UNDERSTANDING PAPER FLATTENING (I). PRINCIPLES AND PROBLEMS OF COMMON FLATTENING TECHNIQUES

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Taller de obra gráfica y papel

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ABSTRACT: *Paper flattening is a very common treatment in paper conservation. Conservators have developed a number of techniques which allow for the successful flattening of very different paper sheets. However, the principles behind these techniques are not always understood. Furthermore, these techniques often have unwanted effects, which are often unnoticed, or not understood. The alteration of the original size of the flattened paper sheet is one of the most important effects. However, so far no research has been done on this problem. This paper describes some of the theoretical and applied results of a collaborative research project developed by IRP and the ai2 on this topic. An analysis of the principles behind paper flattening is presented, and some often unacknowledged problems are outlined. The need for a custom-designed system for the assessment of size variations of paper sheets is also described.*

KEYWORDS: conservation, restoration, paper flattening, hydrogen bond, size, hydration, pressure, tension, stress, strain

A THEORETICAL ANALYSIS OF THE FLATTENING PROCESS

Paper flattening is a very common process in paper conservation. After conservation treatment, paper sheets are expected to be flat, and conservators try very hard to do this. Many different techniques have been applied by conservators all around the world. However, it is not always realized is that every paper flattening technique is based on three basic steps. First, the sheet is wetted. Then, the wet sheet is fixed to form a flat shape. Finally, the sheet is dried. After this process, the sheet loses many of the curls and wrinkles that it would otherwise have had.

The technical reason why this happens is, to a large extent, the same technical reason why paper sheets are able be made in the first place. The physical phenomenon behind it all is the *hydrogen bond*. The hydrogen bond is the electromagnetic attraction (bond) produced between two water molecules or a water molecule and other *polar* molecule. A polar molecule is a molecule in which the centre of their negative charges does not coincide with the centre of their positive charges; it has magnetic *poles* which act as tiny sub microscopic magnets. These *nanomagnets* act as the regular magnets do; when put in an adequate position, they attract each other, sticking together.

Cellulose, the main chemical component of paper fibres, is a very large molecule that has polar 'spots', namely three hydroxyl groups in each monomer. Thus, a cellulose molecule with a degree of polymerisation of 1,000 (i.e., a cellulose polymer with 1,000 monomers) has 3,000 magnetic 'spots', ready to attract and be attracted by other magnetic 'spots' in other polar molecules, such as those of water. Water is in fact a very polar molecule. When a cellulose molecule is wetted, water molecules tend to stick to the hydroxyl groups. If another cellulose molecule is brought close enough, the water molecule can attract another hydroxyl group from the first cellulose molecule and an hydroxyl group from the second cellulose molecule, thus actually holding them together.

Of course, one single water molecule cannot effectively hold together two paper fibres in the conditions in which paper is normally used. Fortunately for papermakers, there are many hydroxyl 'spots' in a fibre, ready to stick to any water molecule that gets close enough, and many water molecules. Furthermore, water molecules can form longer 'threads' or 'chains' contributing to hold the fibres together. Thus, a water molecule can stick to a hydroxyl group and to another water molecule which in turn can stick to another hydroxyl group. This linking 'chain' is composed of two water molecules, but can be longer. Of course, the longer the 'chain', the freer each fibre is to move with respect to the other (figure 1).

When a paper sheet is being produced and has not dried yet, the water-molecule 'chains' between fibres are actually too long, and the fibres can move freely. Thus, the paper is still extremely weak, and can only withstand the most careful handling. However, after the paper is then pressed and allowed to dry: the interfibrilar chain links become shorter, holding the fibres together in a much more effective way.

During both pressing and drying, many water molecules are taken out of the paper. When the sheet is pressed, water is simply squeezed out of the paper; then, more molecules leave the paper, attracted by the drier atmosphere or by the drying material the sheet is put in contact with. Finally, only a mere 5-6% of water remains in the paper –the amount necessary to keep it in a working condition, converting it into the flexible and strong sheet we all know. If the water content of a paper sheet is increased or reduced, the links between fibres will become either too long or too few, thus resulting in a weakened sheet.

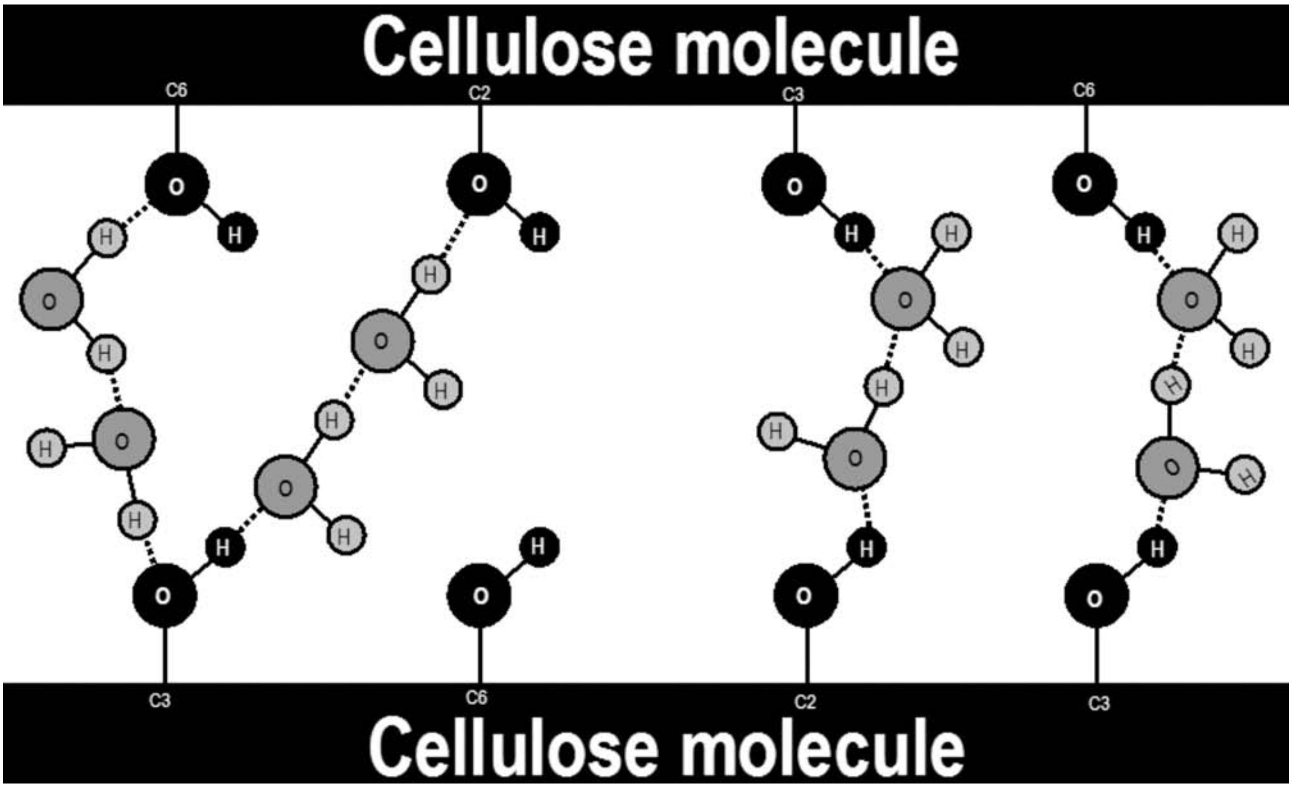

Figure 1. Two cellulose molecules bonded by water molecules. Hydrogen bonds are represented as dotted lines

Fortunately, in most climates, this 5-6% water content is naturally reached in normal atmospheric conditions: when only that little water remains in the paper, we say and feel that the paper is 'dry'; we feel that not because there is no water in the sheet, but rather because no more water will evaporate from the sheet unless some special procedures are applied (heat or vacuum, for instance). In these normal conditions, the paper sheet usually remains relatively strong –the kind of strength we all expect from paper. However, if the sheet is rewetted, the water-molecule interfibrilar links will again become longer that expected, thus freeing the fibres and weakening the paper. This is the first thing the conservator does when trying to flatten a wrinkled paper sheet.

THE FLATTENING PROCESS: WETTING THE PAPER SHEET

A paper artefact can be wet in a variety of manners. The simplest way is to immerse the sheet in water for some time, allowing it to get thoroughly wetted. This procedure has the added advantage that water soluble by-products of cellulose degradation can also be dissolved away at the same time, a property that has rendered it very popular and widespread. However, many other procedures are available to the conservator: water can be added by brushing or spraying, by putting the sheet in contact with wet blotters, by applying poultices, or by using an ultrasonic humidifier (Weidner, 1993; Weidner and Zachary, 1994). Water molecules can also be applied in an even more gentle way, in the form of vapour, by exposing the sheet to a humid environment (usually using a moisture chamber), by locally applying steam or by using different, more complex techniques, such as those described by Futernick (Futernick, 1984). In all cases, the objective is to add water molecules to the paper, so that the interfibrilar links can become looser than they are (figure 2).

In non-sized papers, the weakening caused by their thorough wetting could theoretically lead to the total disintegration of the sheet, but there are actually very few cases of non-sized papers, so that few paper sheets would actually disintegrate through regular conservation wetting. Furthermore, even non sized sheets would require a certain degree of wetting and, perhaps, stirring to be able to disintegrate. Damage can indeed be done, but most sheets simple get weaker and softer. This softening of the sheets is crucial to the conservator, who then *fixes* the sheet in the desired shape –usually in the simple, flat shape we all are familiar with. The sheet is then allowed to dry.

THE FLATTENING PROCESS: FIXING THE SHEET

Fixing the sheet is crucial. When the sheet dries, water molecules leave the paper by absorption or evaporation, effectively shortening the water-molecule interfibrilar chains and thus increasing the paper strength. This shortening is accompanied by the relocation of the fibres, which, because of the wet state of the sheet, can move quite freely, usually resulting in a curling of the sheet.

Curling is a result of uneven drying. If the evaporation or absorption of water molecules took place at exactly the same rate at every single point of the sheet, there would be no need for special fixing procedures: the sheet would gently contract in an homogeneous manner, retaining its original shape without causing the deformation of the sheet. However, this is not the case. Some parts of the paper are more porous than other parts, and contain more water; some parts of the paper are microscopically rougher; some parts are more exposed to air; some parts have been in contact with grease; some parts have been exposed to heat or pressure; some parts are more inked than others; some parts are slightly thicker, etc. The result is that some parts of the sheet will dry (and contract) faster than others. Sheets which are not fixed react to this uneven exodus of water molecules by producing random undulations or curls.

However, conservators take great care in ensuring that the fibres will not move from the desired, flat shape while new interfibrilar bonds become shorter and stronger. If the sheet is fixed enough, the movement of fibres is severely limited. Thus, it is mainly the water-molecule chains that readapt, forming new chains which bond the fibres in the position in which they have been fixed –usually in their flat position.

Figure 2. Humidifying the paper with a sprayer

The techniques used by conservators to fix the sheets can be classified in two broad categories: they can be either *pressure* techniques or *tension* techniques. Actually, there is a system which cannot be categorized as either a pressure or a tension technique: the technique patented by Robert Fieux in 1980, which is based upon the use of electrostatic forces (Fieux, 1980). However, this technique has had little or no relevance in the conservation world, so that the classification we propose here remains essentially valid.

Pressure techniques consist of the application of pressure all over the surfaces of the sheet (i.e., the two larger surfaces of the sheet). This can be done in a variety of ways. The most obvious is, perhaps, simply putting the sheet between two rigid, flat surfaces, adding weight as necessary -or perhaps using clamps to produce the strength. Presses are another obvious possibility. Hand presses, pneumatic presses, or hydraulic presses have been successfully used to this end. Vacuum tables are another variation of this same principley. The sheet is positioned on the vacuum table, and vacuum is produced. The air passes through the paper, drying it. The sheet is held flat by the weight of the air in the atmosphere. This system, however, presents some practical problems: pressure is often too light to effectively hold the sheet flat, and textures may become notably altered.

Tension fixing of paper sheets is based on the fact that the loss of water molecules in wet paper sheets implies a reduction in the size of the water-filled interfibrilar 'gaps', and, thus, a reduction of the overall size of the sheet. If the margins of the wet sheet are fixed on a flat, rigid surface, the tension caused by the shrinking paper will avoid the wrinkling or curling of the drying sheet. In conservation practice, tension drying is usually performed by gently gluing the wet sheet to a suitable flat surface from which it can be separated with a light pull when dry. The margins of the wet, glued sheet are the first part to dry and, thus, they get effectively fixed to the flat surface. When the rest of the sheet contracts, it gets tense, terse and flat (figure 3).

Of course, both methods can be combined. The use of 'friction-mounting' proposed by Keyes is an example, as it includes light pressure and surface adhesion to a backing sheet to produce satisfactory results (Keyes, 1984).

THE FLATTENING PROCESS: DRYING THE SHEET

Sheets which are flattened by tension simply dry by evaporation, so that no further special provisions are required. However, in pressure flattening techniques, as the sheet is not in contact with air, things are not that simple. The conservator has to insert some absorbing material between the pressing surfaces and the sheet being flattened; this material needs to have the capacity to absorb water molecules, with blotting paper being an obvious, much used choice. Often, the absorbing material becomes saturated before the sheet is fully dried, and a new, dry sheet of absorbing material has to be substituted. This process may have to be repeated several times before the paper sheet fully dries. The conservator has to release the pressure, take out the "sandwich" with the absorbing material and the paper sheet, change the absorbing material, put the sandwich back in place and press the whole thing again. This may be a minor annoyance, but it may be more important if there are many sheets being flattened in the same press, or when the sheet is large. In these cases, the substitution of dry absorbing material can be time-consuming, which means that the sheets may dry without being under pressure for some crucial minutes; this, in turn,

Figure 3. Preparing a sheet for tension flattening on a karibari. The karibari is a purpose-built base for paper tension flattening. This base is a traditional tool of Japanese papermakers which has been successfully adapted for its use in paper conservation

may lead to them curling. This risk is especially important in those stages of the drying process where the tendency to curl is extremely high. These stages have been characterized by various authors in different manners. For conservators, the most interesting characterization is that of Sugarman and Vitale, which takes into account factors and symptoms which can be easily reproduced in a conservation workshop (Sugarman and Vitale, 1992): these authors have established that in common papers the 'onset of physical distortion' (the fifth, final stage of the drying process) takes place right after water starts to evaporate from the smaller pores in the paper web, i.e., those which surround fibre-to-fibre bonding regions.

If the sheet starts to curl before it can be put under pressure, the act of putting under pressure implies the risk of the paper folding or curling over itself, thus producing a crease. Paper creases usually involve the localized breaking of the fibres across the crease; this breakage cannot be fully repaired by the conservator. However treated, creases often remain visible, especially when located on large, flat-colour surfaces. Not fully repairing or even concealing existing creases is poor practice, but at least this can be seen as a failure of conservation rather than a failure of the conservator. However, introducing new creases during conservation treatment is indeed a failure of the conservator. To avoid this, a wise option is to simply take the safest route, and restart the flattening process again when even the slightest curl appears in the middle of the flattening process. This may mean a considerable loss of time, but it will not harm the paper artefact.

A CLOSER LOOK: ISSUES OF PRESSURE FLATTENING TECHNIQUES

There are some other problems, however, which have a more permanent effect on the treated sheets. When the sheet of paper is wetted, the volume of the added water molecules is added to the original volume of the sheets, actually increasing its thickness. Later on, when flattening pressure is applied, the thickness of the sheet can be altered to a thickness which it may or may not have been before the process. Fortunately, even if the degree of alteration is relevant, few persons will ever notice (or care about) this variation. The only likely exception to this rule takes place if the flattened sheets come from a book which has to be re-bound again. In these cases, the thickness variations of any and all sheets add up. Thus, many restored books come out from conservation treatment noticeably thinner than they were. Conservators cope with this problem by adapting the original binding in a number of ways, and/or by sewing the sheets in a looser-than-usual manner, but the fact remains that an unwanted, noticeable alteration is introduced because of the pressure-flattening of the sheets.

Another unwanted effect of pressure flattening is the change in the sheet's texture. Because the sheet is in a soft, plastic state along the most part of the flattening process, the texture of the usually harder adjoining materials can be *imprinted* on it. Again, this effect can go unnoticed, but in some cases it can be *very* noticeable –and very annoying (figure 4). As a rule of thumb, the smoother the surface of the flattened sheet, the greater the risk of its texture being changed in a noticeable way: super-calendered papers or *couche* papers, for instance, are very prone to this problem. The worst thing of all is that it has no

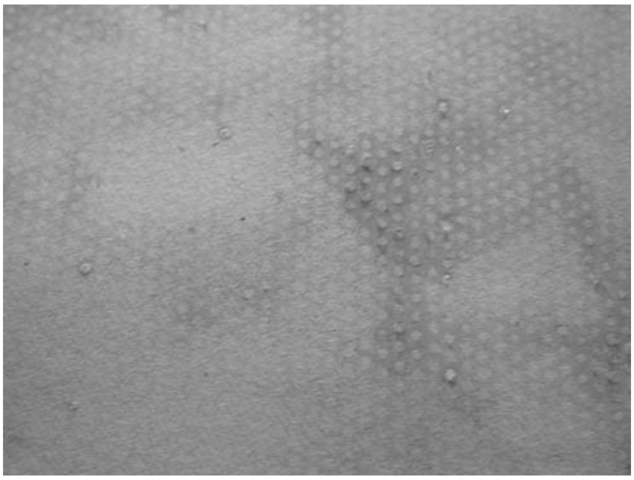

Figure 4. An example of texture alteration caused by pressure flattening. A dotted pattern has been imprinted upon the paper

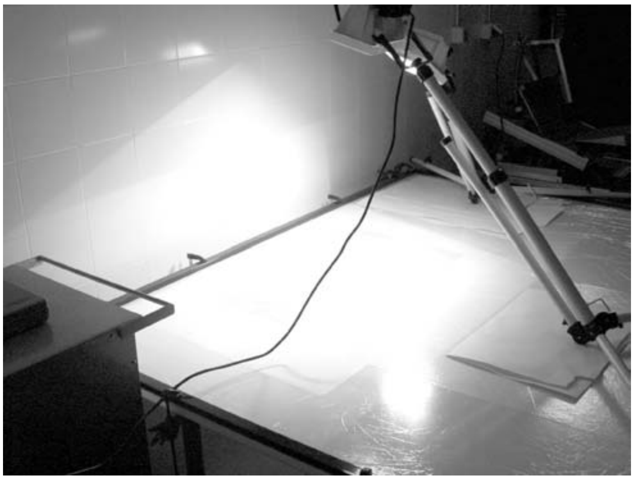

Figure 5. A sheet is being flattened with a new flattening technique which has been recently developed within the IRP. The sheet can be observed as a light grey rectangle]

easy solution: new textures can be imprinted upon the sheet, but the results are seldom satisfactory.

Water molecules do occupy some space, so that the sheet is also larger than it is when in a dry state – in three dimensions. It gets thicker, as has just been discussed, but it also becomes bigger both in height and width. The growth of the sheet can be expressed as a percentage: larger sheets grow more than smaller ones, and in the case of sheets made of the same type of paper, this growth is proportional to the size of the sheet. An increase in the thickness of a *single* sheet may require a special measurement tool for it to be noticed; however, for this same reason, the increase in the height and width of the sheet is clearly more noticeable in these cases.

Different papers can experience very different degrees of wet-growth, depending on its size, calendering, compactness, fibre type, etc. When the wet paper is put under pressure, it is fixed in a flat position, with pressure exerted upon its entire surface. As it dries, the water molecules abandon the paper, which reacts by contracting. However, if the paper is under pressure, it will not be allowed to freely move. The fibres in the paper then readapt themselves to their new position and size. The result is that a flattened sheet usually emerges out of the process not only flatter than it was, but also different in size. The flattening of the sheet is a positive effect on the process, but the variation in the size of the sheet is an unwanted, negative effect. In many cases, this can be tolerated, but in some others it is clearly damaging for the perceived historical integrity of the object. Consider, for instance, the case of an architectural drawing made on transparent paper, measuring 1 x 0.7 m: after pressure flattening, such a drawing may have increased its dimensions by 5 cm. Admittedly, this is an extreme, non-representative case. however, according to our experiments, most machine-made papers have their size increased by between 0.5 and 1% in the cross direction after regular pressure flattening. This is especially important in the case of artifacts which are made up of several sheets of paper. Consider for example the case of a large drawn map consisting of several sheets glued together: since the variations in size are rarely exactly equal even between seemingly similar types of paper, it is rare indeed that the sheets can be safely pieced back together without resulting in line-*breaking* at the edges between sheets. This same problem is often experienced when re-binding sheets which have been pressure flattened: some sheets protrude out of the book block, giving a poor appearance.

THE NEED TO ASSESS SIZE CHANGE

The paper conservation group of the Instituto de Restauración del Patrimonio has developed a flattening system which could help in alleviating the size variation problem. The system puts the sheet under pressure by means of a thin, transparent sheet and a non-woven fabric. Among other advantages, the system allows the sheet to be monitored as the flattening process proceeds (figure 5).

This property may be useful both in a practical and a scientific sense. While there have been a few research works on this topic, none of them has been carried out from the point of view of the paper conservator; furthermore, no research has been made on paper sheets which have dried under the conditions present in conservation pressure flattening. By watching a relevant number of sheets as they are flattened using the new system (which is under development) existing patterns can be revealed, thus allowing us to forecast variations in the future. Perhaps the point at which a sheet contracts most could be established and also the moment of the drying process at which it should be necessary to apply more or less pressure in order to reduce the problems outlined above without compromising the results of the whole flattening process.

On the other hand, even if patterns exist and are detected, monitoring each particular sheet as it dries could allow the point at which it reaches the desired or expected size us to more precisely know, thus providing knowledge of when to apply higher pressure to *lock* it in place.

However, this can be time-consuming. While scientific observations could be made with the help of a simple time-lapse camera, this system would not work when monitoring a real-life flattening treatment. In these cases, information needs to be gathered in real time, in order to react to it as soon as possible. However, this can also be time-consuming. The drying process of a common paper sheet which is being pressure-flattened can take three or four days. A systematic, continued observation of a drying process is beyond any expectation, as it would take up an absolutely unreasonable amount of work time.

In order to solve this technical and scientific problem, a collaborative research project was developed between the IRP and the Instituto de Automática e Informática Industrial of the UPV (ai2). The following article describes the development of an artificial vision system which is both reliable and affordable – that is, a system which can be used by practicing conservators working in real-life conditions.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the support from the "Universidad Politécnica de Valencia" for partial funding of this work, under project number PPI-20040908.

BIBLIOGRAPHY

Fieux, R. (1980): "Means and method of restoring documents, paintings and the like". United States Patent Appl. No. 152,168. May 22, 1980.

Futernick, R. (1984): “Methods and Makeshift”, *The Book and Paper Group Annual* **3** 65-74.

Keyes, K.M., “The use of friction mounting as an aid to pressing works on paper”, *The Book and Paper Group Annual* **6** 102-104.

Sugarman, J.E., and Vitale, T.J. (1992): “Observations on the drying of paper: five drying methods and the drying process”, *Journal of the American Institute for Conservation* **31** 175-197.

Weidner, M.K (1993): “Treatment of Water Sensitive and Friable Media Using Suction and Ultrasonic Mist”, *The Book and Paper Group Annual* **12** 75-84.

Weidner, M.K., and Zachary, S. (1994): “The System: Moisture Chamber/Suction Table/Ultrasonic Humidifier/Air Filter”, in AA.VV., *Conservation of Historic and Artistic Works on Papers. Proceedings (Ottawa, 3-7 october 1988)*, Canadian Conservation Institute, 109-115.

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Versión española

TÍTULO: ***Comprendiendo el alisado del papel (I). Principios y problemas de las principales técnicas de alisado***

RESUMEN: *El alisado del papel es un tratamiento muy común en la conservación de papel. Los restauradores han desarrollado un buen número de técnicas para este fin. Sin embargo, los principios que se encuentran detrás de estas técnicas no siempre son bien comprendidos. Además, estas técnicas conllevan a menudo efectos indeseados, que con frecuencia pasan inadvertidos. La alteración del tamaño original de la hoja de papel alisada es uno de los efectos colaterales más importantes. Sin embargo, hasta ahora ninguna investigación ha podido resolver este problema. Este escrito describe algunos de los resultados teóricos y prácticos de un proyecto de investigación interdisciplinar desarrollado por el IRP y el ai2 en este sentido. En este artículo se presenta un análisis de los principios del alisado del papel, y se comentan problemas frecuentemente desconocidos por los propios restauradores. También se plantea la oportunidad de un sistema para la estimación de las variaciones del tamaño de las hojas de papel.*

PALABRAS CLAVE: *conservación, restauración, alisado del papel, enlace del hidrógeno, tamaño, hidratación, presión, tensión*