# Effect of Circulation Time on the Physical Properties of Currency

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Durability is a very important property of currency and currency paper because currency is circulated in the public for a very long time. The effect of circulation time on the physical properties of currency was investigated. In addition, a crumpling treatment procedure was adopted to simulate the circulation of currency in public. The air permeance of currency that was subjected to eight rounds of crumpling treatment was compared with that of actual circulated currency. As the circulation time increased, the basis weight, thickness, air permeance, and *b** value increased. On the other hand, the stiffness and the *L** value decreased as the circulation time increased. Regarding the air permeance, the slope of the plot was greater than the slopes of other physical properties measured. Air permeance of the samples after the crumpling treatment was greater than that of the circulated currency, which indicated that the crumpling process resulted in more severe changes in air permeance than the crumpling that occurs during the actual circulation of currency.

*Keywords: Currency; Air permeance; Durability; Circulation time; Crumpling treatment*

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## INTRODUCTION

Paper products have been widely used in many applications, including printing and writing, packaging, wrapping, and cleaning. One of the special uses of paper is as a medium of exchange, *i.e.*, banknotes. The use of paper as a medium of exchange started more than a thousand years ago in China. It was adopted quickly because of its many advantages, including convenience of handling and safety associated with not carrying gold or silver. Paper banknotes are still the most widely used currency, even though polymer currency was introduced in 1988 and has expanded to some 22 countries. The most significant advantage of polymer currency lies in the dramatic improvement of the life span of banknotes, which means that more attention and improvement should be made to the durability of paper banknotes. Most banknotes are made from cotton paper with a weight of 80 to 90 grams per square meter. The cotton is sometimes mixed with linen, abaca, or other textile fibers. Generally, the paper used is different from ordinary paper: it is much more resilient and resists wear and tear. It is believed that the average life of a banknote is two years.

The term durability is defined as "a characteristic of paper and paperboard relating to its ability to stand up and retain its original properties under constant use over extended periods of time," according to the Pulp and Paper dictionary (Lavigne 1993). In contrast to durability, permanence is a term to describe a property primarily with respect to its aging process (Luner 1969; Browning and Wink 1969; Hudson 1973; Roberson 1976; Waterhouse 1994). Traditionally, physical properties such as tensile strength, wet tensile strength, tearing resistance, folding endurance, and burst strength have been measured and used to evaluate the durability of currency, rather than directly measuring the durability itself. Kocurek (1992) pointed out that the folding endurance is a unique test that is designed to provide some index of paper durability. This test is performed with paper that is approximately 100 mm by 15 mm in size that is held under tension and is repeatedly folded by the action of a slotted blade. Therefore, it is not too surprising that the folding endurance test has resulted in a high degree of variability compared with the results of some of the other mechanical tests. Sources of this variability include poor sample preparation, cutting and handling, as well as localized changes in moisture content (Kocurek 1992).

The US National Bureau of Engraving and Printing developed a flex tester to measure the endurance characteristics of currency paper (Kocurek 1992). It was noted that only a small area of the sample is tested with the folding endurance tester. The use of a flex tester allows testing the physical properties of the sample after a given number of flex treatments, which makes it possible to use a much larger area for testing. The changes in the properties are then used to evaluate the durability of paper or currency, rather than the paper being flexed to failure. The applied strains and induced stresses are similar to those in the folding resistance tester, although the bend radius is larger. Therefore, the sample undergoes both tensile and cyclic bending stress (Kocurek 1992). Graminski (1973), who plotted the percentage of physical properties against the number of flexes, found that the slope of the plot, as well as the extent of the decline in the physical properties can be used to measure the durability of paper.

Durability is currently measured by soiling test methods and by observing the physical properties of currency after crumpling treatment. Some East Asian countries have specified that the air permeance of currency paper should be measured after the crumpling process has been carried out eight times. An IGT crumpling device was adopted in this study to perform the crumpling treatment, which simulates the constant use of currency over extended periods of time or the circulation of currency in the public (Kim 2007; Kim *et al.* 2008). The air permeance after the crumpling treatments was evaluated, and the results were then compared to actual currency that has been in circulation.

## EXPERIMENTAL

### Specimens

One hundred bills of currency, consisting of ten types of banknotes, were obtained from a local bank in Korea. These specimens were used to investigate the effect of circulation time on the physical properties of currency. The circulation time of each bill was determined from the intrinsic serial number printed on the banknote, which contained information on when the bill was issued. Ten newly made bills were also exposed to the crumpling treatment.

Specimens were classified into ten groups based on their subjective hand feel and degree of soiling. The average circulation time of each group was also calculated. The relationship between the circulation time and hand feel and the degree of soiling was plotted for both the currency that was used in actual circulation and the currency that was artificially crumpled.

### Measurement of Physical Properties

Specimens were preconditioned at 20 ± 1 °C and 65 ± 2% relative humidity (RH). Basis weight, thickness, Taber stiffness, Schopper-type folding endurance, and Bendtsen air permeance were measured according to TAPPI standard T-410 om-98, T-411 om-97, T-489 om-99, T-423 cm-98, and ISO standard 5636-3, respectively. The color was measured using D65/10° conditions with an X-rite spectrophotometer(X-rite Inc., MI). Each of these physical variables was plotted against the circulation time.

### Measurement of Air Permeance after the Crumpling Treatment

Four test pieces that were 67 $mm^2$ in area were cut from the sample to be tested. All of these test pieces were conditioned for 24 h at 20 ± 1 °C and 65 ± 2% RH prior to the crumpling protocol. Each test square was rolled into a tube using the rolling apparatus of the National Bureau of Standards (NBS) crumpling device. The rolled test piece was placed into the crumpling tube and then crumpled by firmly pressing the plunger down until the cantilever weight began to rise. Each test piece was removed from the crumpling tube and gently unrolled and smoothed out with fingers. These test pieces were then rotated 90° and rerolled into a tube and crumpled again as before. This crumpling process was repeated again three more times. Then, the test piece was turned over to repeat the same process again on the other side four times. Test pieces were flattened out to test the air permeance and tensile strength. In some cases, the dimensions of the test pieces used were 140 mm by 75 mm.

## RESULTS AND DISCUSSION

### Relationship between Circulation Time and Visual Rank

Banknotes were classified into ten groups based on their subjective hand feel and the degree of soiling based on visual judgment. The average circulation time was calculated from the intrinsic serial number for each of these groups. The average circulation time for all of the specimens tested was 27.8 months. The relationship between the actual circulation time of currency and the visual ranking of the currency obtained from the hand feel and degree of soiling of each bill is plotted in Fig. 1. Generally, the specimens that were identified as being worn-out based on visual judgement and hand feel had longer circulation times.

### Effects of Circulation Time on Physical Properties

The relationships between circulation time and various physical properties, such as basis weight, thickness, color ($L^*$, $a^*$, $b^*$), and stiffness, were also investigated. Air permeance and folding endurance were added as durability-related factors.

*Basis weight*

The basis weight of the specimens was plotted against circulation time and is shown in Fig. 2. According to these results, the specimen weight slightly increased with circulation time. This is explained by the several contaminants and soil that tightly adhere to specimens as they are circulated in the public.

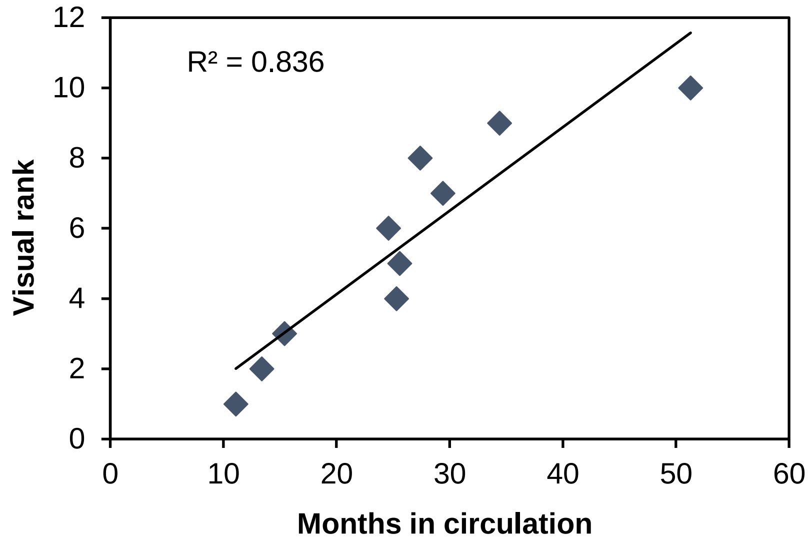



**Fig. 1.** Relationship between real circulation time and visual ranking

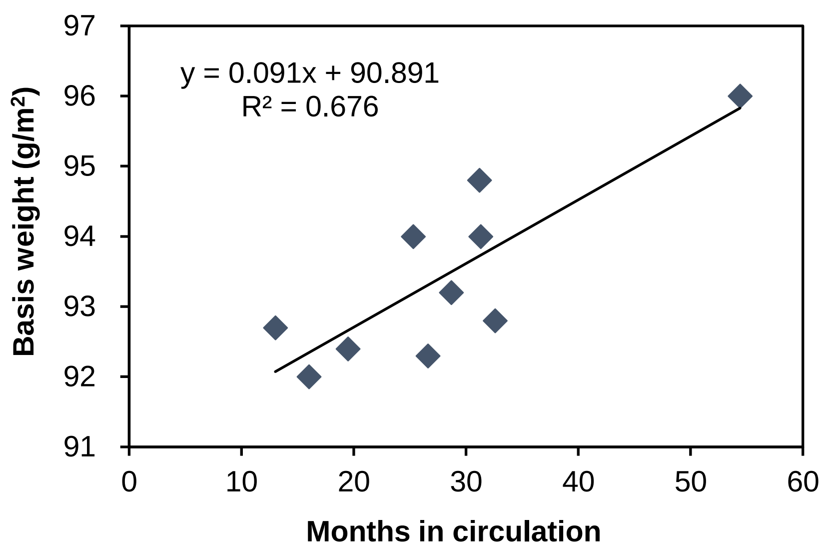



**Fig. 2.** Basis weight as a function of circulation time

Billetes (1993) mentioned that the real soiling process is caused by a random sequence of crumpling, rubbing, porosity increase, and moisture-chemical attack. In this process, the internal structure of a specimen is broken by successive crumpling and rubbing events, which loosens the fiber bonds and increases the porosity, thereby making the specimen spongier. This accelerates the water absorption and frequency of chemical attacks. Also, wherever a fold occurs, the fiber structure is weakened, and the probability that another fold would occur at the same point increases, creating a region more sensitive to physical and chemical damage. After several repetitions, the specimen will have the appearance of disarranged hair. Loose fibers act as electrostatic collectors and abrasive agents that entangle soil particles. Soil consists of the accumulation of dirt and dust in the mesh formed by the loose fibers (Billetes 1993).

*Thickness*

The thickness of each bill and how it relates to circulation time are shown in Fig. 3. In the case of the non-printed area, the thickness increased with circulation time. The reason why these specimens become bulky with circulation time is because the fiber bonds loosen and rise to the surface when circulated in public. This may cause contaminants to adhere to a specimen. However, the thickness of the printed area had different results. The coefficient of correlation was lower than that of the non-printed area.

It appears that the ink particles were irregularly detached from the surface as the circulation time progressed, and this may be especially true in the case of the intaglio printed area because of the protruded printing surface. Although paper thickness increased with circulation time, the correlation between the circulation time and the thickness of the printed area was lower because of the irregular ink detachment from the surface.

*Color of the non-printed area*

The effect that circulation time has on color was also investigated. The variables $L^*$, $a^*$, and $b^*$ are plotted against circulation time in Fig. 4. According to the figures, $L^*$ and $a^*$ increased with circulation time, while $b^*$ decreased.

This indicates that the brightness and whiteness decreased and that the yellowness increased the longer a bill was in circulation in the public. From these results, it is clear that the color of the non-printed area is closely related to the specimens that were actually in circulation and that the color of this area can be used to evaluate durability.

*Stiffness*

People often feel the stiffness or softness of a bill with their fingers. Generally, newly made currency paper has stiff characteristics, and this decreases with time. Thus, stiffness is another closely related physical property of circulation, and the coefficient between stiffness and circulation time was high (Fig. 5). According to the results, the Taber stiffness decreased the longer a bill was in circulation in the public. Throughout circulation, specimens are exposed to rubbing, folding, and crumpling. In these types of situations, the inter fiber bonding partially or entirely breaks, and the specimens lose their stiffness with increasing circulation time.

*Air permeance*

The Bendtsen air permeance of currency paper is generally near zero. The effect of circulation time on air permeance was investigated, and the results are plotted in Fig. 6. As previously mentioned, inter fiber bonding becomes partially or entirely broken in the event of rubbing, folding, and crumpling. Air permeance was found to increase with circulation time because of these types of situations, which cause the fiber network to become more open and porous. According to this figure, the air permeance barely changed in the first twenty months of circulation, but thereafter, the air permeance steeply increased. The slope of this plot is greater than the slopes of the plots of other physical properties that were measured.

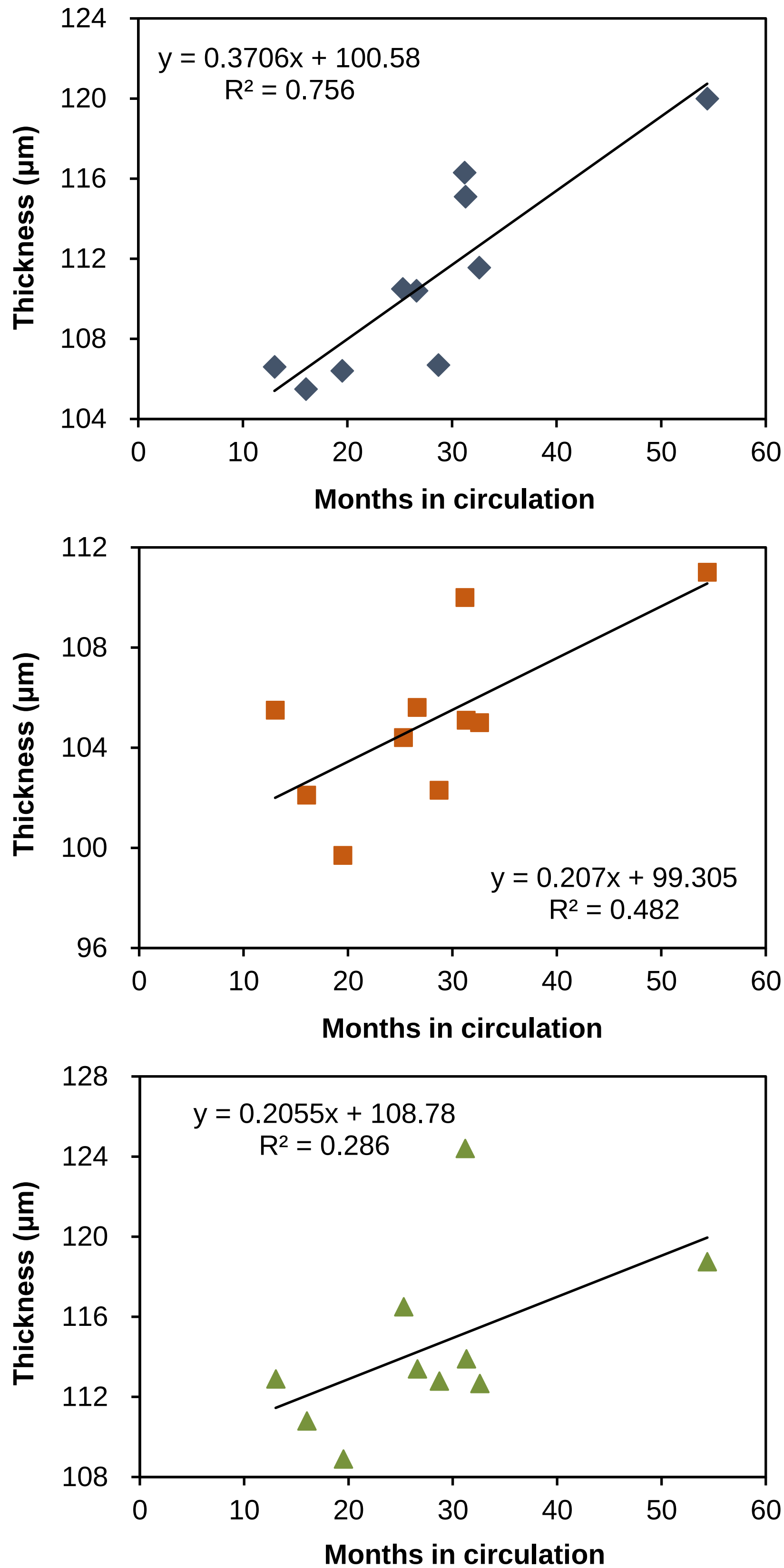
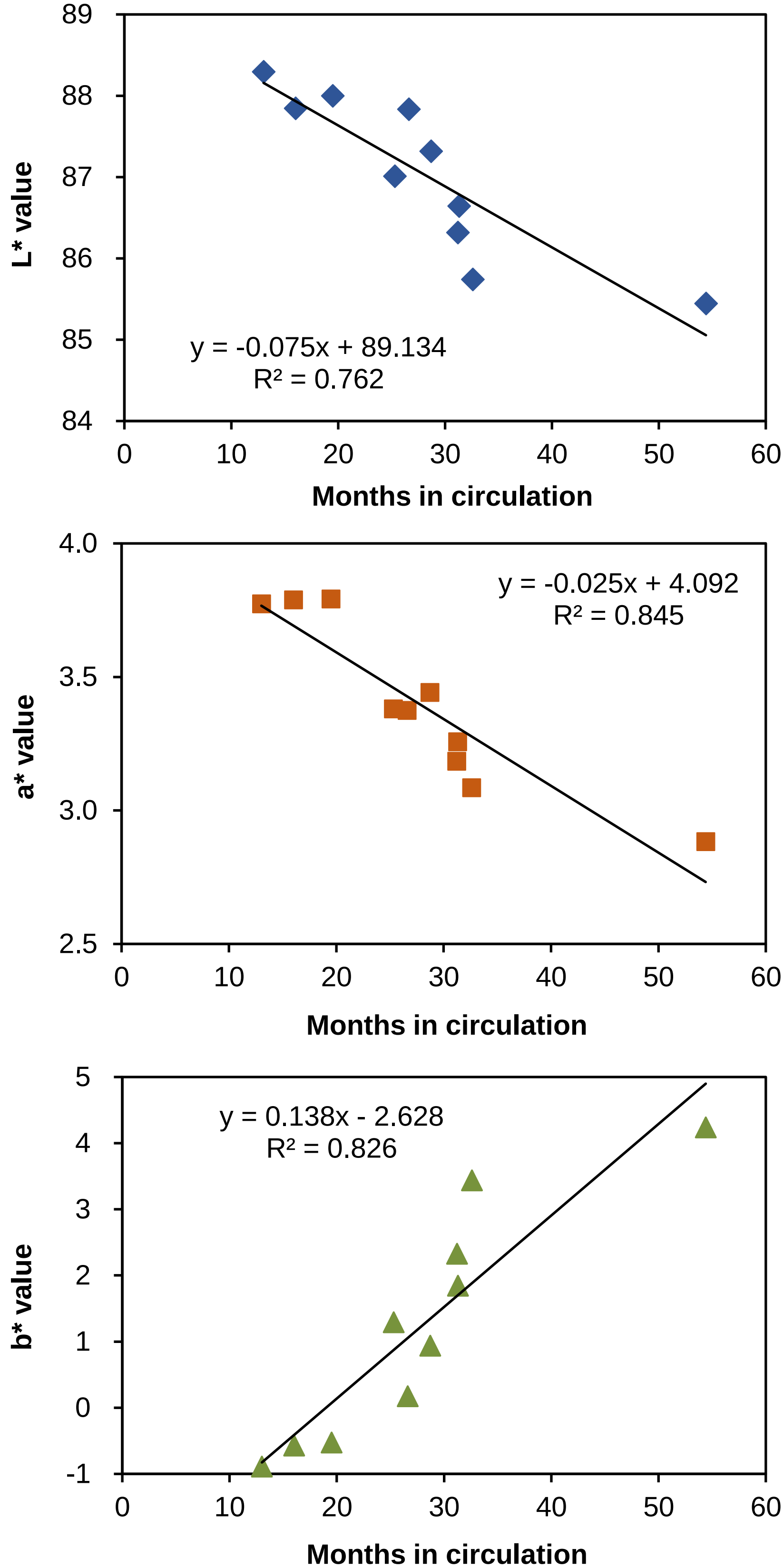



**Fig. 3.** Thickness as a function of circulation time for the non-printed area (top), offset printed area (middle), and intaglio printed area (bottom)




(a) L* value (b) a* value (c) b* value

**Fig. 4.** L*, a* and b* values as a function of circulation time for currency

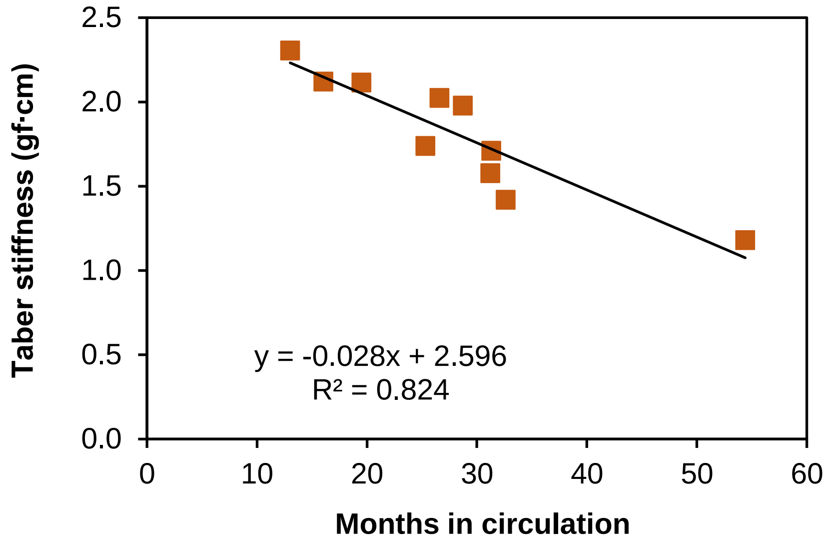



**Fig. 5.** Taber stiffness as a function of circulation time

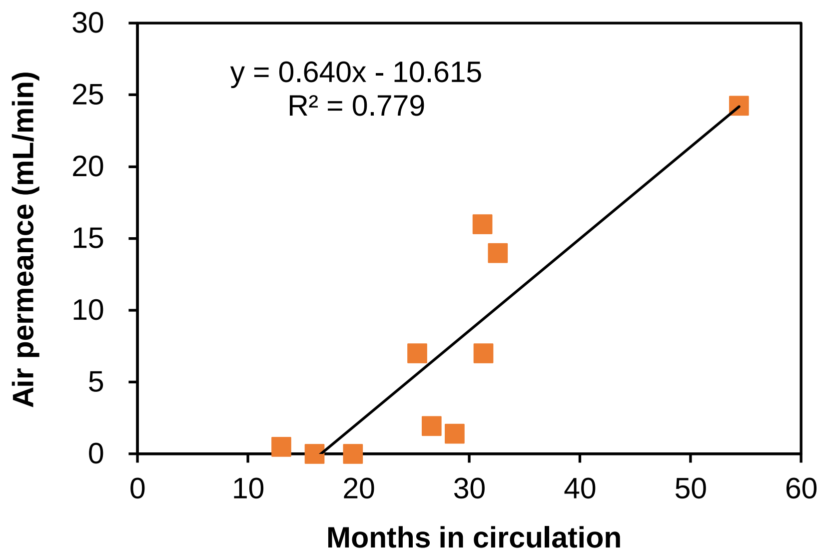



**Fig. 6.** Air permeance as a function of circulation time

*Folding endurance*

The folding test was performed on a very small area of the specimen. The test results had a high degree of variability compared with some of the other mechanical tests that were performed. The reasons for the variability include poor sample preparation, cutting, handling, and formation, which may have caused localized changes in moisture content (Kokurek 1982). The folding endurance was not closely related to the circulation time because of this variability.

*Slope of the plot and percentage decline of physical properties*

The slope of the plot and the decline in the physical properties measured are shown in Table 1. The regression equation was used to calculate the decline of the physical properties, which was the percentage change that occurs when a bill has been in circulation from 20 to 50 months. Considering the slope of the plot and the percentage change from the initial measurements of each physical characteristic, it was found that the air permeance was most closely related to the circulation time, followed by the *b** value, thickness, and stiffness characteristics.

**Table 1.** Slope of Plot and Decline of Physical Properties

| *Properties* | *Slope (absolute value)* | *Decline (%)* |
|---|---|---|
| Basis weight | 0.090 | 2.9 |
| Thickness | 0.370 | 10.3 |
| L* | 0.075 | 4.2 |
| a* | 0.025 | 20.9 |
| b* | 0.138 | 3112.0 |
| Air permeance | 0.639 | 883.4 |
| Taber stiffness | 0.027 | 39.4 |

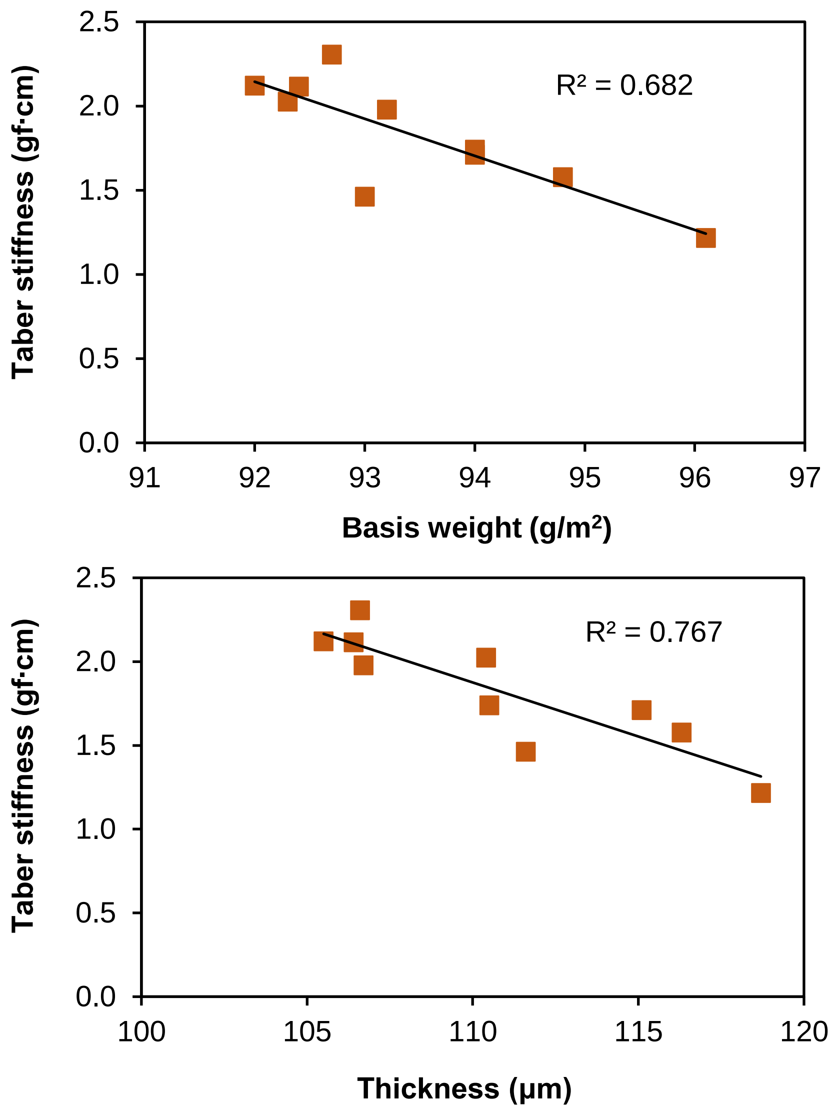



**Fig. 7.** Relationship between basis weight (top) and thickness (bottom) with Taber stiffness

## Relationships between the Physical Properties

The relationships between the physical properties studied were investigated. Generally, stiffness increased with basis weight or thickness. However, the present results showed that paper stiffness decreased as the basis weight and thickness increased (Fig. 7). This is because the weight gain of a specimen was not caused by fibers but instead by soiling. Inter-fiber bonds were loosened and were partially or entirely broken upon crumpling, which increased thickness. Thus, the stiffness decreased despite the increase in weight. A similar relationship was found between stiffness and thickness. As long as all other conditions remained the same, the stiffness increases in proportion to the cube of thickness. However, in this study, the stiffness decreased as the thickness increased. This was because the loosened fiber bonds and the fibers rising to the surface caused the increase in thickness.

As previously mentioned, air permeance was closely related to the circulation time. A few other physical properties were plotted against air permeance (Fig. 8). Air permeance had a positive and linear relationship with basis weight, while it showed a negative and linear relationship with *L** value. This negative relationship with *L** was attributed to the soil gain caused by perspiration, oil, coloring materials, chemicals, *etc.*

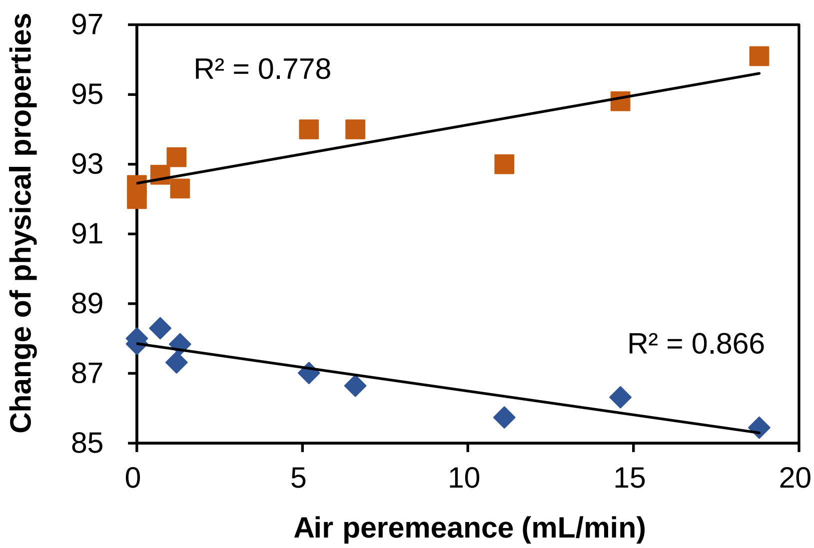



**Fig. 8.** Basis weight and *L** as a function of air permeance

## Air Permeance of Circulated and Crumpled Specimens

Crumpling treatment is used to simulate the constant use of currency over extended periods of time, or the circulation of currency in public. The effect of crumpling treatment on air permeance was investigated because air permeance is the property most significantly influenced by the circulation period. Never-used currency was used for the crumpling treatment, and the Bendtsen air permeance was measured after every other crumpling until the process was executed a total of eight times. Results are shown in Fig. 9. The air permeance of a bill that was subjected to artificial crumpling treatment was compared with that of the bill that was circulated. The air permeance of a new bill that had been crumpled twice was similar to that of a bill that had been circulated for approximately 30 months. Similarly, the air permeance of a new bill that had been crumpled a total of eight times was much higher than that of a real bill that had been publicly circulated.

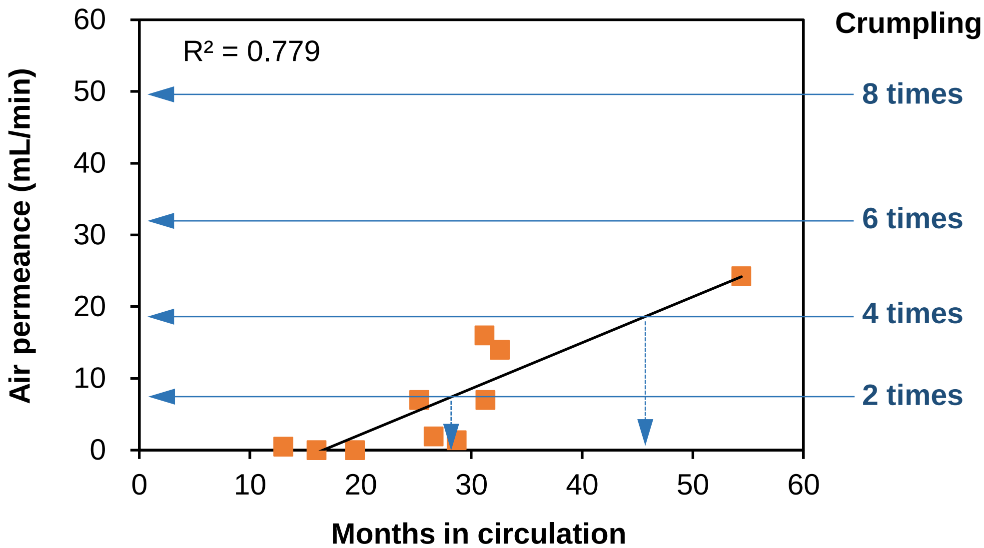
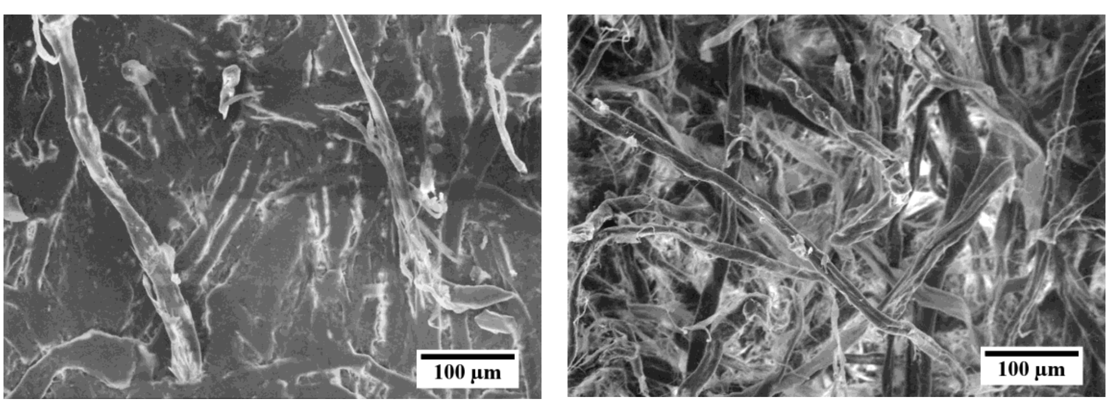



**Fig. 9.** Comparison of air permeance between real circulation and crumpling treatment

This result suggests that two sets of crumpling treatments imparted to bills the same air permeance of currency that had been in actual circulation for about 30 months. It also shows that the crumpling treatment provides an opportunity for quality change during circulation. However, crumpling times of less than five should be employed to test the property change accompanying the actual use of currency. Our experiences also tells that the increase in air permeance is considerably greater for crumpled specimens than what occurs in a heavily used specimen. Therefore, the air permeance of currency is far more dependent on the crumpling process than on very extensive wear and tear.

## Surface Images

The severe action that the crumpling treatment had on currency was confirmed with SEM imaging of the surface of the paper. While there were some hairy fibers that appeared on the surface, most of the fiber network was firmly preserved in the specimens that were in actual circulation. On the contrary, the loose and bulky fiber network was detected on the surface of the crumpled specimen. For these reasons, there may be a noticeable air permeance difference between crumpled specimens and actually circulated specimens.




(a) circulated specimen (b) crumpled specimen

**Fig. 10.** SEM surface image

## CONCLUSIONS

1. As circulation time of paper currency increased, the basis weight, thickness, air permeance, and $b^*$ value increased. On the other hand, the stiffness and $L^*$ value decreased as the circulation increased. Among the properties examined, air permeance was determined to be the most appropriate property to estimate the circulation time of Korean currency.
2. The air permeance of a specimen after crumpling treatment was found to be higher than that of a specimen that had been in actual circulation. Results showed that two cycles of crumpling treatments gave the air permeance of currency that had been in actual circulation for about 30 months.
3. This crumpling treatment can be used to estimate certain of the property changes or the projected circulation lifetime of newly developed currency.

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