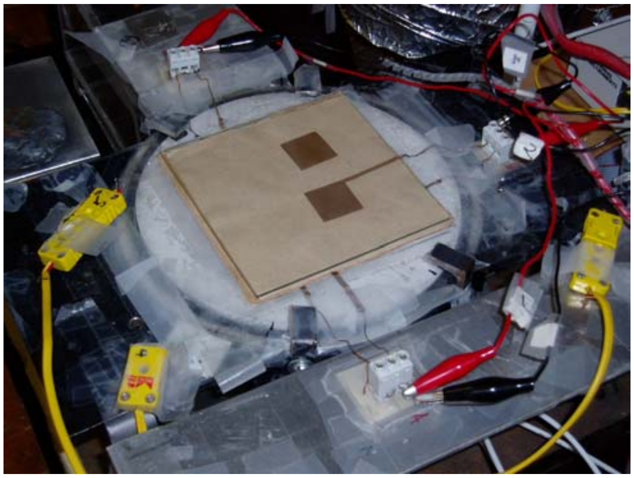

Figure 2 b) Test unit showing copper mesh electrodes

A schematic of the test rig used for wetting experiments is shown in Figure 2. Two or three layers, together with the copper meshes and targets are assembled. A wet cloth attached to the pressure block is then used to wet the top layer. A Labview program is used to acquire data from a Hewlett Packard 4263 impedance meter reading impedance data and from a type 12U Kuda eddy current system from Kaman. Measured impedance and eddy current voltage data are then used to estimate moisture content and displacement of the sheet, using calibration curves.

Calibration for moisture and displacement measurements

In order to estimate moisture content of a sheet using impedance data, the relationship between the impedance and moisture content needs to be established for each type of sheet to be tested. Dependency of impedance on the pressure and test frequency has been studied earlier *(4)* and based on this work, a test frequency of 100 kHz has been used for all experiments. A test pressure of approximately 2.6 kN/m^2 was used for all experiments as this is sufficient to provide good contact between the sheet layers and the copper mesh electrodes/targets. Unbleached kraft pine pulp from Kinleith mill was used to form 80gsm single layer test sheets using the Dynamic sheet former (PDF) in Ensis, New Zealand. With the PDF, two different types of sheets were formed; a directional sheet with fibres preferentially oriented in MD and a sheet with randomly oriented fibres. The difference in orientation of the formed sheets was subsequently tested with ultrasonic tensile stiffness measurements which gave an MD/CD ratio of 1.8 for directional sheets compared with 1.1 for random sheets.

Impedance readings at moisture contents ranging from 7 to 60 % were obtained for both types of formed sheets. Different moisture levels were obtained by re-wetting the sheets and air drying to approximately the target moisture level. The moisture content of the sheets was obtained gravimetrically by weighing on an analytical scale. Loss of moisture during a calibration test was minimized by sealing the edges with tape and any loss that may still occur was taken into account by taking the average moisture content before and after the test. The mean impedance value after the reading stabilized was taken for impedance value, corresponding to the average moisture content. The calibration curve obtained for the PDF formed unbleached kraft pine sheets (80gsm, 100µm thick) is shown in Figure 3. The relationship between impedance and moisture content is evidently close to linear over the range of moisture tested and using line of best fit permits moisture contents to be estimated to +- 3%. No significant scatter was seen between the data points for differences in formation; hence all data for these kraft pine sheets were fitted into one calibration curve.

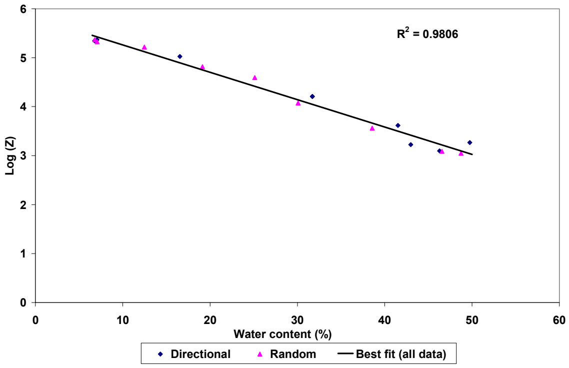

Figure 3 Impedance Vs water content for unbleached kraft pine sheets (80 gsm)

A calibration curve was also obtained for each displacement sensor. For this purpose, the targets were placed on plastic sheets of known thickness to obtain corresponding voltage readings. The effect of the presence of another target on top of the main target (as would occur in a pair of electrodes) was considered by using the same layer set up as in wetting experiments. In order to check if the presence of moisture has an effect on the eddy current voltage signal, a set of readings were also obtained with damp plastic sheets. The deviation of these points off the calibration line was very small (less than 3%). A typical calibration curve for one of the sensors is shown in Figure 4.

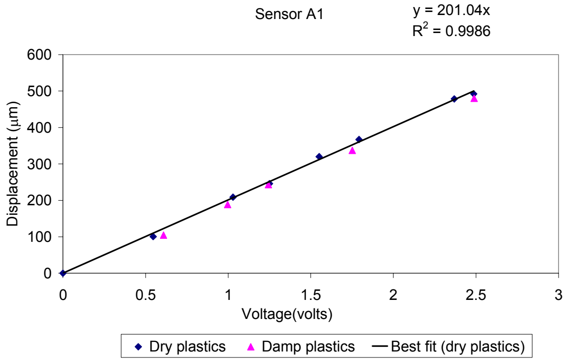

Figure 4 A typical calibration curve for displacement sensors

RESULTS OF WETTING EXPERIMENTS

Initially, in order to get good contact between copper meshes and the sheets, the sheets were re-wetted before being dried in situ on the rig, using a heater block. After being allowed to cool sufficiently, the heater block was then carefully replaced with the pressure block attached with the wet cloth. The impedance and eddy current voltage data were recorded at a time interval of 2.5 seconds. These data were then used to obtain a moisture profile and swelling over time. However, it was subsequently found that the sheets re-wetted and dried in-situ on rig can increase the variability of particularly the swelling measurements, and hence this practice was halted. The results reported here were carried out on never rewetted samples, unless otherwise stated.

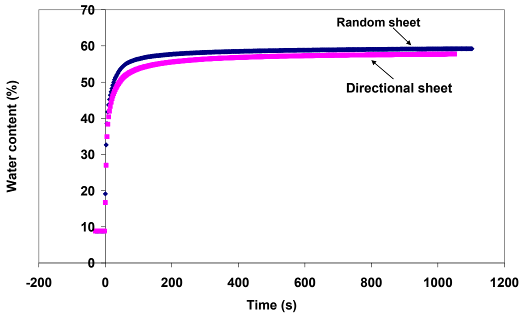

Figure 5 Water penetration into a single layer of 80 gsm never re-wetted sheets for random or directional fibre orientation

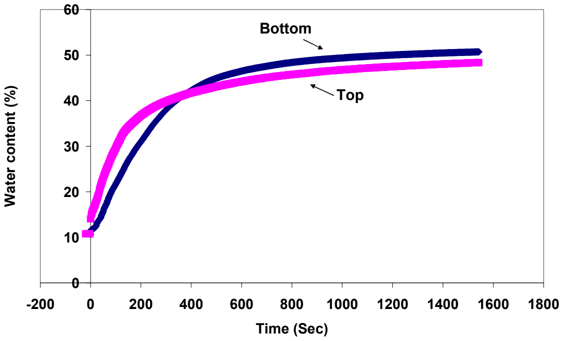

Figure 6 Water penetration into two layers of rewetted randomly oriented 80 gsm sheets

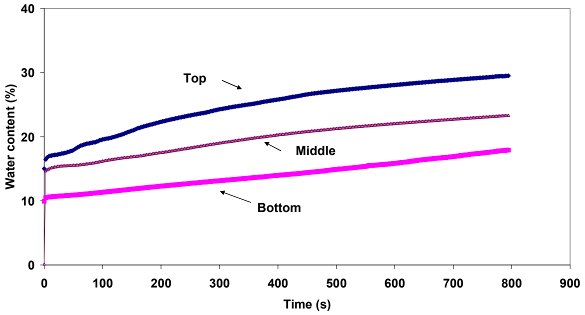

Figure 7 Water penetration into a rewetted three layer sheet configuration (80 gsm randomly oriented sheets)

Figure 5 shows the water penetration data obtained for single layer never re-wetted sheets. Each curve represents an average of two measurements. The scatter of data between experiments was very little and not plotted here for clarity. As expected, the water uptake is very fast, reaching its equilibrium value within about a minute. The differently formed sheets (directional versus random) showed no difference in the maximum amount of water uptake.

Figure 6 shows a typical water uptake pattern in a two layer configuration of paper sheet (re-wetted and dried on rig). The general pattern shows expected behaviour in that the top layer absorbs water first, and then the water content of the bottom layer increasing at a slower rate, as water is drawn into the bottom layer form the top. It takes longer for the two layered sheet to reach its equilibrium water content. This is because for the two layered sheet, water first absorbs from the cloth into the top layer and the bottom layer gradually absorbs water form the top layer. For a three layered sheet configuration (Figure 7), it was noticed that the water absorption rate for each layer is even slower. A mass balance carried out on random sheets (Figure 8) for a two layered case reveals that the amount of water absorbed by two layers is approximately same as twice the amount of water absorbed by a single sheet, also indicating that the wet cloth is acting as an infinite reservoir, supplying water to meet the demand.

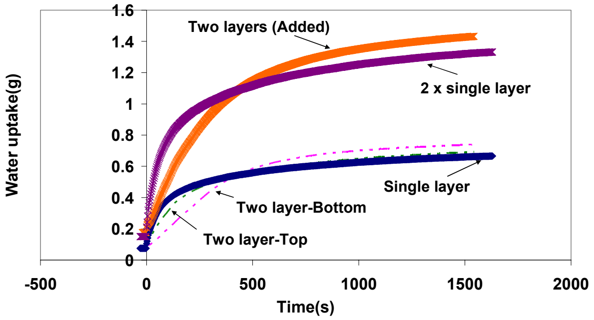

Figure 8 Mass balance for water uptake (random sheets)

Swelling

Swelling data generally shows expected trends i.e. increasing swelling with increasing water content. A small amount of initial settlement (shrinkage) is sometimes observed and this could be due to the targets settling into the sheet as it gets wet. It was speculated that the swelling could be constrained due to the load applied on the sample. This would occur if the swelling pressure developed is lower than the pressure applied on the sample. A review of swelling pressure measurements available in literature indicate that swelling pressures due to wetting of paper, can start developing very quickly and that these pressures can be quite high, depending on the furnish *(7)*. The reported swelling pressures are of the order of 10-50 kN/m^2 for commercial sheets and hand sheets made of different types of pulp, with the high values obtained for TMP pulp containing fines and the low values for LWC base stock *(7)*. The pressure used (2.6 kN/m^2) in the present work is small in comparison.

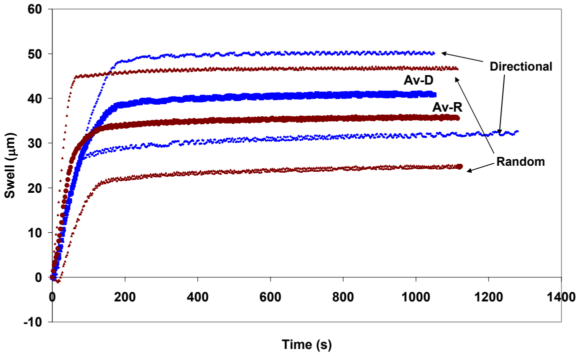

Figure 9 Two replicate measurements and their average for measurement of swelling Vs time for never re-wetted single sheets

Figure 9 shows swelling pattern with time for wetting never re-wetted single sheets with water. The average curves for directional and random sheets are plotted in thick lines and marked as Av-D/Av-R. The time taken to reach the maximum swelling vary between 60-180 seconds. On average, slightly higher swelling is observed for the directional sheet, than for the random sheet. Figure 10 shows the swelling pattern with respect to water content for the same experiments. As expected, swelling increases with increasing water content. Very little swelling is observed at low water contents. As the water content reaches its maximum values, the maximum swelling values of the order of 25-50 µm are recorded.

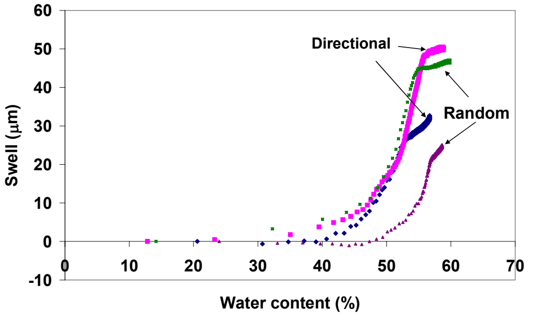

Figure 10 Typical swelling pattern for never rewetted single sheets (80 gsm)

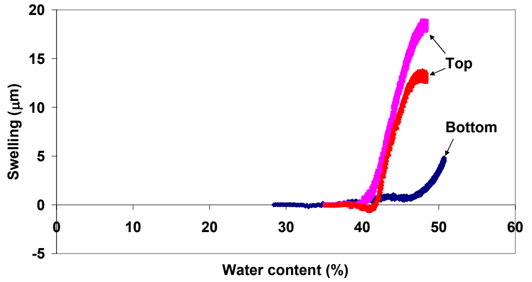

Figure 11 Swelling Vs water content for a two layered configuration (Random sheets)

Figure 11 shows the swelling of the top and bottom layers for a two layer configuration, for the random sheets corresponding to Figure 6. The top layer swells more than the bottom layer, even if the maximum water content reached is almost the same for both layers. A possible explanation for this lies in Figure 10, where the two independent wetting experiments for random sheets show a range of swelling of about 2-17 µm. The bottom layer swelling seems to fall towards the lower of the range while the top layer swelling seems to fall toward the higher of the range.

Wetting of sized sheets

In order to investigate the wetting characteristics of sized sheets, some of the formed sheets were subsequently sized using an AKD solution in heptane. The sheets were sized in the laboratory by dipping the sheets in AKD solution (0.16 g AKD in 200 ml of heptane) and drying in the oven at 105^0 for 40 minutes. This method of sizing resulted in a contact angle of $115\text{-}120^0$ with water, as measured with a dynamic absorption tester (DAT). The sheets were tested after three to four weeks of storage time. Heptane was used for the sizing solution due to its non-swelling characteristics so that the structure of the formed sheets is not altered during sizing *(8, 9)*. The sized sheets were wetted with water containing a wetting agent (10% isopropanol). A wetting agent was used for the sized sheets to facilitate faster wetting and are commonly used in inkjet inks.

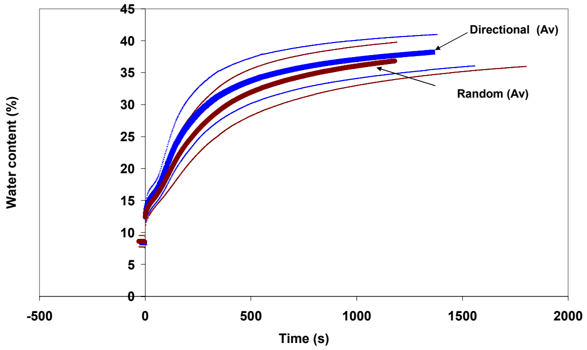

Figure 12 Wetting of sized sheets with water containing isopropanol (10%)

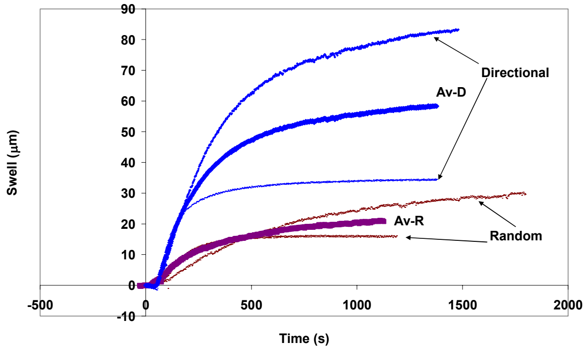

Figure 13 Swelling Vs time for sized sheets (wetting with water containing 10% isopropanol)

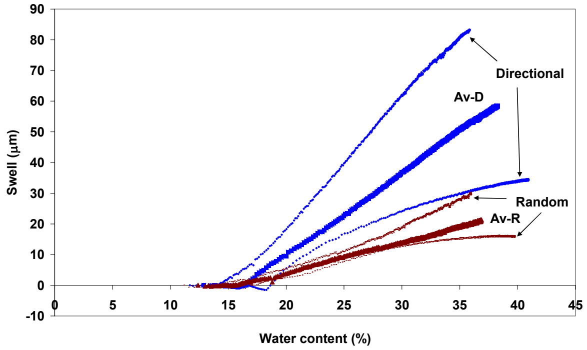

Figure 14 Swelling of sized sheets due to wetting with water containing isopropanol (10%)

Figure 12, shows the wetting behaviour of AKD sized sheets with water containing isoproponol (10%). The wetting rate is much slower, compared to wetting unsized sheets with water. Averages of two experiments are shown in thick lines, while the thin lines are plotted to show the variability. Again, there is no significant difference between the water uptake characteristics of the random and the directional sheet, but the swelling data shows significant differences between the two types of sheets. Figure 13 and

Figure 14 suggest that on average, the maximum swelling obtained for the directional sheet is higher than that for the random sheet. Randomly formed sheets may have a more interlocked structure, inhibiting swelling while the directional formation may more easily swell. With sized sheets, swelling also seems slower, taking about 5 minutes or longer to develop maximum swelling (Figure 13 as compared to wetting of unsized sheets with water (Figure 9). Swelling starts to develop at a lower water content of about 15- 20 %(Figure 14), compared to about 35% (Figure 10) for the unsized sheets, and spans over a wider range of water contents. Thus, wetting of sized sheets with water containing isoproponol, seems to have slower water uptake as well as swelling, compared to wetting unsized sheets with water. However, it is understood that the factors such as the level of sizing, time allowed to develop sizing before testing and the level of isoproponol in water etc. can contribute to change the time scale of wetting and swelling phenomena.

CONCLUSIONS

An experimental unit based on impedance measurements has been used to measure water penetration into a multilayered linerboard sheet. Water penetration curves for up to three layers of sheet shows a response that can be qualitatively explained. Water uptake for single sheets is very fast. For a two layered configuration water uptake is slower compared to a single sheet wetting while that for a three layered configuration is even slower. No significant difference was seen between the water uptake characteristics of random and directional sheet formations.

The swelling data suggest that a directionally formed sheet swells slightly more than the randomly formed sheets. A randomly formed sheet may be inhibiting swelling while the directional formation allows more swelling, possibly due to the differences in the structure of the fibre network. Further work is needed in this area to test this hypothesis.

Wetting of sized sheets with water containing 10% isoproponol, indicates that the sizing slows down the wetting process as well as the swelling due wetting, although factors such as the level of sizing and level of isopropanol etc can change the time scale of wetting of sized sheets.

ACKNOWLEDGEMENT

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