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Biodegradation and Characterization of Water-degraded Archaeological Textiles Created for Conservation Research

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Modern undyed natural fiber textile fabrics were experimentally biodegraded for use in archaeological textile conservation research. Specimens were exposed to soil burial in sandy loam, soil burial in peat, and prolonged soaking in unchanged distilled water for periods of 0.5–32 weeks. The degraded fabrics were evaluated by microscopic examination, chemical analysis, and physical methods of testing. Results of macro- and micromorphological analysis are reported. Fabric cross-sections were analyzed using light microscopy, and fabric, yarn and fiber surfaces were examined by scanning electron microscopy. Soil burial was more aggressive than prolonged soaking, and sandy loam more aggressive than peat except for the wool. Cellulose-based fabrics were less resistant to biodegradation than protein-based fabrics, linen was less resistant than cotton, and wool was less resistant than silk. Based upon visual assessment, the experimentally-degraded fabrics are similar to both water-degraded archaeological textiles and burial-induced degraded modern textiles reported by other studies. Copyright © 1996 Elsevier Science Limited

INTRODUCTION

Archaeological contexts are rarely sympathetic to the survival of textiles, yet frozen, waterlogged, and desiccated burial environments possess microclimates which often lead to the remarkable preservation of this material. Wet archaeological textiles are waterlogged or water-saturated in that all pore spaces are filled with water; in addition, they are, to some degree, water-degraded in that microorganisms have degraded the textile, often consuming material so that the physical structure has weakened (Christensen, 1970). There has been little systematic study of how wet or frozen burial contexts alter the basic chemistry and morphology of natural fiber textiles; yet, it is these alterations which decisively influence the post-excavation conservation requirements of these materials.

Natural archaeological textiles are characterized by a high degree of variability and therefore are rarely suitable for experimental research because variations in results can be attributed to the nature of the specimen rather than the particular conservation treatment under investigation. A study was carried out to investigate the creation of research archaeological textiles in which burial alterations are simulated by experimentally degrading modern materials (Peacock, 1993). These textiles would have a known history and well-characterized properties thus would be useful for research on the conservation and characterization of archaeological textiles, and for the practical training of textile conservators. The present paper reports the laboratory simulation of wet archaeological burial environments, and the macro- and micromorphological patterns of burial-induced decay of modern textile fabrics subjected to laboratory soil bed burial.

EXPERIMENTAL

Fabrics

Test fabrics selected for use in this study consisted of four undyed, woven 100% natural fiber fabrics: dryspun, unbleached linen (*Linum usitatissimum* L.); bleached cotton (*Gossypium*); degummed silk crêpe de chine (*Bombyx mori*); and worsted wool flannel (*Ovis*). Fabric specifications are presented in Table 1. The unbleached linen was a fabric produced for testing (Lambeg Industrial Research Association, Northern Ireland), as was the silk crêpe and wool flannel (Testfabrics, Inc., USA; styles 601 and 526). The combed cotton fabric, Shirley Soil Burial Test Fabric (Shirley Institute, now BTTG, UK), is produced especially for soil burial testing (Walton & Allsopp, 1977; BSI, 1981; Sagar, 1988). This fabric is characterized by equally spaced colored stripes in the warp direction which are woven into the fabric to facilitate sampling for tensile testing.

Fabrics were preshrunk by wetting out in deionized water for 2 h, air-dried at ambient temperature, and conditioned according to BS 1051 (BSI, 1972). Fabric was cut into 10×5 cm (warp × weft) samples, and eight samples constituted one set. Control samples were stored in darkness at ambient temperature for the duration of the study.

Archaeological fabrics used for comparison were obtained from museums and universities in Norway, Denmark and the United Kingdom. These were both freshly excavated and dried woven linen, silk and wool textiles recovered from wet and frozen archaeological contexts. No naturally degraded woven cotton fabrics were obtained for this study.

Experimental degradation

Soil burial

Soils

Two types of soil were investigated: sandy loam BSI (British Standards Institute) complying with the requirements of BS 6085 (BSI, 1981) and a garden peat, hereafter referred to as burial loam (BL) and burial peat (BP). Soil pH was measured by the electrometric determination of a soil suspension following BS 1377, Test 11(A) (BSI, 1975). The amount of organic matter present was calculated by per cent loss in weight following ashing (% LOI) (Allen, 1989). Moisture content (MC) was measured by thermal drying to a constant weight according to BS 1377, Test 11(A) (BSI, 1975) modified for field-moist samples (Bascomb, 1974). The method was modified for analysis of the peat according to Head (1984). The percentage maximum water-holding capacity (MHC) was determined by absorption of water by capillarity to equilibrium followed by drying in an oven until a constant weight was reached (Rubidge, 1977). The burial loam (BL) had a soil pH of 6.51, a moisture content of 31%, a water-holding capacity of 43% and contained 18% organic matter. The burial peat (BP) had a soil pH of 3.65, a moisture content of 77%, a water-holding capacity of 43% and contained 95% organic matter.

Procedure

The test procedure was patterned closely after BS 6085 (BSI, 1981) supplemented by practical details from various textile industry and field ecology studies (AATCC, 1945; Batson *et al.*, 1944; Harrison *et al.*, 1988). Sturdy polypropylene storage bins (60×30×30 cm) were lined with polyethylene sheeting. The soil was passed, in the fresh condition, through a 5-mm mesh sieve into the bins. Two bins, each containing 45 l of soil, were prepared for each soil type.

Table 1. Test Fabric Specifications

	Cotton		Linen		Silk		Wool	
	Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft
Structure	Plain weave		Plain weave		Plain weave		2×2 twill	
Areal density (mg/cm^2)	26.53		39.01		8.40		30.18	
Ends/cm	34	18	14	13	58	45	26	28
Yarn								
Ply	2 S	2 S	–	–	–	–	2 S	–
Twist dir.	Z	Z	Z	Z	none	S, Z	Z	Z
Twist	light	light	light	light	none	light	light	medium
Colour								
NCS[a]	0500N		3010–Y20R		0502–Y		000N	
Munsell[b]	4.3GY 9.2/0.2		0.9Y 5.6/1.8		4.2Y 9.3/0.08		4.6Y 8.4/1.6	

[a]Natural Color System using artificial illuminant D_{65}. This illuminant is based on the spectral composition of daylight with a color temperature of 6500K.
[b]Munsell Color System using the CIE (Commission Internationale de l'Eclairage) standard artificial illuminant C which represents the light from overcast daylight (color temperature 6774K).

Two preliminary studies were carried out to determine both whether the fabrics were susceptible to microbiological degradation and the incubation periods for which there would be very little to appreciable fabric degradation. Small swatches of the test fabrics were exposed to the two soils using the baiting technique described by Parbery (1977) to assure that both soils would degrade all the fabrics. Another set of samples was buried in miniature soil beds patterned after Wälchi (1967) to establish the general rate of degradation.

Prewetted, non-sterilized samples were inserted vertically into the soil to a depth of 10 cm below the surface level with 2–3 cm horizontal distance between samples (SIS, 1977). Cotton and linen samples were buried together but in separate bins from the wool and silk specimens. The bins were covered to prevent excess water loss through evaporation and were stored in darkness at 65±2% RH and 21±2°C. Samples were buried for predetermined progressive periods of time based upon the miniature soil burial series. One set of specimens of each fabric type was incubated for each of four degradation periods (Table 2).

Samples were excavated carefully to avoid pulling and damage, and causing disturbance to the other specimens. Upon retrieval, samples were carefully brushed free of adhering soil, rinsed in deionized water, and sterilized in 70% ethanol at room temperature for 4 h according to BS 6085 (BSI, 1981). Sterilized samples were rinsed in deionized water and dried at ambient room temperature.

Waterlogging
Small glass aquarium tanks (10 l capacity) were filled with deionized water, covered, and stored in darkness at ambient room temperature. The soaking solution was not analyzed either prior to, during, or following prolonged soaking. Prewetted, non-sterilized fabric samples were freely suspended in the water. Separate immersion tanks were used for each fabric type. One set of specimens for each cloth type was experimentally degraded for each degradation period (4, 8, 16 and 32 weeks). Following removal, samples were treated in the same manner as the soil-degraded specimens.

Table 2. Periods of Soil Burial

		0.5	1	2	4	8	16	32	Weeks
Loam									
	Linen	X	X	X	X				
	Cotton		X	X	X	X			
	Silk				X	X	X	X	
	Wool				X	X	X	X	
Peat									
	Linen				X	X	X	X	
	Cotton				X	X	X	X	
	Silk				X	X	X	X	
	Wool				X	X	X	X	

METHODS OF ANALYSIS

The experimentally-degraded specimens were evaluated by microscopic examination, chemical analysis and physical methods of testing (Peacock, 1992, 1993, in press). The specific nature of the biodeteriorating microorganisms was not determined and no attempt was made to measure enzyme activities. Despite the innumerable microorganisms, the mode of degradation falls into limited decay patterns; therefore, species identification was of less relevance to, and beyond, the scope of the study.

Conditioning

Fabric specimens were conditioned prior to sampling. Samples were conditioned and tested in the standard atmosphere for testing textiles as defined in BS 1051 (BSI, 1972).

Microscopy

Light microscopy
Cross-sectional profiles of the experimentally degraded (initial and final degradation period) fabric specimens were analyzed. 0.5 × 2.5 cm (warp × weft) samples were embedded in Araldite CY.212/HY.956 resin to form a block. Thin cross-sections (0.5 mm) were cut from the block using a low-speed diamond saw (Isomet), and analyzed using an analytical light microscope (Olympus BH-2) with diffused transmitted illumination. These prepared fabric cross-sections show warp yarns in cross-section and transversing weft yarns.

Scanning electron microscopy
Experimentally degraded (initial and final degradation periods) fabric specimens and naturally degraded archaeological fabrics were analyzed. Samples were securely mounted on to 15 mm diameter aluminium stubs using electrically

conducting copper tape. The examination surface was then sputter-coated with a gold–palladium alloy. Coated samples were examined using a scanning electron microscope (ISI 100A) and 2 keV accelerating voltage.

RESULTS

Burial-degraded specimens became thinner and water saturated with increased burial time (Fig. 1). In sandy loam soil, cotton samples were thin and fragmentary following 4 weeks of burial, and linen specimens were severely deteriorated after 2 weeks. These fabrics were completely decomposed by the end of the burial period, 8 and 4 weeks, respectively. Silk and wool specimens were complete and intact following 32-weeks burial, but with thin areas. In peat soil, buried cotton and linen were almost completely decomposed after 32 weeks, but silk and wool were complete and intact.

All fabric samples were complete and intact, but with a slightly slimy surface following 32-weeks prolonged soaking. This was especially the case for the linen. The soaking solutions became cloudy but did not change color with the exception of that containing the linen samples which became densely cloudy.

Appearance

Specimens buried in sandy loam soil changed considerably in hue, value, and physical dimension. Value is the quality which describes lightness, darkness, tone or shade. Color changes were predominantly in the form of gradual to extensive staining. The bleached white colored cotton shifted to a yellow color and then became dark and fragmented. The straw colored linen became nearly black and fragmented, and shrank considerably. The off-white silk shifted to a yellow–orange color and became darker, and the white wool darkened and shifted to a yellow color, but there were no readily apparent change in physical appearance for these fabrics.

Burial in the peat caused changes in color and physical appearance (Fig. 1). Color changes were in the form of gradual to extensive staining. The bleached white-colored cotton became dark and

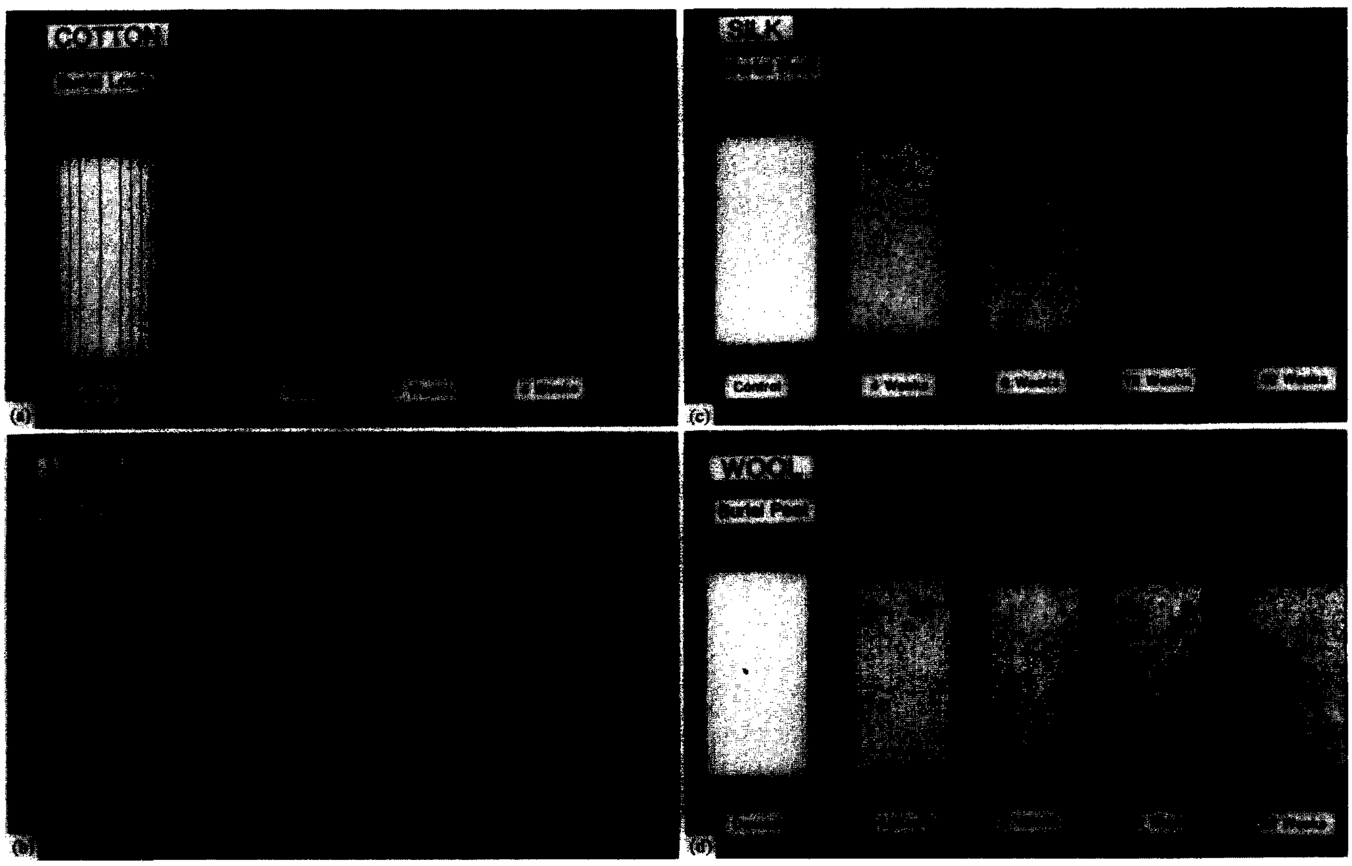

Fig. 1. Fabric specimens following soil burial (0.25×). (a) Cotton — loam; (b) Linen — loam; (c) Silk — peat; and (d) Wool — peat.

shifted to orange; linen became dark and shifted to red–brown. Cotton shrank in the warp direction and linen shrank in both directions, and both became fragmented. Wool and silk became dark and orange in hue and the wool shrank in the warp direction.

Prolonged soaking led to slight shifts in hue and lightness. There was little discernible difference in the cotton over the 32 weeks. Linen shifted to orange, then to yellow, and later developed a blackening along the edges. Wool and silk became dark and shifted to yellow. Physical or structural changes were not visible except for linen which exhibited some shrinkage at 32 weeks.

Microscopy

Light microscopy

Cellulosic fiber fabrics

Soil burial caused severe changes to both the cross-sectional structure and the degree of lightness of the cotton. Yarns shrank in upon themselves causing the fabric to buckle. Fabric shrinkage was more severe across the thickness of the fabric than in the weft direction. Although warp yarns became compact, they were not pulled closer together; thus, the resulting weave is more open than the new fabric. The water-degraded samples (32 weeks) became slightly dark with fewer surface fibers.

Linen became dark with yarns showing severe decomposition following soil burial. Yarns collapsed in upon themselves resulting in shrinkage in the weft direction and across fabric thickness creating a buckled weave. Little of the resulting weave structure can be distinguished for loam-degraded samples. Water-degraded specimens (32 weeks) exhibit darkened and compacted yarns with several warp yarns less bound to the weft yarns.

Proteinaceous fiber fabrics

Burial-degraded silk samples are darker and yarns became compact. The loam-degraded cross-sectional profile is more compact than the new silk. Yarns became compact and warp yarns are less bound to the the weft yarns following prolonged soaking. Wool samples have fewer surface fibers and appear darker and bulkier following soil burial. Water-degraded samples are slightly bulkier and have fewer surface fibers than the new wool.

Scanning electron microscopy

Cellulosic fiber fabrics

Cotton. Soil-degraded samples show severe organic decay of yarns. Loam-degraded yarns became flattened but the crowns did not collapse. The resulting weave structure is more open than the control fabric. There are no surface fibers, and yarns are composed of collapsed, extensively pitted and corroded fibers which have latched together forming a smeared surface over the yarns. There is longitudinal splitting and cracking of the fibrillar structure with loosening fibrillar bundles and chunks of the fiber broken away.

The peat-degraded two-fold warp yarns split into component yarns but did not collapse as severely as the loam samples. The resulting weave undulates in contrast to the planar new fabric. Surface fibers latch on to yarns which are also composed of pitted, decayed fibers. These are not as decomposed as the loam samples but there is more fibrillation.

The water-degraded fabric is bulkier than the new cotton, and shows no evidence of organic decay. The warp yarns increased in volume, and the fibers are bulkier and more loosely bound into the yarns. There appear to be more disorganised fibers on the surface.

Linen. There is a loss of definition of the fabric surface after burial in the sandy loam soil. Yarns collapsed and shrank resulting in flattened crowns and a netlike weave structure. The woody linen fibers exhibit broken ends, longitudinal splitting, cleavage, and cavities. They have been broken down into fibrils which have reacted like papier mâché and covered the surface.

Peat-degraded linen exhibits a different degradation pattern. The yarns decayed, but warp yarns retained their circular cross-section although they too became encased in a papier mâché-like material. Unlike the open weave of loam-degraded samples, peat samples shrank forming a tight, closed, concertina-like structure. Individual fibers exhibit less surface degradation than loam-degraded fibers but they have collapsed.

Yarns of water-degraded samples are slightly contracted and the fine structure has begun to separate. The crowns became slightly raised causing a buckled fabric morphology. Yarns and individual fibers are covered with a fine threadlike veil, but are not decayed to the same degree as the soil-degraded samples.

Proteinaceous fiber fabrics

Silk. Yarns in the soil-degraded silk became compact, and spacing in the warp direction decreased, causing a corrugated surface morphology, but the weave is more open than the new silk (Fig. 2). The surface morphology of the individual fibers does not exhibit obvious damage, with the exception of slight pitting of a few fibers. Deterioration was greater for loam-degraded samples. Soaking-degraded samples show some tightening of the yarns, shrinkage in the warp direction, and a corrugated fabric morphology. Several fibers in both peat- and water-degraded specimens exhibit very fine strands.

Wool. Wool buried in soil is characterized by fewer surface fibers. Spin and ply of warp yarns of the loam sample are coming undone and there are broken and severely fibrillated fibers. Spin and ply are intact in peat-degraded yarns and fibers lie closer together forming a more compact yarn. These fibers are characterized by longitudinal splitting and extensive fibrillation which has led to broken fibers. Damage is not confined to fibers lying on the very surface of the yarns. The spin and ply of the yarns is less orderly and the density of surface fibers in the water-degraded sample is greater than the control wool. There is no readily apparent damage to the fibers other than some sign of fibrillation, and scale patterns remained intact on unaffected fibers.

DISCUSSION

Unlike specimens subjected to prolonged soaking, it was not possible to monitor the progress of fabric samples buried in the soils. The miniature soil bed study provided guidelines for rate and degree of deterioration, and this was especially helpful in the latter stages when specimens were severely decomposed. With increased burial time, samples had a reduced ability to tolerate physical handling, and retrieval required specialized techniques used to excavate water-degraded textiles from archaeological contexts.

Specimens degraded by prolonged soaking were uniform because they were exposed to a uniform moisture content. There was little visible biodeterioration indicating that the initial soaking solutions did not contain an inoculum of microbes and the highly processed fabric specimens did not introduce any microbes. Linen degraded because impurities in the raw linen fabric activated a further retting of the material. Soil burial-induced degradation was not uniform and this is a general criticism of the method. Fabric specimens act as a wick conducting water from the surface downwards or from wetter horizons upward (Latter & Howson, 1977). There was more variation within each set of soil-degraded cellulose-based fabrics than protein-based fabrics, and greater variation for the loam-buried fabrics than for the peat-buried fabrics. Janaway (1989) reported a variation between similarly field burial-degraded wool, silk and linen fabrics, with linen being the most variable.

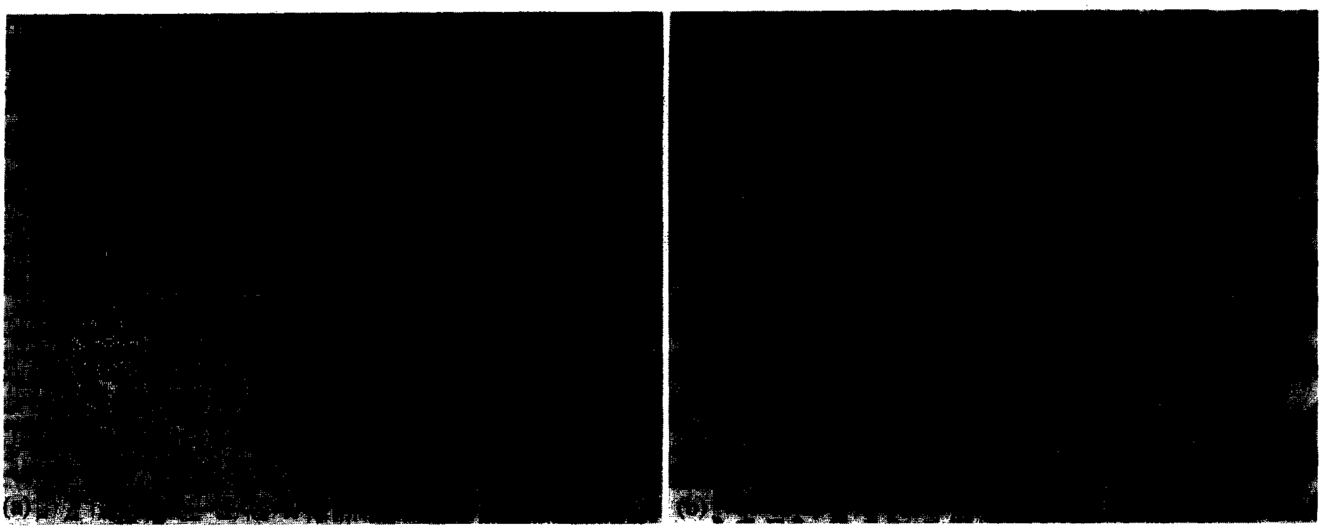

Fig. 2. Experimentally-degraded silk (15/30×). (a) New fabric; (b) loam-degraded (32 weeks).

A biodeterioration method based upon a combination of soil burial and prolonged soaking would resolve some of these problems. A method similar to that used by Nilsson (Nilsson, T., The Swedish Agriculture University, personal communication, 1990), Omar *et al.* (1989), Yamane and Sato (1967), or Mortimer (1941) would combine the microbiological activity of soil with the waterlogging of prolonged soaking, thus reducing the variability of soil burial and increasing the degree of biodegradation of prolonged soaking.

Appearance

Burial-degraded specimens underwent considerable changes in appearance, but there was a dramatic difference in the degree of change in both color and physical condition between the cellulose-based and protein-based specimens. Cotton and linen were affected more quickly and more extensively by soil burial than wool and silk, and quicker in loam than in peat. Both experienced severe deterioration with linen experiencing more extensive changes. Wool and silk specimens became progressively dark with some signs of biodeteriation, but no apparent dimensional change. The overall visual changes in silk buried in peat were greater than those in wool, but changes in sandy loam were similar. This concurs with the generally held view that wool and silk are more resistant to microbiological attack than natural cellulose fibers (Marsh, 1947).

Field studies of weathering carried out in the textile industry, generally conclude that cotton is more susceptible to microbiological degradation than linen. The results of the present study in which linen experiences more extensive changes than cotton do not support this. In a literature review, Wessel (1954) cites Fargher (1945) who emphasized that most comparisons of cotton and linen have been based on tests of loom-state (i.e. unbleached) cotton cloth competing with linen produced from twice-boiled or boiled and bleached yarns, thus giving rise to the idea that linen is more resistant. Wessel concluded that scoured or bleached cottons are less susceptible to mildew than gray goods, and results in the present study correlate well with this.

Changes in color of cotton and wool specimens following burial in a sandy loam soil reported by Needles and coworkers (Needles *et al.*, 1986; Needles, 1987; Needles & Regazzi, 1987) were similar to changes observed in this study. The fragmentation, total decomposition, staining/ darkening, and loss of material experienced by the fabrics in this study are in general agreement with descriptions of wet archaeological textile materials (Schweger & Kerr, 1987; Cooke & Lomas, 1987), textiles subjected to laboratory study of simulated archaeological contexts (Tarleton & Ordeñez, 1995), and textiles buried in field simulations of archaeological contexts where cellulosic fiber fabrics were found less resistant to deterioration than proteinaceous fiber fabrics (Jewell, 1963; Evans & Limbrey, 1974; Janaway, 1987, 1989; Barford, 1979; Batzer *et al.*, 1983). The lack of staining and darkening of samples exposed to prolonged soaking is also seen in marine and limno-archaeological textiles which, although water-degraded, are not discolored to the extent that terrestrially wet-degraded archaeological textiles are, arctic textiles excepted.

Microscopy

Light microscopy

Burial-induced degradation caused changes in both darkness and cross-sectional morphology. The degree of increase in darkness and the degree of cross-sectional distortion of the fabrics were greater for the cellulose-based fabrics than for the protein-based fabrics. Fabric cross-sections showed that linen fabric was more affected by experimentally induced degradation than the cotton over similar periods of time. Soil burial degradation caused severe changes to both cotton and linen, but cotton was more resistant. Both fabrics became darker from the action of the soil solution and microbiological decomposition. As a result of the loss of substance by biological removal of cellulose, yarns shrank in upon themselves causing a buckled weave structure. This is seen in terrestrially water-degraded archaeological cellulosic fabrics. Water-degraded cotton and linen did not experience as severe darkening as the soil-buried specimens, and this is in agreement with marine and limno-archaeological textiles.

The silk and wool fabrics did not reveal any obvious changes in cross-sectional morphology following experimentally induced degradation, but both fabrics became darker after burial. Under similar burial and prolonged soaking conditions, the silk appeared to be more resistent to biodegradation than the wool, especially the burial-degraded samples. This may be partly because bacteria and fungi, that are able to degrade silk fibroin, were either not present or present in lower numbers than microorganisms capable of reducing wool keratin.

Scanning electron microscopy

Cellulosic fiber fabrics

SEM analysis did reveal severe changes in the specimens exposed to prolonged soaking or soil burial. The linen fabric was less resistant to degradation by these biodegradation methods than the cotton over similar periods of time. Linen experienced greater reduction in fabric density (loam) and shrinkage of fabric structure (peat) than did cotton. The surfaces became smeared at the fabric level by decomposed linen fibers; this pattern was evident at the yarn level in the cotton samples. The smearing of surface fibers and shrinkage of fabric structure corresponds well with the archaeological linen from the arctic that was examined (Fig. 3).

Both cotton and linen fibers were characterized by pitting, corrosion, splitting, and fibrillation. These changes are typical of microbiological degradation of cellulosic fibers (Clegg, 1940; Basu & Ghose, 1962; Nilsson, 1974b) and of natural or simulated wet archaeological cotton and linen textiles (Schweger & Kerr, 1987; Jewell & Dimbleby, 1966; Evans & Limbrey, 1974; Janaway, 1989; Jakes & Mitchell, 1992). SEM photomicrographs of microbiologically degraded cotton in deGruy *et al.* (1973) illustrate this same cracking and fibrillation. Collapsed cellulose fibers indicate interior biological decay, as the result of the loss of substance by biological removal of the cellulosic material and the formation of cavities (Nilsson, 1974a). Prolonged soaking caused the linen fiber bundles to separate into ultimates (i.e. individual fiber cells) probably by pectin-retting bacteria. The veil-like surface coating has been described by Nopitsch (1953) as thread-like or slimy colonies of water bacteria that cause textile assemblies to stick together.

Proteinaceous fiber fabrics

SEM analysis revealed obvious changes in wool and silk exposed to prolonged soaking or soil burial. There was tightening of yarns and fabric shrinkage in both fabrics, and fewer surface fibers in the wool resulting from surface tension during air drying following prolonged exposure to water saturation. The wool fabric was less resistant to degradation than the silk. Damage at the fabric level was more extensive for the wool with loss of order in ply and spin twist of yarns, and broken fibers, but there was some pitting and fibrillation in the silk.

Based upon damage at the fiber level, loam soil caused more damage to the silk and less damage to the wool than peat soil. It is suggested that there was a relatively greater availability of bacteria and fungi to produce enzyme hydrolysis of the silk fibroin in the higher pH (6.5) aerated loam soil. Wool fibers were broken and fibrillated, with transverse cracking and longitudinal splitting, and the beginning of breakdown into corticle cells especially in the specimens buried in peat. This fiber damage is in agreement with descriptions of natural and simulated wet archaeological wool (Schweger & Kerr, 1987; Cooke & Lomas, 1987; Hearle *et al.*, 1989; Tarleton & Ordeñez, 1995;

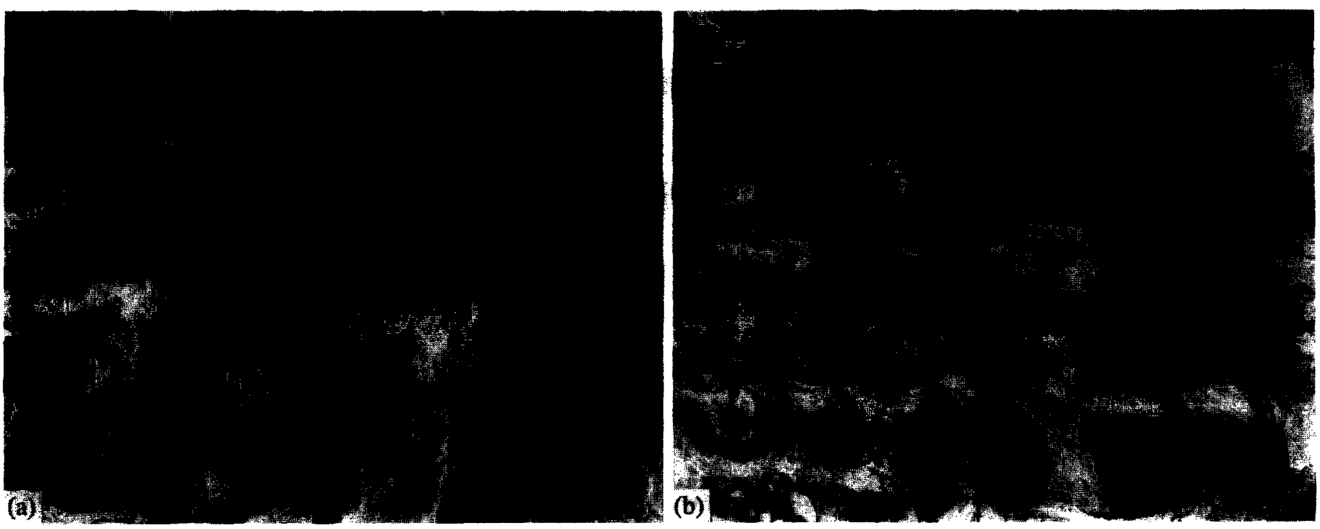

Fig. 3. Burial-degraded linen fabric (15/30×). (a) Archaeological textile from the arctic; (b) loam-degraded (2 weeks).

Jewell & Dimbleby, 1966; Janaway, 1989; Evans & Limbrey, 1974) and microscopical analysis of microbiologically degraded wool (Lewis, 1981; von Bergen, 1963).

The wool fibers revealed more damage than the well-preserved wet archaeological textiles examined (Fig. 4(a)). Similar fibrillation and breakdown into corticle cells are illustrated by photomicrographs in Lewis (1973) and McCarthy and Greaves (1988). However, the specimens did not exhibit the degree of pitting or loss of epicuticle which can be seen in the less well-preserved archaeological finds examined (Fig. 4(b)). In addition, neither hollowed-out tubes described by Gabriel (1932) nor lifting of scales as described by English (1965) and Race (1950) which are characteristic of more-degraded wet archaeological material were present. There was no evidence of the advance stages of microbial deterioration described in the literature where whole fibers separate into cortical cells. At this level of damage, however, fibers begin to disintegrate and there no longer exists a cohesive fiber assembly.

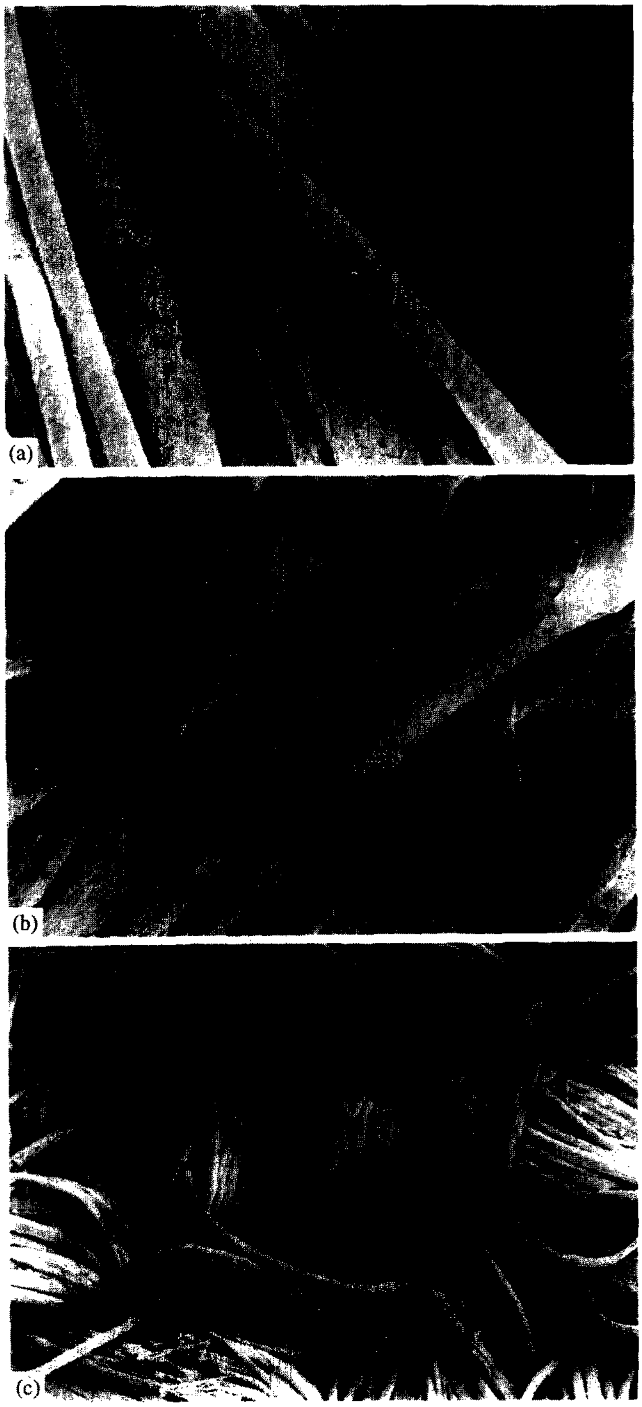

Fig. 4. Naturally- and experimentally-degraded wool. (a) Archaeological textile from excavations in Trondheim, Norway (270×); (b) archaeological textile from the arctic (350×); (c) experimentally loam-degraded specimen (32 weeks) (85×).

The lack of studies of microbiological degradation of silk limited comparisons with results of microscopical analysis of silk in this study. Analysis of the water-degraded archaeological silk specimens showed some fibrillation, errosion, perpendicular splitting, and pitting. The fibrillation or exfoliation (Mauersberger, 1947) seen in the experimental water-degraded silk was the start of very fine axial splitting called lousiness which can result from prolonged wetness (Lomas, retired, University of Manchester Institute of Science and Technology, personal communication, 1992), acid hydrolysis (Husemann, 1943), or boiling (Cadwallader *et al.*, 1941).

CONCLUSION

Experimentally induced biodeterioration was investigated as a method to simulate water-degraded archaeological textiles for conservation research. Soil burial caused fiber damage to all fabrics investigated. Linen was affected most severely, followed by cotton, wool and silk, respectively. Sandy loam soil was more destructive than peaty soil to the fabric and fiber morphology of the cotton, linen and silk, and less destructive to the wool. Prolonged soaking brought about some changes affecting linen and silk the most.

Patterns of damage were in agreement with descriptions of microbiological degradation of these fiber types, in both archaeological and experimental material, and were not characteristic of wear, mechanical damage, or the physicochemical damage of weathering. The principal agent of deterioration was microbiological, although chemical attack cannot be ruled out, as textile fibers can be denatured and degraded by soil chemistry. Freshly excavated specimens retrieved from the later periods of degradation resembled natural water-degraded archaeological textiles, and following air drying were disintegrating, buckled or stiff similar to natural archaeological textiles subjected to uncontrolled drying.

Degradation by soil burial was not uniform although desired patterns of damage in both general appearance and morphology were achieved. Degradation by the application of enzymes would also achieve these patterns, probably more uniformly and without the work involved in soil bed treatment. Soil burial introduces soil particulate matter and exposes specimens to other possible soil system interactions (e.g. dyestuff alteration). Characteristics such as adhering soil strongly influence the conservation requirements of archaeological textiles. Degradation by prolonged soaking was uniform but not extensive. A suggested method based upon a combination of soil burial and soaking would resolve these problems.

The soil-wet degraded textiles subsequently provided experimental material for research into the drying of water-degraded archaeological textiles. The sufficient number of representative test specimens with known history and well-characterized properties enabled proposing drying systems for natural archaeological textiles having varing degrees of burial-induced damage.

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