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SOME OBSERVATIONS ON THE NATURE OF PAPYRUS BONDING

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ABSTRACT.—Papyrus (*Cyperus papyrus*, Cyperaceae) was a multi-use plant in ancient Egypt. Its main use, however, was for the production of laminated leaves which served as writing material in the Mediterranean world for almost 5000 years. Being a royal monopoly, the manufacturing process was kept secret. Plinius Secundus, who first described this process, is unclear as to the adhesive forces bonding the individual papyrus strips together. Various authors of the past century advanced their own interpretation on bonding. The present authors believe that the natural juices of the papyrus strip are sufficient to bond the individual strips into a sheet, and that any additional paste used was for the sole purpose of pasting the individual dried papyrus sheets into a scroll.

RESUMEN.—El papiro (*Cyperus papyrus*, Cyperaceae) fue una planta de uso múltiple en el antiguo Egipto. Su uso principal era la producción de hojas laminadas que sirvieron como material de escritura en el mundo meditarráneo durante casi 5000 años. Siendo un monopolio real, el proceso de manufactura se mantenía en secreto. Plinius Secundus, quien describió este proceso por primera vez, no deja claro qué fuerzas adhesivas mantenían unidas las tiras individuales de papiro. Diversos autores del siglo pasado propusieron sus propias interpretaciones respecto a la adhesión. Consideramos que los jugos naturales de las tiras de papiro son suficientes para adherir las tiras individuales y formar una hoja, y que cualquier pegamento adicional se usó unicamente para unir las hojas secas individuales para formar un rollo.

RÉSUMÉ.—En Egypte ancienne, le papyrus (*Cyperus papyrus*, Cyperaceae) était une plante à utilisations multiples. Cependant, son utilisation principale était la production du papier laminé utilisé pour la rédaction de documents dans le bassin Mediterranéen pendant près de 5000 ans. En tant que monopole royal, le procédé de fabrication était resté secret. Plinius Secundus, qui a été le premier à décrire ce procédé, demeurait imprécis quant aux forces d'adhésion maintenant les fibres du papyrus ensemble. Différents auteurs du siécle passé ont avancé leur propres interprètations de ces liaisons. Les auteurs du présent article pensent que les jus naturels des tiges de papyrus suffisent pour lier les bandes individuelles en une feuille et que toute colle utilisée en plus avait pour seule fin de coller les feuilles de papyrus entre elles en un rouleau de papier laminé.

INTRODUCTION

Laminated papyrus was the writing material of the Mediterranean world for over 5000 years. The oldest papyrus in existence is an uninscribed roll from the tomb of Hemaka at Saqqarah, in the first dynasty, and is about 5200 years old. Papyrus was the vehicle through which knowledge passed from one generation to the next. It was partially replaced by parchment and vellum and later by linen pulp paper, which was invented by the Chinese some time before A.D. 105. The Arabs learned this true paper-making process from prisoners at the siege of then Chinese Samarkand in A.D. 751. Baghdad soon saw the establishment of the first Arabian pulp paper factory in A.D. 795. Being easier and more economical to make, such pulp paper-making resulted in the abandonment of both papyrus-making and the cultivation of papyrus on plantations. Thus, in the second half of the tenth century, the famous Egyptian papyrus protopaper manufacture died out, as did soon afterwards that near Palermo, where papyrus probably was introduced by Arab merchants before A.D. 972. Today there are small industries at Syracuse in Sicily, and at Giza, Cairo, producing primarily papyrus souveniers for the tourist trade.

Papyrus, *Cyperus papyrus* L. (Fig. 1), was a multi-use plant. The flowering heads were used as garlands; the roots as food, fuel, and for making utensils. The culms, or stalks, were used in early architecture, for shelter, boats, sails, mats, baskets, cloth, sandals, cordage, as well as for food, incense, medicinal ash, and for many other uses (Täckholm 1941:102–133). Above all, papyrus was used for the production of laminated protopaper (Fig. 2) used primarily for scrolls.

Papyrus scrolls served as currency in Egypt's foreign trade and topped the export lists along with linen textiles. The royal house proclaimed papyrus manufacture and trade a state monopoly, allowing no private production of it. Thus, no records of papyrus sheet-making were depicted in tombs or temple paintings, cut into stone, or written on papyrus itself.

The papyrus plant is a perennial reed which grows in lakes and pools in shallow, stagnant water. From its pith *(bublio),* leaves *(scrools)* or books *(biblos, biblion)* were made which, by 670 B.C., were traded to the Greek world through the Phoenician port of Gubal. The Greek word for papyrus reed *(bublos)* is reflected in Byblos, the Greek name for this port. The origin of the term *papuros,* attested in Greek since Theophrastus, is thought to be of Egyptian origin, meaning "that of the king." The words *paper, papir, Papier, papel,* and *papiro* are all derived from it.

PAPYRUS MANUFACTURE

The classical reference on ancient papyrus manufacture is Pliny's (A.D. 22–79) *Natural History XIII,* 74–82. He probably never saw papyrus sheet production himself, but must have had it explained to him. After explaining different grades of papyrus, he writes: "texitur omnis madente tabula Nili aqua. turbidus liquor vim glutinis praebet" (Plinus XIII, 77, 1967:443) (Every [type of paper] is fabricated on a board moistened with water from the Nile; the muddy liquid supplying the strength of glue) (retranslated by the authors).

Basically, a papyrus sheet is made by carefully cutting a papyrus culm into pieces of desired sheet length (in ancient times, about 40 cm), peeling the rind off these, and slicing the pith into thin layers from the narrowest of the three angles of the triangular stem to the middle of the opposite side. Further cuts are

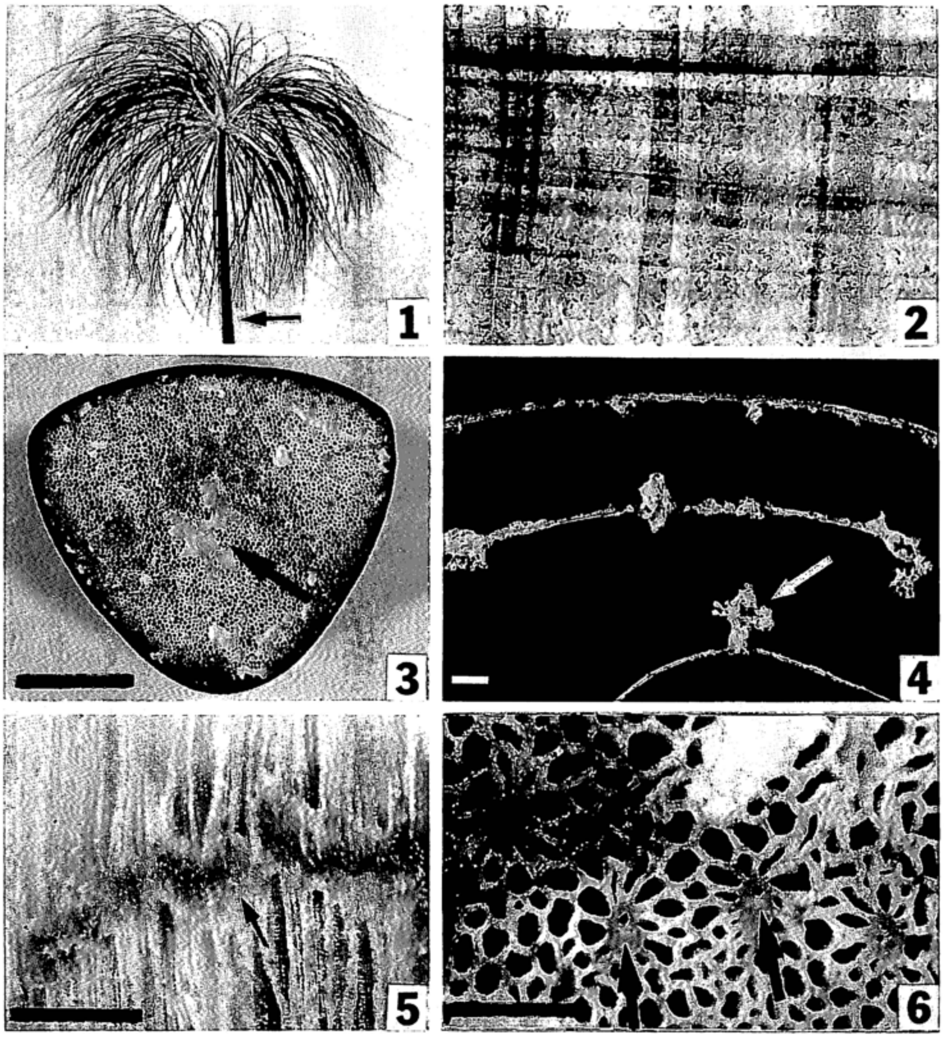

FIG. 1—6. (1)—*Cyperus papyrus* floral head and culm (arrow). 1/10 natural size. (2)—Laminated papyrus paper sheet with small specs. 1/2 natural size. (3)—Cross section of papyrus culm with polysaccharide exudates (arrow). Bar equals 0.5 cm. (4)—Fibrovascular bundles with polysaccharide exudate (arrow) after cellulase-pectinase digestion. Bar equals 2 mm. (5)—Phloem bundle exudate (arrow) traversing longitudinally cut culm cells. Bar equals 1 mm. (6)—Cross section of papyrus culm showing distances between fibrovascular bundles (arrow). Bar equals 1 mm.

then made parallel to this longest cut. These strips are leached in water until translucent, and pounded. Then, while still moist, they are laid horizontally on a board, one above the other overlapping by 1–2 mm. A second layer is then laid at right angles vertically covering the first layer, and both are pounded and subsequently pressed together until dry. Hendriks (1980), as well as Wallert (1989), propose that next to this strip method, papyrus may also have been made by the peeling method.

After drying, the edges of the sheets are cut straight and used individually or assembled to form a scroll, which often contained 20 or more sheets. Sheets are assembled all with the horizontal layers on one side and the vertical layers on the other, overlapping the right-hand sheet by about 1 cm. The overlap is pasted together with paste made from fine wheat flour and then pounded together. It is said that the invention of papyrus was important for the development of hieratic writing, which was written from right to left (Möller 1909:4). The individual characters, however, were written from left to right. Since a smooth flow of the writing brush was important, the overlap of the papyrus sheet had to be from the left to the right. The brushes were made from halfagrass, rushes, and split palm leaves. Later, a reed was cut and used as a pen. In antiquity, scrolls were prepared in factories. Individual scribes cut or augmented such standard scrolls themselves as needed by adding individual sheets or parts of another scroll. In some instances, the backside, or *verso,* was used to finish a story.

In order to protect the writing, a scroll was rolled with the horizontal fibers on the inside. In later times, scrolls were rolled around a shaft of wood, and both edges were reinforced with an additional vertical papyrus strip as protection from fraying. Papyrus was not folded; its resistance to folding was minimal. There were many qualities of papyrus used in ancient times. Pliny enumerates them in detail, and Dziatzko (1900:49–103) gives a good account of their various sizes.

THEORIES ON THE NATURE OF BONDING

Ever since interest in papyrus-making was kindled in the last few centuries, one point of the papyrus production procedure remained a mystery far into the second half of our century—namely, whether the horizontal and vertical layers of which a papyrus sheet consisted were pasted together with any type of adhesive. We shall consider a few opinions on this matter.

As Lewis (1974:22) points out, according to Theophrastus's *Historia Plantarum,* people chewed the papyrus stalk, raw, boiled, or baked ... and it was one of the three sweetest aquatic plants growing in Egypt. Bruce (1805:20), who described his paper-making attempts in Abyssinia and Egypt, added that it appeared to him "that the sugar or sweetness, with which the whole juice of this plant is impregnated, is the matter that causes the adhesion of these strips together." Both authorities implied that sugar was present.

From sugar to starch was only a small step. Thus, Täckholm (1941:102–133) reported that the papyrus rhizomes were starchy, and Lewis (1974:22) in a reprint of his doctoral dissertation of 1934 states that "next to providing the raw material for the paper of antiquity, the commonest use of the papyrus plant was as a foodstuff. The plant is, in fact, a fairly good source of starch.'' The *Introductory guide to the Egyptian collection* (British Museum 1964:81) suggested that the natural starch in the juice of the plant itself acted as adhesive. As late as the 1970s, Dimbleby (1978:48) wrote that for the manufacture of large papyrus sheets, wheat starch was added as an adhesive. However, Möller (1909:4), describing the pressing and pounding of the vertical and horizontal layers together, added: ''Wobei eine ganz dünnflüssige Gummilösung als Bindemittel diente'' (whereby a very thin rubber solution served as binding agent), and von Wiesner (1928:676) stated that for adhesion, ''ein Kleister benutzt (wurde) der aus unreiner Staerke, vielleicht aus Mehl, bereited wurde'' (an adhesive was used which was made out of impure starch, perhaps of flour)(translations by the authors).

Cerny (1952:3–36) noted that the fibers of ancient papyrus were joined together by an adhesive soluble in water, probably gum arabic or egg white. And Forbes (1954:244) wrote that ''the gum produced by *Acacia nilotica* was used in making papyrus.''

The *Encyclopedia Judaica* (1971:71) noted that paper was made from the stalk '' ... which was cut into fine strips and stuck together in length and in breadth with glue—the *kolon shel soferim* (''scribes glue'') ... '' Other advocates of imagined paste, as well as those who believed it was not necessary, are listed in Lewis (1974:21–69).

CHEMICAL INVESTIGATIONS

The present authors, however, did not detect any sweetness in taste tests. Nor did they detect any starch in tissues of the rhizomes or in those of the culms, which they tested at different growing stages with I_2KI, potassium triiodide. Neither starch nor pectic substances had been detected by Buchala and Meier (1972), who investigated the inner white tissue of papyrus culms, finding fructose, glucose, sucrose, and other oligosaccharides, and traces of polysaccharides in aqueous and 2% ammonium oxalate extracts of the plant material. Reynolds (1967) did not detect any starch, and postulated that galactans and arabans which he isolated in the stem sap served to glue the papyrus strips together, aided to some degree by other carbohydrates and by nitrogenous and phenolic polymers. Both of the latter authors analyzed greenhouse-grown plants.

Votocek (1937), working on dried papyrus strips, had already isolated water-soluble glucose and fructose. By hydrolysis of hemicellulose, he obtained xylosans and glucosans and by hydrolysis of cellulose he obtained d-glucose.

Muthuri and Kinyamario (1989) found 10.9% of crude protein in juvenile umbels and 3.9% in juvenile culms. This percentage dropped to 4.2% and 1.9% in dead tissue, respectively. Thus, the nutritive value of papyrus for grazing potential was similar to East African range grasses. McGovern (1982) found that 13% of the parenchyma pith tissue had lignified in mature papyrus culms, and de Seabra (1955) reported that cortical papyrus culms contained 49% of total cellulose.

Our investigation did not detect any starch nor did that of Buchala and Meier (1972). This is in direct contrast to the reports of Täckholm (1941:102–133) and Lewis (1974:21–69) that starch was present in papyrus. Our inability to detect any sweetness in papyrus is also in contrast to the report of Theophrastus and to that of Bruce (1805).

We believe that sugars may be present as fructans, long chains of fructose molecules, common in grasses. Laboratory hydrolysis releases the fructose molecules which are very sweet and also the sucrose present at the ends of the long chains. This would account for the finding of these molecules by Buchala and Meier (1972). Boiling and baking would also hydrolize the fructans and explain the statement by Theophrastus. Bruce's remark (1805) we can only try to explain by the fact that at the end of harvest time, the fructans are converted into sucrose to be translocated to the rhizomes for storage and the possiblity that Bruce harvested and tested the papyrus just as the right time of translocation. Another possibility may include mutation of papyrus.

MODERN PAPYRUS MANUFACTURE

The art of papyrus-making has been resurrected in modern times. At Anapo, Syracus, Sicily, fabrication according to Pliny's description began towards the end of the eighteenth century by F.S. Landolina with local plant material from the river Ciane (Ragab 1980:94). Bruce (1805), in the late eighteenth century, made several pieces of papyrus both in Abyssinia and in Egypt. He described it as always thick and heavy, drying very soon, then turning firm and rigid, and never white. In Berlin, Ibscher produced satisfactory white papyrus leaves early in 1913 from plants grown at the Berlin Botanical Garden (Deissmann 1923:21–22). Gunn made good papyrus in Cairo from plants grown in his own garden at El Ma'adi (Lucas and Harris 1962:138). It was nearly white but, according to him, unfortunately marred by numerous small light brown specks (Fig. 2), which he thought could have been avoided by special precaution. A similar account was iterated by Cerny (1952:3–36). Von Wiesener (1928) thought they represented thin oblique vascular bundle strands connecting the regular vascular bundles. Ragab (1980) called them ''diaphragmes'' and Wallert (1989) ''interconnecting slanting thin fibrous bundles.'' These specks, in the opinion of the present authors, were amorphous polysaccharide exudates (Fig. 3, 4, 5) emanating from the vascular bundles (Fig. 6) into the surrounding parenchyma cells. We digested the cellulose of the middle lamella and the cell walls enclosing the middle lamella with a solution of 0.5% pectinase and 1.5% cellulase (Fig. 4). These exucates are genus specific and can be used to detect adulteration of some of today's papyrus with corn (*Zea mays* L.) or *Cyperus alopecuroides* Rottb., which grows abundantly in Egyptian waterways.

Following Gunn's method, Lucas, who had been previously unsuccessful making papyrus using dried stem material from the Sudan, succeeded in producing papyrus similar to Gunn's (Lucas and Harris 1962:137–140). More recently, satisfactory papyrus has been produced by Baker of the British Museum (Lucas and Harris 1962:137–140) and also by Hepper of the Royal Botanic Gardens at Kew (Reynolds 1967). In 1968, Dr. Hassan Ragab opened the Papyrus Institute in Giza and reintroduced papyrus-making as a cottage industry in that region.

He described the bonding of his modern papyrus as the hooking together of fibers during pressing and forming to hold the strips together (Ragab 1972). Later, he proposed that the cells of the strips formed dove-tail joints under pressing (Ragab 1978). Thus, the adherence was perceived to be more physical than chemical, with the vascular bundles strengthening the cross-laminated sheet in both directions. Later, however, he understood augmented adhesion to be due to increased pressure, which causes the squashed parenchyma cells to fill the open spaces of the interstices to form a very smooth structure (Ragab 1980).

McGovern (1982), interested in bonding mechanisms of various pith-containing plants, found that the parenchyma network was compacted in papyrus and corn mats which he produced by ambient press drying.

The present authors produced many cross-laminated papyrus sheets from fresh garden material harvested in 1988. We made papyrus sheets using their natural juices only. Many were excellent. Sheets made from dried papyrus slices, which prior to use were soaked in water for three days, also gave good adhesion for over three years. We do not recommend polishing the upper surface with stone, shell, wood, ivory, or pumice to remove blemishes, as mentioned by Plinius (XIII, 81), Täckholm (1941):102–133), Cerny (1952:3–36), Lucas and Harris (1962:137–140), and Bell (1985:146). Such polishing will disturb the smoothness of the outer pressed parenchyma tissue and may result in feathering of the ink. Any hole in a sheet or any thin area is easily patched by adding a fresh strip of the required length over the defective place and thoroughly pounding it until it merges into the rest of the sheet. Then the sheet should be pressed between felts until dry. Several changes of felts are necessary during the press-drying period.

We also tried various additives as mentioned by previous authors. We brushed a wheat flour slurry or egg white between the papyrus layers. These sheets later became stiff and hardly flexible, however. Additional sheets made from macerated and pressed pith tissue were coarse and not at all suitable for writing upon. Other sheets made from macerated pulp into which wheat flour (5%) or egg white (3%) had been added were strong and smooth to write on (Figs. 7, 8), but extremely stiff. To investigate the theory of interfelting, we pressed sheets from macerated pulp from which all protoplasmic cell parts had been flushed away, so that only the fibrous material was left (Fig. 9). These sheets held together firmly, but were not at all suitable for writing because of the coarseness of the fibrous material.

In our culm material, we observed the spacing of the monocot xylem and phloem bundles to average 1.2 mm apart (range 0.6–2.0 mm) (Fig. 6). Pith slices cut lengthwise from the lowest 30 cm of culm above water level averaged 2 mm in thickness. Pressing these pith slices together compressed the density of the fibrovascular bundles in a papyrus sheet more than six-fold after drying. As structural reinforcement, these bundles provide tensile strength in both directions of the laminated papyrus sheet. They also provide a framework around which hemicelluloses, including their exudates and other chemical substances naturally present in the compacted parenchyma, are firmly set and bonded. The lignified fibers (Fig. 9) were nonbonding. No dovetailing of joints was detected. We thus believe that the natural juices of the culms are sufficient to bond the individual

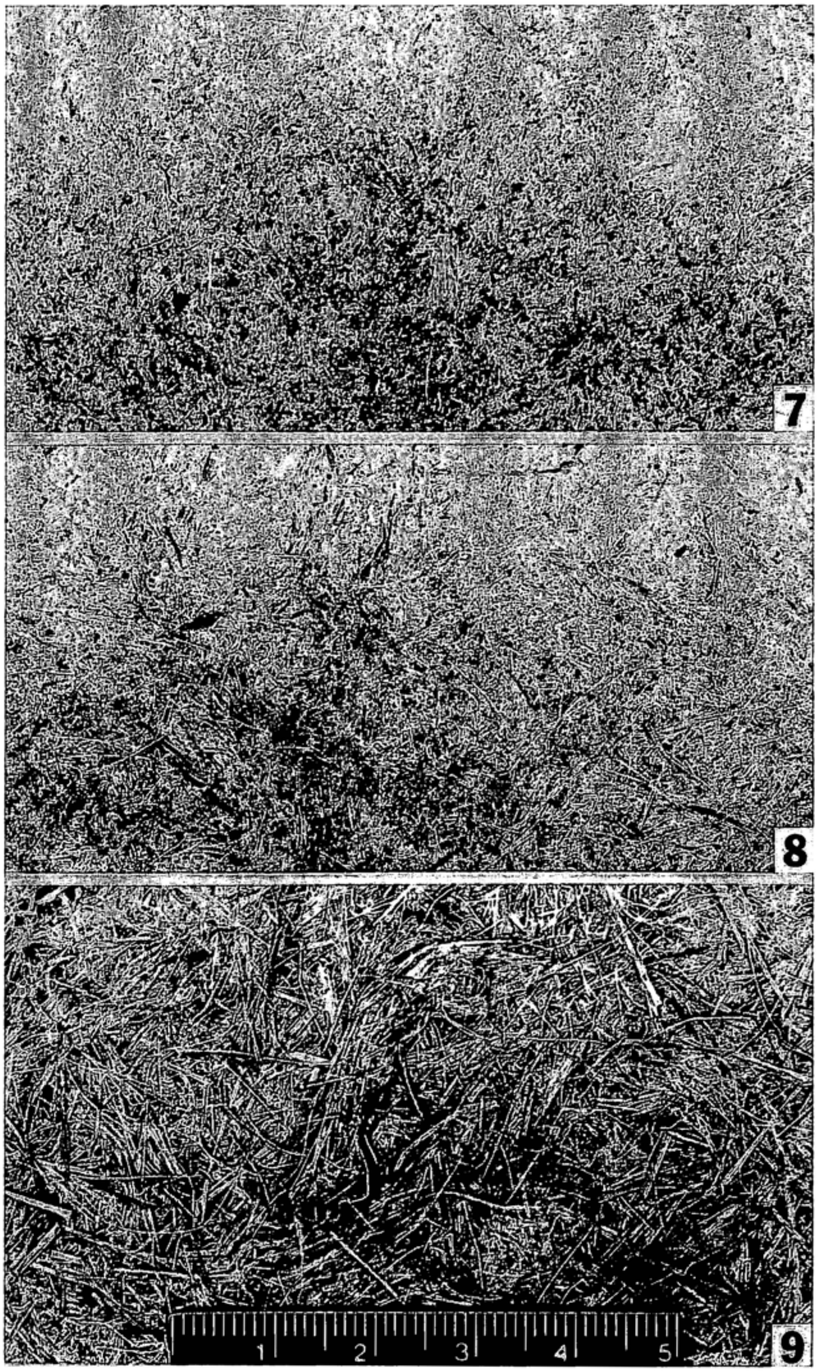

FIG. 7–9. (7)—Macerated papyrus pulp sheet with addition of wheat flour. (8)—Macerated papyrus pulp sheet with addition of egg white. (9)—Macerated papyrus pulp sheet with protoplasmic substances flushed away.

strips together. This suggests that any glue that might have been used such as mentioned in Plinius, referred to the pasting of dried papyrus sheets together to form a scroll, and not to the manufacture of a papyrus sheet *per se.*[1]

We would like to remark on the continuous peeling method suggested by Hendriks (1980) and Wallert (1989). Peeling 10 cm long debarked pieces of fresh papyrus culms with a needle continuously around the core presented no difficulties after initial trials. Peeling 30 cm long culm pieces (about the minimum size of many ancient papyrus sheets) presented various difficulties in peeling. Even large culm sections, with circumferences of about 8 cm, yielded a 9 x 10 x 11 cm wide strip, with one end 9 cm and the other end 11 cm wide. This difference was due to the acropetal tapering nature of the culm.

To produce a 30 x 30 cm large sheet, two layers of 3–4 such wide strips have to be assembled. Each strip has alternating orientation of the basal ends. The discarding of the rest of the culms represents an enormous waste of culm material. The additional time used for peeling versus cutting strips is not regained by speedier assembly. Our trials to continuously peel the culm material at successive stages of desiccation demonstrated that it was increasingly difficult to peel the culm with advanced desiccation. This suggests that after harvest in the swamps, the culms would have had to be speedily debarked, continuously peeled, and flattened.

NOTE

[1]Plinius (XIII, 82, 1967:445): ''glutinum vulgare e pollinis flore temperatur fervente aqua, minimo aceti aspersu, nam fabrile cummisque fragilia sunt. Diligentior cura mollia panis fermentati colat aqua fervente; minimum hoc modo intergerivi, atque etiam lini lenitas superatur omne autem glutinum nec vetustius esse debet uno die nec recentius, postea malleo tenuatur et glutino per curritur, iterumque constricta erugatur atque extenditur malleo.'' [Common paste made from the finest flour is mixed in hot water with a sprinkle of vinegar, for carpenter's glue and gums are brittle. A more careful process percolates hot water through the crumbs of leavened bread; by this method (such) a small amount (of paste) is placed (between the overlap) that even the softness of linen is surpassed. But all the paste used ought to be exactly one day old, not more nor less. Afterwards (the overlap) is flattened with a mallet and run over with paste, and then again has the creases removed and is smoothed out with a mallet.] (retranslated by the authors).

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