Variation of Physical Properties of Sri Lankan Currency Notes due to Their Usage

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ABSTRACT

This study examines the variation of two physical properties i.e. moisture absorption and mechanical strength, of Sri Lankan currency notes due to usage. Furthermore, inter-relations between their variation patterns are discussed and underlying reasons for the observed patterns are explained at fibre level of the currency note paper. Tests have been conducted on a sample of local ten Rupee notes categorized into two subsets as uncirculated notes and unserviceable notes.

Rate of moisture absorption and equilibrium moisture content of notes are found to increase with usage at any given humidity and temperature. Also the net exposed surface area of fibres increases by about 20% and strength of chemical coating decreases by about 20.7% during the life time of a currency note. Breaking strength and elastic modulus are found to decrease while the plasticizing becomes higher. Number of unbroken fibres in the cross direction of a note decreases by nearly 23% during its life time. The embedment of security thread was found to introduce a weakness of 4.3% to the overall strength of an uncirculated note. Strength degradation is encouraged at high humid conditions. In addition, currency notes are prone to transient creep during day to day usage, mostly due to inappropriate handling. Safe limit for the endurable load that gives no substantial creep for a fresh note is 0.5N. Experimental results are suggested to be used in fields of effective identification of overused notes, counterfeit deterrent and in order to urge general public to carefully handle currency notes.

1. INTRODUCTION

All Sri Lankan currency notes except for Rs. 200 polymer based note and the commemorative Rs.1000 note are printed on paper made with 100% cotton fibre and amounts of wet resins. At the production, the paper is immersed in gelatin to add strength and finally the note is coated with a melamine based compound which adds to its thickness and protects it from soiling and moisture absorption. However, unlike metal mints paper money is more prone to deformations physically, chemically, and structurally with increased usage, which is why currency notes possess a life time – time period between its uncirculated state to unserviceable state. Usually the life span markedly decreases for lower denominations of currency notes, where the mean life span of Rs. 10 note is 18 months [4].

In addition to manners of handling, extremes and rapid fluctuations in temperature and relative humidity can lead to a number of problems in material quality [1]. In high humidity conditions organic thin material such as paper rapidly absorbs water causing swelling of fibres and lessening of strength. As for a currency note, different parts containing different compounds such as the water mark and security thread absorb different amounts of water, encouraging higher distortions around their boundaries.

There had been less amount of scientific work conducted on physical properties of currency notes although much literature can be found related to properties and durability of other types of paper. In 1991, Hall and Brodeur [5] conducted experiments on physical properties of used and unused U.S. bank notes and notes subjected to crumple test. The results showed an increase of average thickness and roughness in few micrometers and a slight decrease in porosity for highly used notes and a falling of tensile strength with usage. In 1997, it was reported [2] that gelatin may partially buffer paper against changes in relative humidity (RH). It was later found [2] that gelatin sized paper gained slightly less moisture at high RH and lost slightly less moisture at low RH than unsized paper. Analysis done by Batchelor and Westerlind [3] on stress strain curves of kraft paper for short span tensile measurements revealed that for sheets made of bleached pulp, breaking strain decreased with refining while fracture stress/breaking stress increased. However, to our knowledge, no scientific investigation was carried out related to physical properties of Sri Lankan currency notes.

The objectives of this study are to identify moisture absorption patterns, breaking strengths and stress-strain variations of uncirculated and unserviceable currency notes at different humidity conditions. Then mutual relationships between moisture absorption and strength measurements are developed, and effects of usage on net exposed surface area of fibres, coating strength, and fibre breakage have been estimated. Additionally, the weakness introduced due to embedment of security thread is estimated and the creeping effect on an uncirculated currency note under a static load at constant temperature and humidity is studied. A sample of 300 Rs.10 notes consisting of both unserviceable and uncirculated notes, obtained from the Central Bank of Sri Lanka, has been employed in the test.

2. METHODOLOGY

2.1. Preparation of Test Sample

Samples of uncirculated and unserviceable notes were allowed to oven dry in a DV-61 oven at 105 °C for 1hour to remove moisture. Then they were taken out and each sample was sealed inside previously weighed polyethylene bags to calculate the dry masses of uncirculated and unserviceable notes. Before conducting tests under controlled humidity, test samples were dried in the above manner, placed in sealed in polyethylene bags and these bags were kept in thick plastic folders until tested. Care has been taken to conduct tests on dried sample on the same day.

2.2. Experimental Setup

The humidity control chamber shown in Figure 1, was designed to control its internal relative humidity at different levels between 25% and 80%, by injecting ambient air (RH≈ 80%) into the chamber at suitable rates with a 12V DC fan and allowing it to mix with dry air (RH≈ 25%) produced by an air compressor [6]. It has been modified in such a way to monitor moisture absorption of a note while both surfaces are exposed to surroundings. Two Senserion SHT75 sensors were fixed on the chamber walls facing either side of the tested note, and average values of measured relative humidity and temperature were displayed using a PIC based circuit with an accuracy of ±1% and ±1 °C.

An instrument for measuring tensile stress has been integrated to the chamber in order to take strength measurements while keeping the note in a controlled humidity condition. The lever arm of the tensile stress instrument was inserted into the chamber by cutting a rectangular aperture on a wall leaving just enough space for free movement of the arm during the note's straining process. A digital camera has been used to record time-dependant elongation when a time-dependant stress is applied. Time-dependant loading was done by allowing a container at the loading end, to be filled by a constant rate water flow attained using a constant pressure head.

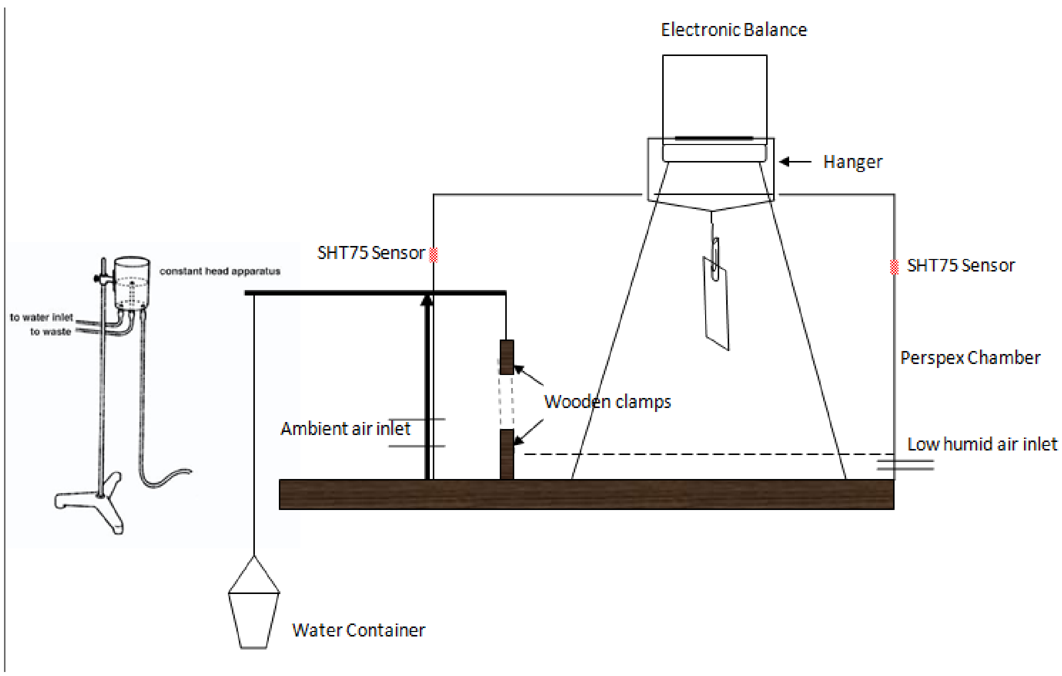

Figure 1 : Schematic diagram of humidity control chamber

2.3. Experimental procedure

In order to carry out moisture absorption measurements, an electronic balance was placed on the stand on top of the chamber with a wire hanger placed on its weighing tray. After the chamber was humidified to the desired value, a dried note was attached to the hanger and the mass of the note was recorded with appropriate time intervals.

For breaking strength and elongation tests, first the loading rate of the constant water supply was calibrated. Then a dried note was firmly clamped inside the chamber controlled at a desired humidity and kept for 30 minutes till the note reaches its equilibrium moisture content. Loading was then initiated and continued till the note breaks, while movement of the indicator is recorded by a digital camera. Frames that were obtained from the video clip at constant time intervals using Adobe Premiere Elements 2.0 multimedia processing software were used to determine the displacement (in pixels) of the indicator at different times, and to obtain the strain vs. stress curve.

3. RESULTS AND DISCUSSION

3.1. **Moisture absorption patterns**

Dry basis moisture content is given by the expression,

$$Dry\ Basis\ Moisture\ Content = \frac{total\ mass - dry\ mass}{dry\ mass} \tag{1}$$

Figure 2 shows that the absorption rate and equilibrium moisture content is higher for used currency notes at any given relative humidity. A Higher relative humidity produced faster absorption rates and increased equilibrium moisture contents.

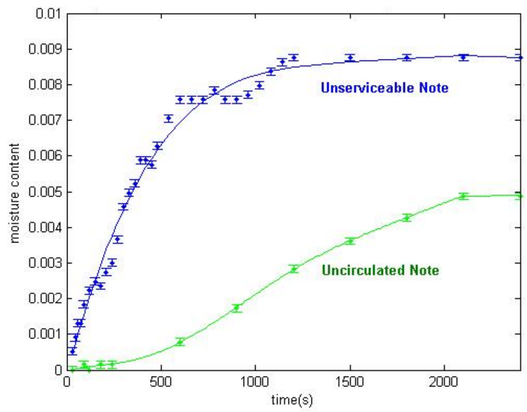

Figure 2 : Moisture absorption at different levels of relative humidity

It was hypothized, that one factor affecting increased absorption in used notes is the increase net exposed surface area due to broken fibre segments standing out of the plane of paper. To test the validity of this hypothesis, an unserviceable note was tested for moisture absorption patterns (Figure 3) at constant temperature and relative humidity, before and after pressing it with an electric iron. The absorption rate and the equilibrium moisture level were found to be decreased after pressing, which indicates the correctness of our hypothesis. To further establish its validity, the note was reused and tested again. The same two parameters are now increased but not up to those of initial unpressed instant. However, even after pressing, the absorption rate does not decrease down to that of an uncirculated fresh note. It implies the effect of factors other than the net surface area that contribute for absorption rate, such as porosity and protective coating on the note.

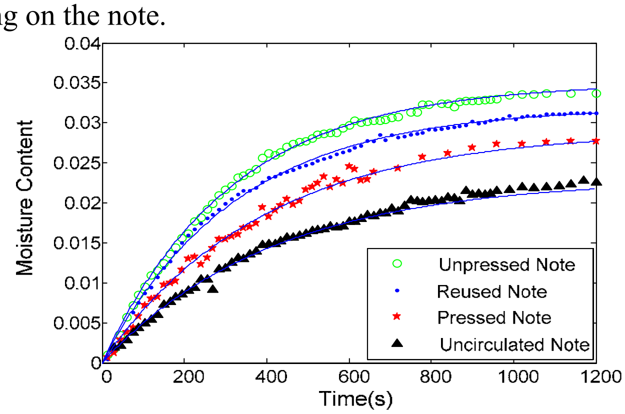

Figure 3 : Variation in absorption patterns with net surface area

General equation for the absorption pattern can be given by equation 2, where τ is the time constant or the time taken for moisture content to rise from zero to 63.2% of its final value.

$$f(t) = M(1 - e^{-t/\tau}) \qquad (2)$$

Table 1 shows the time constant values for absorption isotherms in Figure 3.

Table 1 : Time constant values for absorption isotherms

	Equation of the fit	Time Constant
Unpressed note	$f(t) = 0.035(1 - e^{-0.003169t})$	$\tau = 315.56$
Reused note	$f(t) = 0.032(1 - e^{-0.003098t})$	$\tau = 322.8$
Pressed Note	$f(t) = 0.029(1 - e^{-0.002579t})$	$\tau = 387.75$
Uncirculated Note	$f(t) = 0.023(1 - e^{-0.002417t})$	$\tau = 413.74$

Assuming that equilibrium moisture content (M) is directly proportional to the effective net surface area (A), and inversely proportional to the coating strength (C),

$$\Rightarrow M = \frac{KA}{C} \qquad (3)$$

where K is the proportionality constant.

Hence assuming that the coating strength (C) is not affected by pressing, and using values of $M_{unpressed}$=0.035 and $M_{pressed}$=0.029 from Table 1,

$$\frac{A_{unpressed}}{A_{pressed}} \times 100 = \frac{0.035}{0.029} \times 100 = 120\%$$

If surface area of the pressed note is assumed to be equal to the surface area of an unused note, the percentage increase of net surface area of a currency note due to usage ≈ 20%.

Substituting values for the unserviceable pressed note and the uncirculated note in equation 3, and assuming their net surface areas are equal,

$$\frac{C_{pressed}}{C_{uncirculated}} \times 100 = \frac{0.023}{0.029} \times 100 = 79.3\%$$

Therefore percentage decrease of coating strength of a currency note due to usage ≈ 20.7%

3.2.Breaking strength and elongation

It is seen that breaking stress of an unserviceable note is lower compared to an uncirculated note at any given humidity (Figure 4). However, the strength of a note, in general, decreases with increasing humidity. This weakening can be incorporated to the higher amount of moisture absorbed at higher humidity conditions.

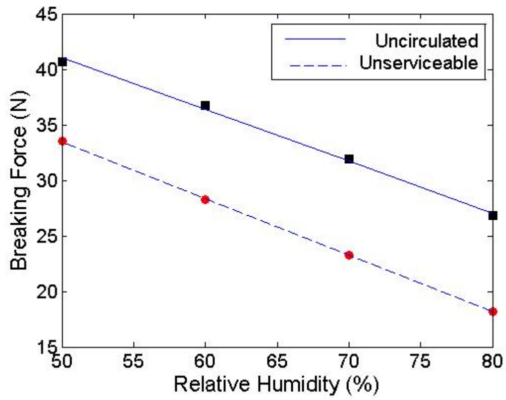

Figure 4 : Variation of breaking force with relative humidity

Strength of note mainly depends on the strength of fibre. Assuming that the fibre strength is in fact the strength contributed by undamaged fibres, and that the breaking force per fibre is a constant,

$$\frac{F_0}{n_0} = \frac{F_1}{n_1} \quad (4)$$

Where, F_0=breaking force of uncirculated note, F_1=breaking force of unserviceable note, n_0=number of unbroken fibres in the uncirculated note, and n_1=number of unbroken fibres in the unserviceable note.

From figure 4, $\frac{F_0}{F_1} \approx 1.3$

From equation 4, $\frac{n_1}{n_0} \times 100 \approx 77\%$

Therefore approximately 23% of fibres are broken when a currency note is used up to its unserviceable state.

A general characteristic seen in the obtained strain vs. stress curves was that for a certain lower range of stress ($0 - 4\times10^6$ Nm^{-2}), the note undergoes elastic straining, then after a limiting point, it enters into a plastic straining region where the deformation could not be recovered (figure 5). Usage as well as presence of water has increased the straining at a given stress level. Also the extent of plasticization seems to increase noticeably with humidity and level of usage.

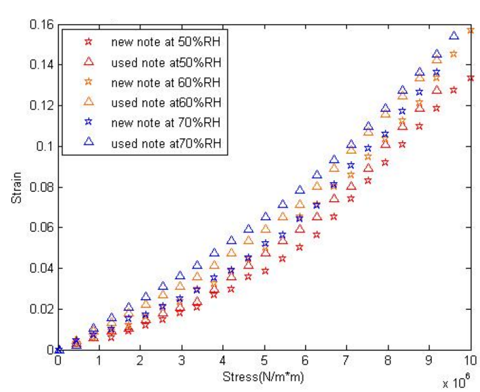

Figure 5 : Comparison of Stress-Strain curves

Calculated elastic modulus values (table 2) are plotted against relative humidity in figure 6.

Table 2 : Elastic Modulus calculation

Relative Humidity (%)	level of usage	Gradient	Elastic Modulus $N/(m^2)$
50	uncirculated	5.8×10^{-9}	1.7×10^{8}
	unserviceable	7.1×10^{-9}	1.4×10^{8}
60	uncirculated	7.6×10^{-9}	1.3×10^{8}
	unserviceable	1.0×10^{-8}	9.3×10^{7}
70	uncirculated	8.2×10^{-9}	1.2×10^{8}
	unserviceable	1.2×10^{-8}	8.0×10^{7}

Elastic modulus was lower for used notes, which implies that with usage, strength of inter-fibre bonds of the note degrades. Again the note is more easily deformed when it contains higher amounts of moisture.

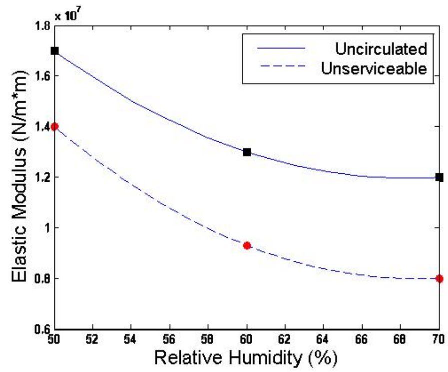

Figure 6 : Elastic modulus vs. relative humidity

3.3. Weakness introduced due to security thread embedment

Breaking force of the note including the thread and that of excluding the thread were compared to evaluate the introduced weakness as a percentage out of the strength of the note without any embedment (table3).

Table 3 : Calculation of weakness

RH	Breaking force including thread (N)		Breaking force excluding thread (N)		Weakness (%)	
	uncirculated	unserviceable	uncirculated	unserviceable	uncirculated	unserviceable
50	40.7	33.5	43.2	34.3	5.8	2.3
60	36.7	28.3	38.0	29.3	3.5	3.2
70	31.9	23.3	33.3	23.9	3.9	2.8
80	26.8	18.2	27.9	18.8	3.8	3.0
				Average weakness	**4.3**	**2.8**

3.4. Creep of a fresh note

Creep effect on an unused note has been tested, in order to investigate its mechanical instability when subjected to different magnitudes of stresses for extended times. For higher loads the creep curve starts to enter into the third stage of creeping during the 15 minutes of testing time (figure 7).

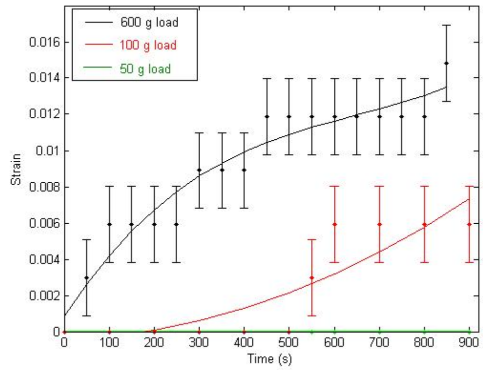

Figure 7 : Creep curves for uncirculated notes under different applied forces

4. CONCLUSION

Moisture absorption rate and the equilibrium moisture content of a currency note increases considerably with usage. It was verified that the net exposed surface area of fibres which is increased by about 20% and the strength of protective coating which is decreased by about 20.7% during the life time of a note, affects the rate of absorption of moisture from surrounding environment. Ten rupee currency notes show elastic behavior where modulus of elasticity decreases with usage, while plastic straining is exhibited for larger applied forces. The breaking strength is also lower for used noted. Furthermore, a note of any state is more easily deformed when it contains higher amounts of moisture. Hence the mechanical strength degradation introduced with usage is also due to presence of higher amounts of moisture as well as due to fibre breakage. It was estimated that within the lifetime of the note about 23% of its fibres tend to break.

Interestingly the embedment of the security thread introduces a weakness of about 4.3% to the overall cross directional strength of an uncirculated note which could be explained in terms of inter-fibre bonds that break or loosen during the insertion of thin polyester film/thread. In addition, a fresh note was found to demonstrate substantial creeping for loads higher than 0.5N.

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