A mechanical study of the deterioration of coconut leaf thatch under natural and accelerated environmental conditions

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The deterioration of coconut leaf thatch, a cheap roofing material, has been studied by following the changes in strength on its exposure to both natural and accelerated environmental conditions such as natural weathering, accelerated conditions of rain and alternate wet and dry climate and micro-organisms such as fungus. Strength was found to decrease with time during deterioration. Scanning electron and stereo-optical microscopes were also used to study the fracture phenomena and surface changes during deterioration. It has been found that the major factors contributing to the deterioration of coconut leaf thatch are identified as rain, alternate wet and dry weather, decay by fungus and the brittle nature of the leaf itself. It appears from the present study that the deterioration of coconut leaf thatch occurs as a result of progressive embrittlement with possible contributions from environmental stress-cracking.

1. Introduction

Coconut leaf thatch is a cheap roofing material used widely in India (Kerala), Sri Lanka and in some Polynesian countries by millions of households. The leaves are available to the extent of 5.6 million tons in Kerala whereas the worldwide production may exceed 42.00 million tons. The large availability of this renewable resource can contribute much in solving the housing problem in the developing world. However, the thatch made from coconut leaves undergoes rapid deterioration and needs annual replacement. Although a number of empirical studies have been reported on the prevention of deterioration [1–3], there appears to be no fundamental work on the causes and mechanism of deterioration of coconut leaf thatch. The phenomenon of deterioration as applicable to lignocellulosic materials like wood is known to be a complex process which is yet to be satisfactorily understood [4]. In this paper, the progressive change in structure and mechanical properties of coconut leaf thatch with increasing exposure time to various environments (rain, alternate wet and dry conditions, micro-organisms such as fungus, etc.) under normal and accelerated conditions is reported.

2. Experimental procedure

2.1. Materials and methods

Since flexure and compressive behaviour of the leaves are not easy to measure, changes in tensile strengths have been used as a measure to follow the deterioration of coconut leaves in all experiments. Tensile strength was found to vary from leaf to leaf and leaflet to leaflet even in the fresh or undeteriorated leaves. In order to minimize the variation in measured strength between the specimens for a particular experiment, the following procedure was followed in all experiments. Coconut leaves at the bottom-most part of the crown of a mature coconut tree were cut when they started ripening. They were then dried to a moisture content of 15%. Specimen samples of the required size were then cut out from the leaflet at a distance of approximately 0.2 m from the petiole end of the leaflet and the rest of the

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leaflet rejected. The mean value of the property measured in each experiment was then computed for 25 samples.

2.1.1. Natural weathering studies

The coconut leaves were retted in water for two days and plaited. The plaited leaves (thatch) were tied to a bamboo frame and exposed to natural weathering during the south western monsoon. The experiments were carried out, one with the upper surface of thatch exposed and the other with the lower surface exposed.

2.1.2. Accelerated weathering studies

2.1.2.1. Rain and alternate wet and dry conditions. Specimens of coconut leaves were alternatively soaked in water for 4 h and then dried in an air oven at 50–60° C for 2 h for a number of cycles. Some specimens were also subjected to a water shower of force 2.6×10^5 MN m^{-2} for 2 h and then dried in an oven at 50–60° C for another 2 h and the cycle repeated 8 times in all.

2.1.2.2. Exposure to ultra-violet light. The leaf specimens were exposed to ultra-violet light of wavelength 320–400 nm using an ultra-violet lamp for a period of 100 h in a closed chamber.

2.1.3. Inoculation studies

A controlled humidity chamber at a temperature of 30° C and relative humidity of 90–95% was used for the study of decay by fungus [4, 5]. Decayed thatch containing mycelium or fungal spores were added to sterilized wheat bran which was used as the nutrient. Fresh dry coconut leaf strips were introduced into the chamber and samples taken out at regular intervals.

2.1.4. Strength measurements

0.06 m long and 5.0×10^3 m wide specimens were used for tensile testing on FG 100 or an Instron Testing Machine at an extension rate of 2.5 cm min^{-1}. The leaf specimens could be readily gripped and were breaking almost at the middle of the specimen.

2.1.5. Chemical analysis

Alkali solubility tests [6] were also used to follow deterioration by measuring the changes in lignin content of the leaves during deterioration.

3. Results and discussion

Fig. 1 shows a typical stress–strain diagram of dry coconut leaf. It can be seen that the leaf is elastic up to the point of rupture when it fails by brittle

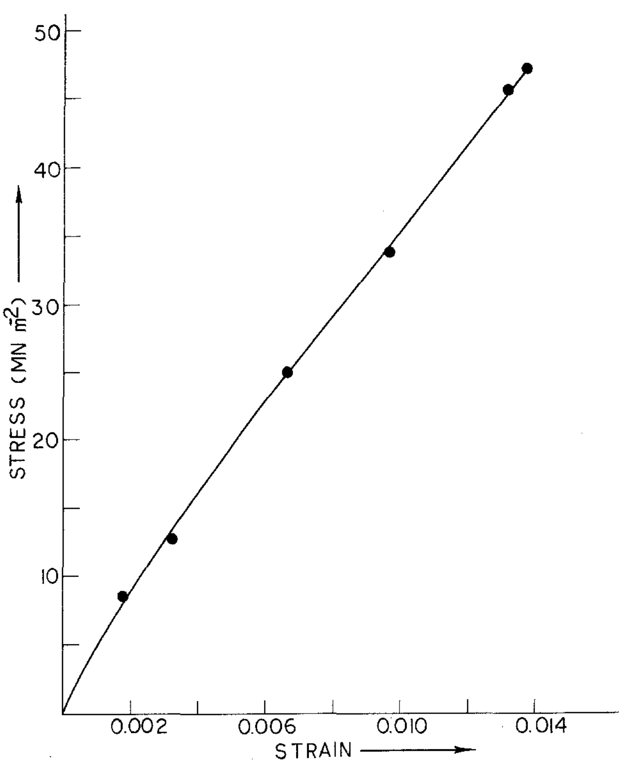

Figure 1 Typical stress–strain diagram of dried coconut leaf.

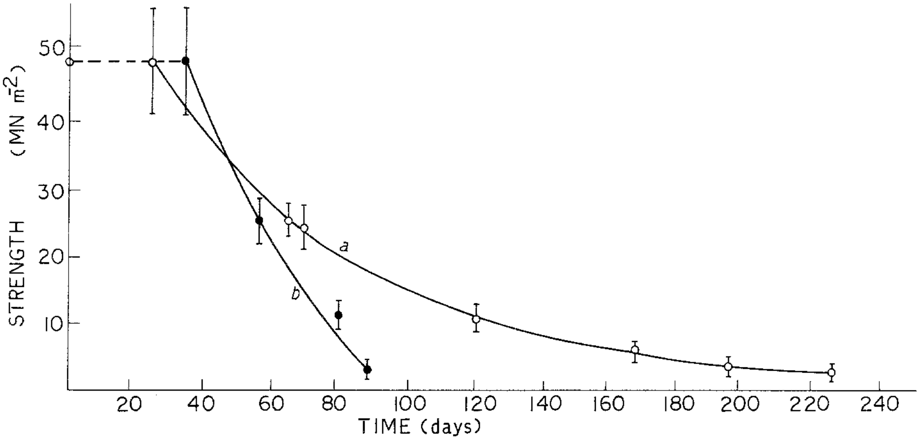

Figure 2 Variation in strength of coconut leaf thatch during natural weathering: (a) upper surface of leaf exposed; (b) lower surface of leaf exposed.

fracture similar to a brittle solid [7]. When exposed to natural weathering, the strength of the leaf decreased with time as shown in Fig. 2. There was an initiation period of about 30–40 days after which the strength began decreasing exponentially reaching an asymptotic value of 2.0 MN m^{-2}. The rate of decrease in strength was faster when the lower surface of the leaf was exposed to natural weathering (curve b, Fig. 2). The percentage reductions in strength were 90% in 230 days and 94% in 90 days, respectively, when upper and lower surfaces were exposed. The presence of a thicker waxy cuticular layer on the upper surface of the leaf may be the reason for the longer life of the thatch when the upper surface was exposed. During deterioration, reduction in strength has also been reported in the case of ligno-cellulosic material like wood [4]. The SEM fracture surface of the leaf before and after exposure (Figs 3 and 4) also show considerable changes. The portion which appears to be a set of tubes that

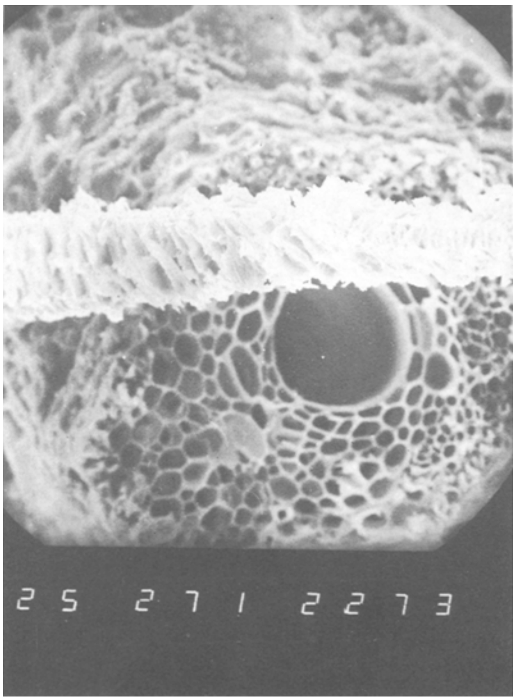

Figure 3 SEM of the fracture surface of dry leaf showing brittle fracture of the vascular bundles of the leaf, X 641.

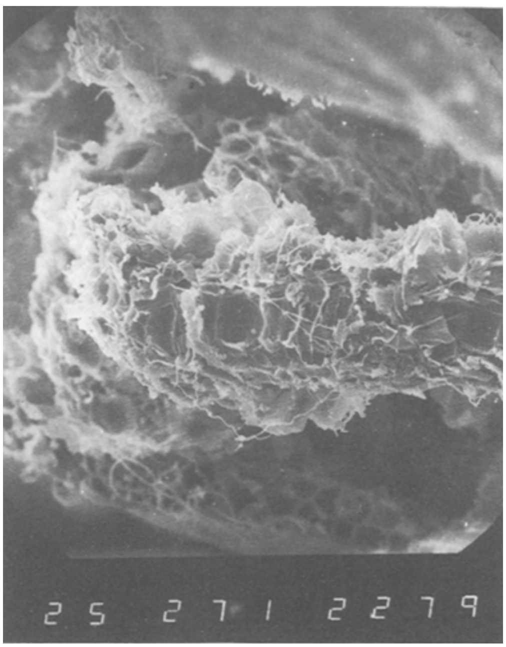

Figure 4 SEM of the fracture surface of the leaf exposed to natural weathering showing extensive damage to the cell, X 675.

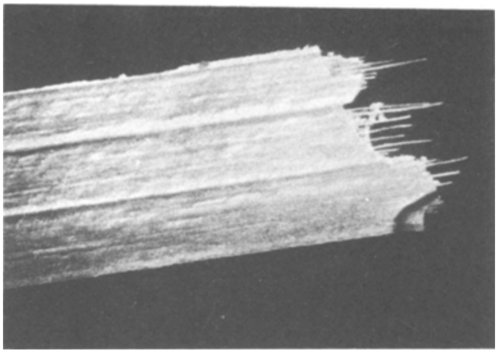

Figure 5 Fractograph of dry coconut leaf, × 8.

underwent a neat brittle fracture is the vascular bundles (conducting tissues of the leaf) [8]. The vascular bundles appear damaged after deterioration under natural weathering (Fig. 4). The fractographs of leaves (dry and deteriorated) when observed through an optical stereo-microscope are presented in Figs 5 and 6. In the dry leaf while there is zig-zag brittle fracture, some pull-out of fibres is observed. The weathered leaf appeared damaged and there is almost no fibre pull-out.

Considerable changes were also observed on the surface of the leaf during deterioration. The colour of the leaf underwent a change from pale brown to brown grey, greyish black and finally almost to black. Figs 7–10 show SEMs of the surface fractures of green, dry and deteriorated leaves. The green leaf showed almost a smooth surface whereas in the dry leaf, the cuticular wax on the surface of the leaf appeared flaky (possibly due to escape of moisture during drying). Extensive surface damage is indicated in Fig. 9 even after a few months' exposure to natural weathering. The cuticular surface layer seems to have been eroded due to wear or leaching by rain. As deterioration proceeds, the upper surface layers are worn off

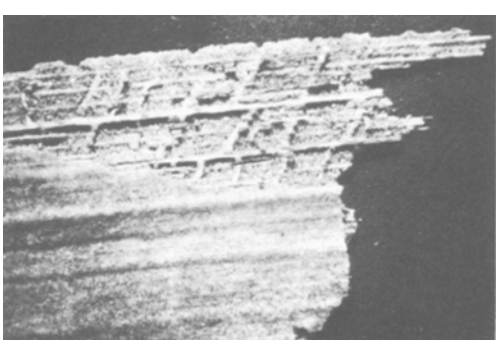

Figure 6 Fractograph of deteriorated coconut leaf, × 8.

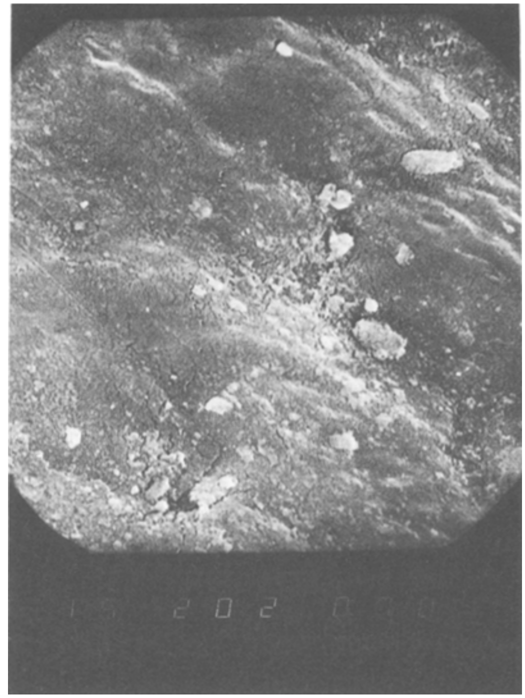

Figure 7 Scanning electron micrograph of the upper surface of green coconut leaf, × 2375.

and inner fibres (Fig. 10) at an acute stage of extensive damage are visible, indicating the role of weathering on the surface.

Table I lists results of alternate wet and dry

Figure 8 SEM of the upper surface of dry coconut leaf showing flakes of cuticular wax, × 2375.

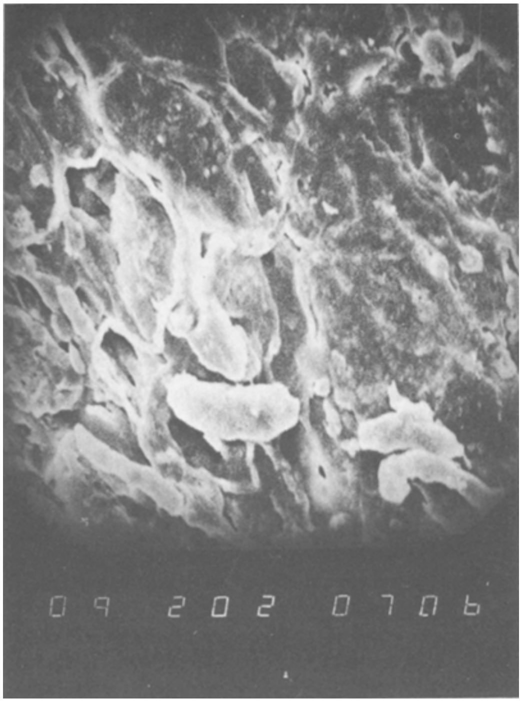

Figure 9 SEM of the leaf showing changes in the surface after exposure to natural weathering for a few months, X 2375.

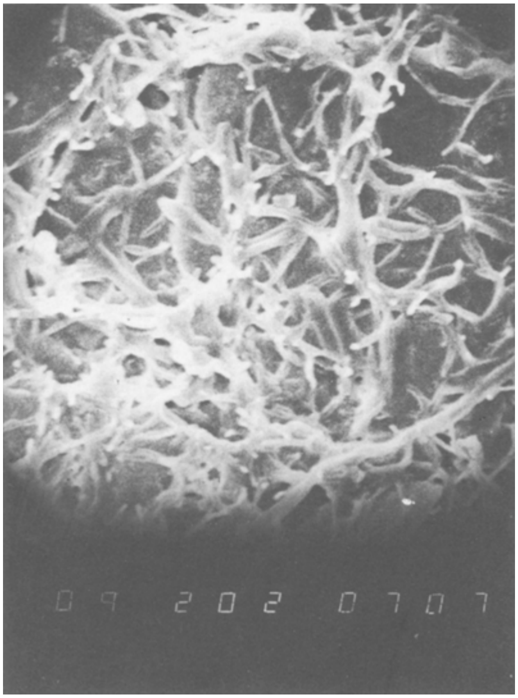

Figure 10 SEM of the leaf showing changes in the surface after extensive weathering, X 2375.

TABLE I Breaking load of coconut leaf subjected to alternate wet and dry condition for various periods

No. of cycles (4 h soaking 2 h drying)	Average breaking load (kg)	Sample standard deviation (kg)
Control	8.23 (dry leaf)	1.20
4	7.50	1.20
6	6.73	0.86
12	5.66	1.30
2 h shower and 2 h drying total eight cycles	5.01	0.81

experiments. It can be seen that the breaking load decreased from 8.23 kg to 5.66 kg after 12 cycles of alternate wet and dry experiments whereas it decreased from 8.23 kg to 4.6 kg within 8 cycles when the leaves were subjected to a shower treatment followed by oven drying at 50–60° C. It is clear from this experiment that the alternate wet and dry climate which is prevalent during the monsoon in this region may produce changes in the leaf contributing to failure. It is possible that the alternate wet and dry climate may produce cyclic swelling and contractions of the leaf which would result in the building up of compressive and tensile stresses on the leaf. Similar changes have been reported to occur on the surface layers of wood [4, 9]. Since the leaf blades are thin and their strength less when compared to wood, the changes produced by weathering on the leaf are much more extensive than those in the case of wood. Since the strength was reduced to a greater extent when a shower was used for the experiment, rain

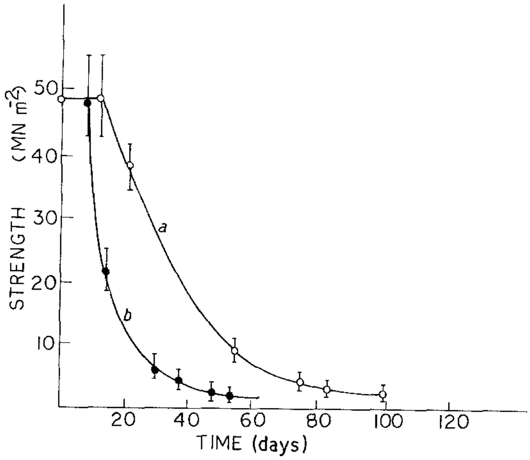

Figure 11 Variation of strength with time during fungal decay of coconut leaf thatch under controlled conditions (30° C and r.h. = 90–95%). (a) Lower concentration of fungus. (b) Higher concentration of fungus.

Figure 12 Surface preparation of dry coconut leaf showing growth of mycelium, × 150.

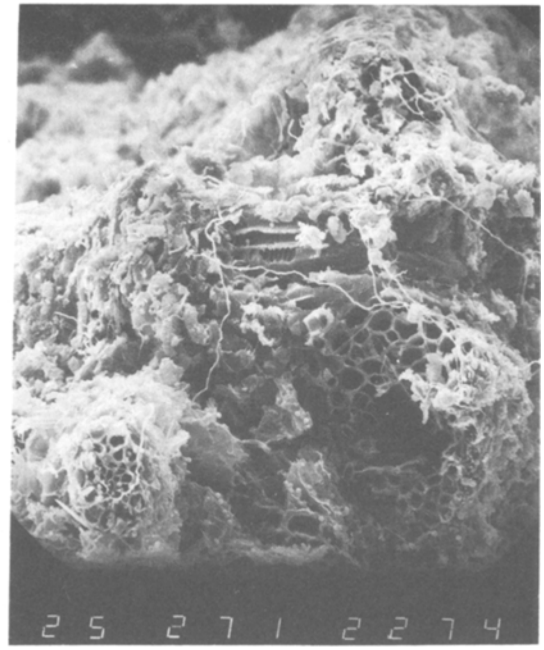

Figure 14 SEM of the fracture surface of fungal-attacked leaf. See that all structures of the vascular bundles are not much affected, × 540.

also can be considered a contributing factor to deterioration, apart from the wet and dry climate.

It is well known that micro-organisms like fungi grow on lignocellulosic materials and produce various changes in their properties [4, 5]. Fig. 11 shows that fungi reduces the strength of coconut leaf when allowed to grow on it under controlled conditions. The strength of the leaf is found to decrease asymptotically as in natural weathering but the initiation period is only 8–12 days. More than 90% reduction in strength occurs just after 30 days exposure to optimum conditions of growth. Fig. 12 is a picture of mycelium growing on the surface of the leaf and Fig. 13 indicates that the entry of the fungus into the leaf possibly takes place through the stomatal openings on the lower surface of the leaf. Fig. 14 shows the fracture surface of the coconut leaf after fungal attack indicating that apart from a few cells around the vascular bundles, the system as a whole seems to have lost its regular arrangements of cells. They appear to be a mass of amorphous material (rich in lignin which is shown to be increased in content by alkali solubility tests [6]) loosely packed with discontinuity of cell structure which enhances the brittle nature of the system.

Although a reduction in strength is observed during deterioration, it is interesting to note that there was an increase in strength of the leaf when the green leaf was dried to a moisture content less than 15% (see Fig. 15).

It is apparent now, that the structure and properties of coconut leaf thatch seem to be affected by deterioration during exposure to various environmental conditions. That rain and alternate wet and dry conditions of weathering contribute to deterioration is evident from Table I and also from the SEM picture of the surface at various stages of deterioration exposed to natural

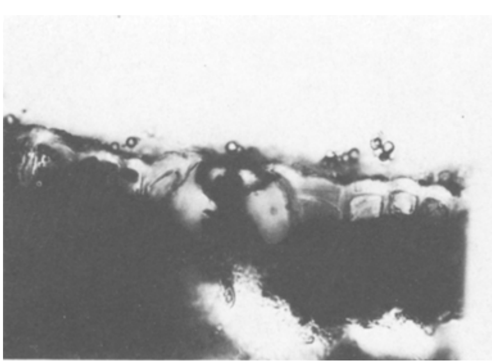

Figure 13 Optical micrograph showing the germination of fungal spores through the stomatal opening of the leaf in a controlled humidity chamber: 30° C, r.h. 90–95%; × 80.

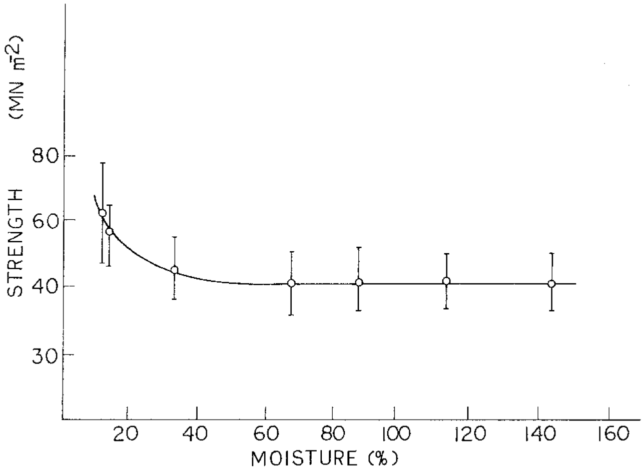

Figure 15 Variation of moisture content with strength of coconut leaf.

weathering (Figs 7–10). Since fungi used for the controlled decay experiments were isolated from decaying thatch exposed to natural weathering, a similar effect, but at a reduced level could be envisaged during natural weathering as well. The overall deterioration may thus be a combined effect of the various factors like rain, alternate wet and dry climate and fungus. Although no appreciable change in strength was observed during exposure up to 100 h to ultra-violet light, photosensitized oxidation cannot be ruled out since

Figure 16 Optical micrograph showing the dissolution of mysophyl tissues of the leaf, in a controlled humidity chamber: 30° C, r.h. 90–95%; × 150.

cellulosic polymers are known to undergo cleavage of bonds under such circumstances particularly in the presence of moisture [10, 11]. Hydrolysis of the cellulose molecule can also be envisaged particularly under environments where acidic rain is possible [12]. The environmental condition thus has both the embrittling as well as the stress-generating situations. It has been observed that at the later stages of deterioration, the thatch can be crumbled at the slightest stress and can easily be powdered. The dry leaf showed a percentage elongation in the range 1.4–2.6 which was found to decrease during deterioration. The value tends towards zero at the later stages of deterioration.

The fungal attack may produce discontinuities in the leaf by preferential dissolution of the cells (for example, Fig. 16; the thin-walled mesophyll tissues are preferentially dissolved during fungal attack), that can easily be digested. It appears that the fungal attack enriches the leaf with an amorphous residue rich in lignin (unpublished results). Fungal decay of cellulose is reported to be localized which can produce localized discontinuities that may enhance the brittle nature of the leaf [13]. It appears, therefore, that the overall effect of deterioration in the case of the coconut leaf thatch results in a progressive embrittlement [14, 15] of the leaf. Since both the environment and stress (produced by the cyclic swelling and contraction of the leaf during alternate wet and dry climate), also exist; it is possible that some contributions to fracture by environmental stress-cracking [14, 15] may also occur during the deterioration of coconut leaf thatch.

It appears from the present study that the prevention of deterioration of coconut leaf thatch can be attempted considering that the leaf is brittle in nature, that the deterioration involves an embrittlement process and fungus is also involved. Thus introducing a combination of a plasticizer and a fungicide into the leaf with a water repellent surface (which will prevent wetting of the leaf as well as the entry of fungus into the leaf through the stomatal openings of the leaf) may be useful. The leaf could also be strengthened by *in situ* polymerization of a polymeric fungicide having water-repellent properties.

4. Conclusions

(1) The major factors contributing to the deterioration of coconut thatch include rain, alternate wet and dry climate, decay by micro-organisms like fungus, and the brittle nature of the leaf.

(2) Weathering produces extensive damage to the surface of the leaf showing erosive wear. The top surface layers are worn off with time and the inner fibres and vascular bundles are soon affected.

(3) The stress–strain diagram of dry coconut leaf indicates that the leaf is brittle and undergoes brittle fracture. The percentage elongation 1.4–2.6% was also found to decrease during deterioration. The strength of the leaf drops by more than 90% during deterioration.

(4) The overall effect of deterioration appears to be a case of progressive embrittlement, with possible contribution from environmental stress-cracking, the latter resulting from the cyclic shrinkage and swelling of the leaf during alternate wet and dry weather.

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