Moisture adsorption and desorption properties of some tropical woods

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The sorption of moisture for ten species of tropical wood, in the density range 480–1120 kg m^{-3} was investigated by measuring the moisture content (MC) and dimensions (DC) during relative humidity (RH) cycling. In general, it was found that there was an increase in dimensions as well as moisture content on increasing the RH, while there was a decrease in dimensions as well as MC on decreasing the RH. Hysteresis effects were observed both in the DC–RH and the MC–RH curves on RH cycling. The hysteresis properties were observed to be not only anisotropic but also species specific. In addition, an anomalous contraction was observed at moisture contents below 2%. The shell–core model is advanced to explain this anomalous behaviour of wood.

1. Introduction

The study of moisture content and its effect on the behaviour of wood is well established for temperate species of wood [1–3]. This present work was concerned with short-term effects of relative humidity (RH) changes on tropical species and the consequent swelling and shrinkage due to moisture gain and loss, respectively.

Wood is a natural composite of cellulose fibre in a polymer matrix which is an amorphous matrix of hemicellulose and lignin [4]. The cell wall of wood is highly hygroscopic because its main constituent, cellulose, contains numerous hydroxyl groups which are strongly hydrophylic [5]. Wood, therefore, would either adsorb or desorb moisture readily when subjected to changes in RH. It has been reported [6] that when wood is subjected to a decrease in moisture content at a constant temperature, a sigmoid desorption curve results. For corresponding conditions with an increase in moisture content, a sigmoid shape is also observed for adsorption. Further, the adsorption and desorption curves do not coincide but the adsorption curve usually falls below the desorption curve forming a hysteresis loop. Thus, the sorption of water by wood exhibits hysteresis.

In this study, the adsorption/desorption properties were investigated for ten species of tropical wood in each of the three dimensions of wood, that is, tangential, radial and longitudinal.

2. Experimental procedure

The ten species of wood investigated are listed in Table I. These are species which are of significant economic importance in many tropical countries.

TABLE I Species of wood

Botanical name	Common name	Density (kg m^{-3})
Manilkaran bidentata	Balata (Ba)	1120
Peltogyne prophyrocardia	Purpleheart (Ph)	880
Tectona grandis	Teak (Tk)	640
Mora excelsa	Mora (Mo)	960
Carapa guianensis	Crappo (Cr)	640
Terminalia amazonia	Olivier (Ol)	800
Swietenia macrophylla	Mahogany (Ma)	560
Hieronyma caribaea	Tapana (Ta)	800
Cordia alliodora	Cypre (Cy)	560
Cedrela odorata	Cedar (Ce)	480

The apparatus consisted of eight RH chambers (see Fig. 1) with various ancillary equipment for maintaining constant relative humidity in each chamber and for measuring adsorption or desorption suffered by wood samples.

The sample preparation process is shown diagrammatically in Fig. 2. Wood samples were cut into standard testing size pieces, 5 cm × 2 cm × 2 cm [7]. They were then weighed and baked at 103 ± 2 °C to constant weight (ISO 4470-1981[E]). After baking, the samples were cooled, then weighed again before placing in the chamber of lowest RH (i.e. $LiCl{\cdot}H_2O$-11.3%). Three samples of the same species were placed under dial gauges in this chamber. The axes of the samples were arranged for monitoring dimensional changes in the tangential, radial and longitudinal directions to an accuracy of ± 500 μm.

Dimensions were recorded at the start and at various intervals until a final reading was taken at the end of 12 h. The samples were then weighed again and

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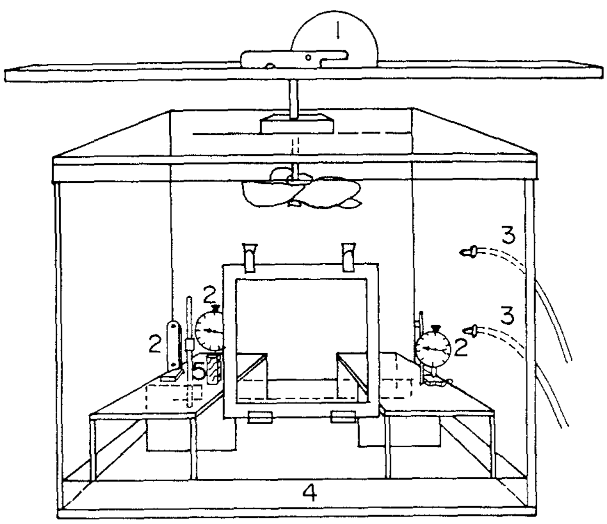


Figure 1 A relative humidity chamber. 1, Fan controls; 2, dual gauges; 3, inlet/outlet tubing to hydrometer; 4, trough for saturated solution; 5, wood samples.

positioned as before, but this time in the chamber of 19% RH and left for a further 12 h (see Fig. 3). Weighing was performed at each stage of the process in order to obtain the necessary data for computation of MC of the wood samples. The process described was continued, samples being placed in chambers of increasing RH until measurements were completed in the chamber of highest RH (97%). This completed the adsorption part of the adsorption/desorption cycle and provided the data to obtain DC and MC changes on increasing the RH. To continue the process into the desorption half of the cycle, the general procedure was the same except that the samples now moved to chambers of successively lower RH until the three samples reached the chamber of lowest RH. With the inclusion of the 12 h baking period, the entire process, which will be referred to subsequently as a cycle, takes 8 days for the three samples.

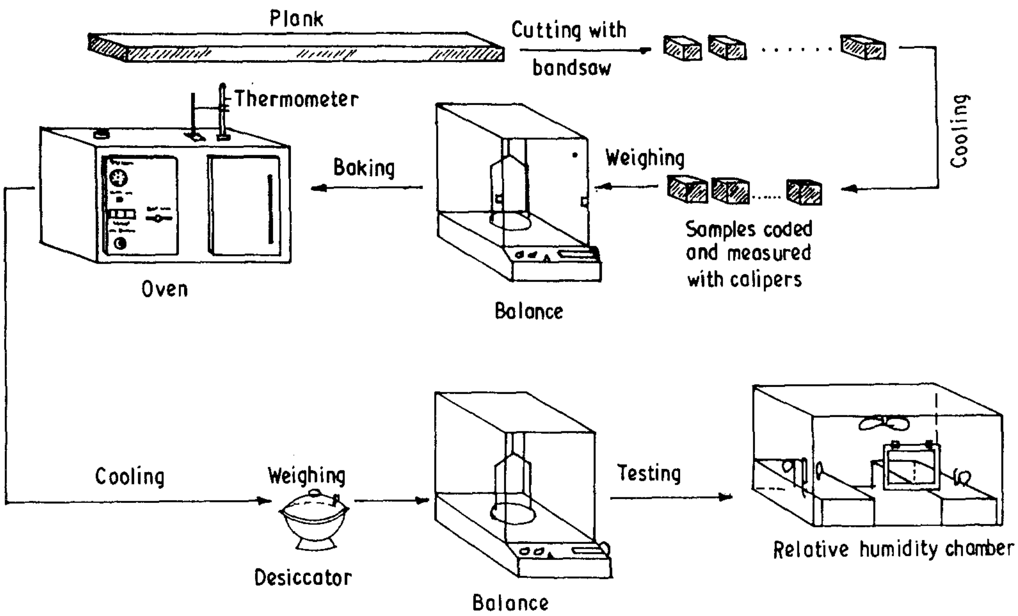


Figure 2 Procedure for sample preparation.

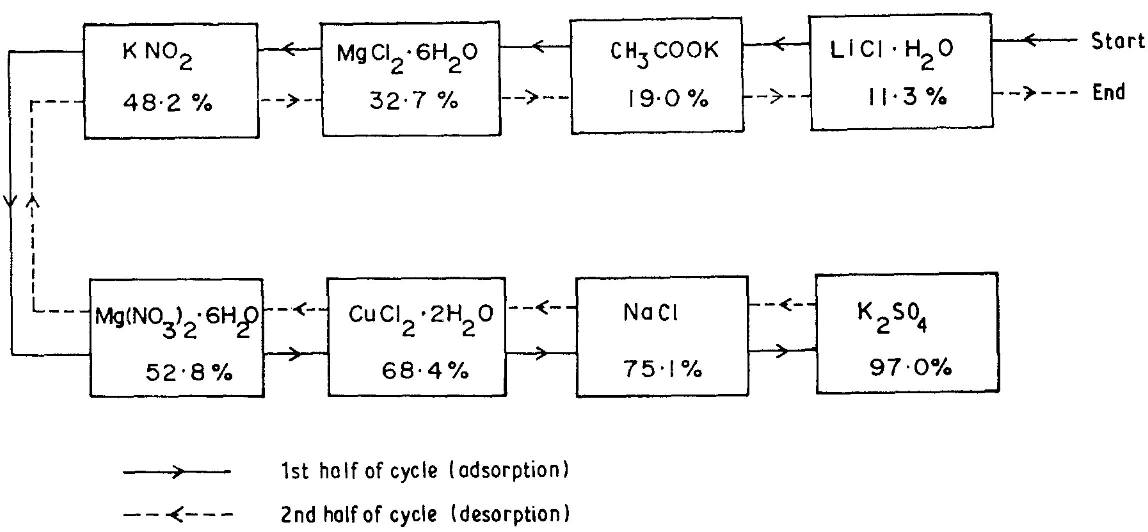


Figure 3 Movement of samples through chambers during an adsorption/desorption cycle.

For each of the ten species studied, 12 sets were examined. Hence, by considering the three dimensions, a total of 360 samples were used. Dimensional changes and changes in moisture content of these wood samples were measured for increasing and decreasing RH to determine to what extent hysteresis exists for tropical species.

3. Results

3.1. Adsorption

For the ten species studied, there was a decrease in dimensions as the RH is increased at low RH levels (11.3% RH). This was followed by a gradual then a rapid expansion as the RH was increased (see Fig. 4). No pronounced saturation effect is observed as the RH approaches 100%.

In the tangential, radial and longitudinal directions, the graphs "fan out" and separate characteristically for the individual species, indicating that expansion is species-specific for the experimental conditions used. Examination of the results (see Fig. 4) also reveals that in the tangential and radial directions, maximum expansion is closely correlated with species, whereas in the longitudinal direction, a correlation is not evident. It should be noted that the scale for the graphs in the radial and tangential directions is 14 times that for the longitudinal direction.

3.2. Desorption

The desorption curves for the ten species in the tangential, radial and longitudinal directions reveal a decrease in sample size as the RH is decreased. Different species again follow different curves (see Fig. 5) as RH decreases, an indication that the contraction process is also species-specific.

3.3. Adsorption/desorption curves

The mean expansion/contraction curves on adsorption and desorption were plotted for data in the tangential, radial and longitudinal directions for each of the ten species studied (see Fig. 6). These graphs show clear evidence for hysteresis effects, the expansion and contraction curves following different isotherms.

Examination of the hysteresis loops shows that hysteresis effects are greatest in the tangential direction followed by the radial and finally the longitudinal direction for all species examined.

3.4. Moisture content curves

Plots of MC versus RH on cycling for the ten species show an increase in MC with increase in RH and a decrease in MC with decrease in RH for all species. There is also a fanning out of the curves indicating that MC is species specific (see Fig. 7). Again no "saturation" effect is observed as the RH is increased. The amount of moisture adsorbed, at the maximum RH used, varied between 4.04% (*Manilkaran bidentata*) and 15.76% (*Cedrela odorata*). As with dimensional changes as a function of RH for the expansion/contraction cycle, there is again evidence for hysteresis. Examination of the hysteresis loops indicate that the magnitude of the hysteresis effects appear to vary from species to species.

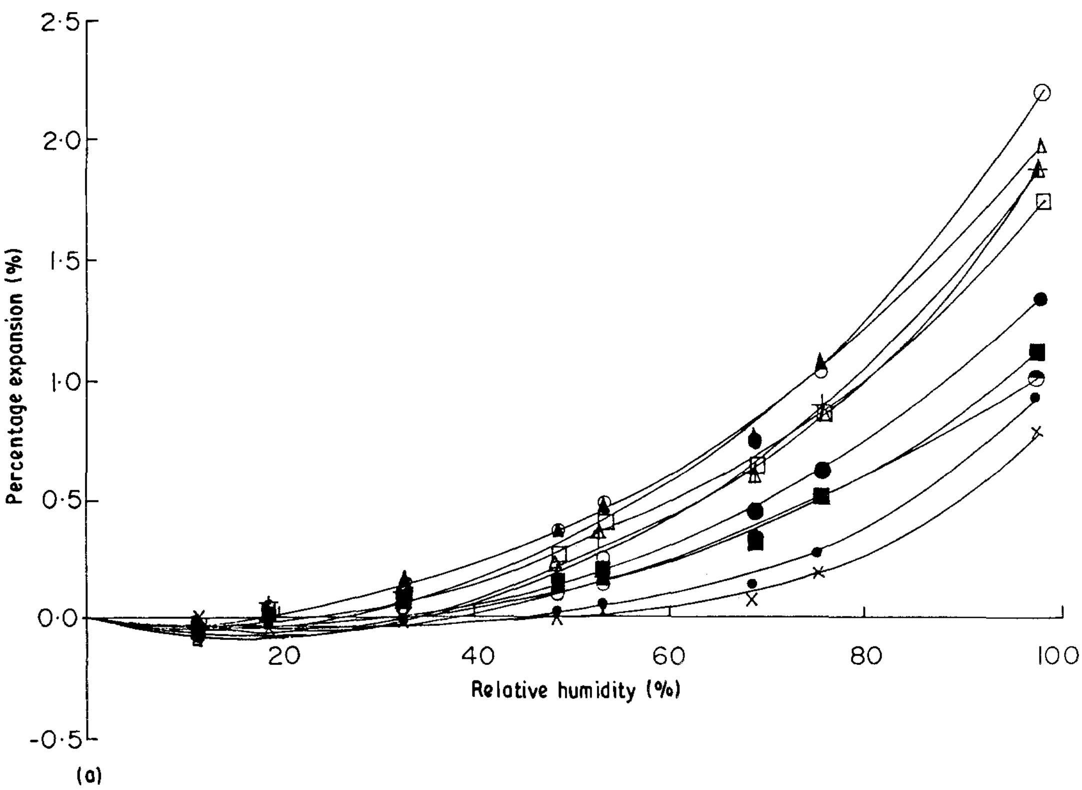


Figure 4 Graphs of percentage expansion, (a) tangential, (b) radial and (c) longitudinal, versus relative humidity for ten species of tropical wood. (×) *Manilkaran bidentata*; (□) *Cedrela odorata*; (○) *Carapa guianensis*; (△) *Cordia alliodora*; (■) *Swietenia macrophylla*; (●) *Mora excelsa*; (+) *Terminalia amazonia*; (○) *Peltogyne prophyrocardia*; (▲) *Hieronyma caribaea*; (•) *Tectona grandis*.

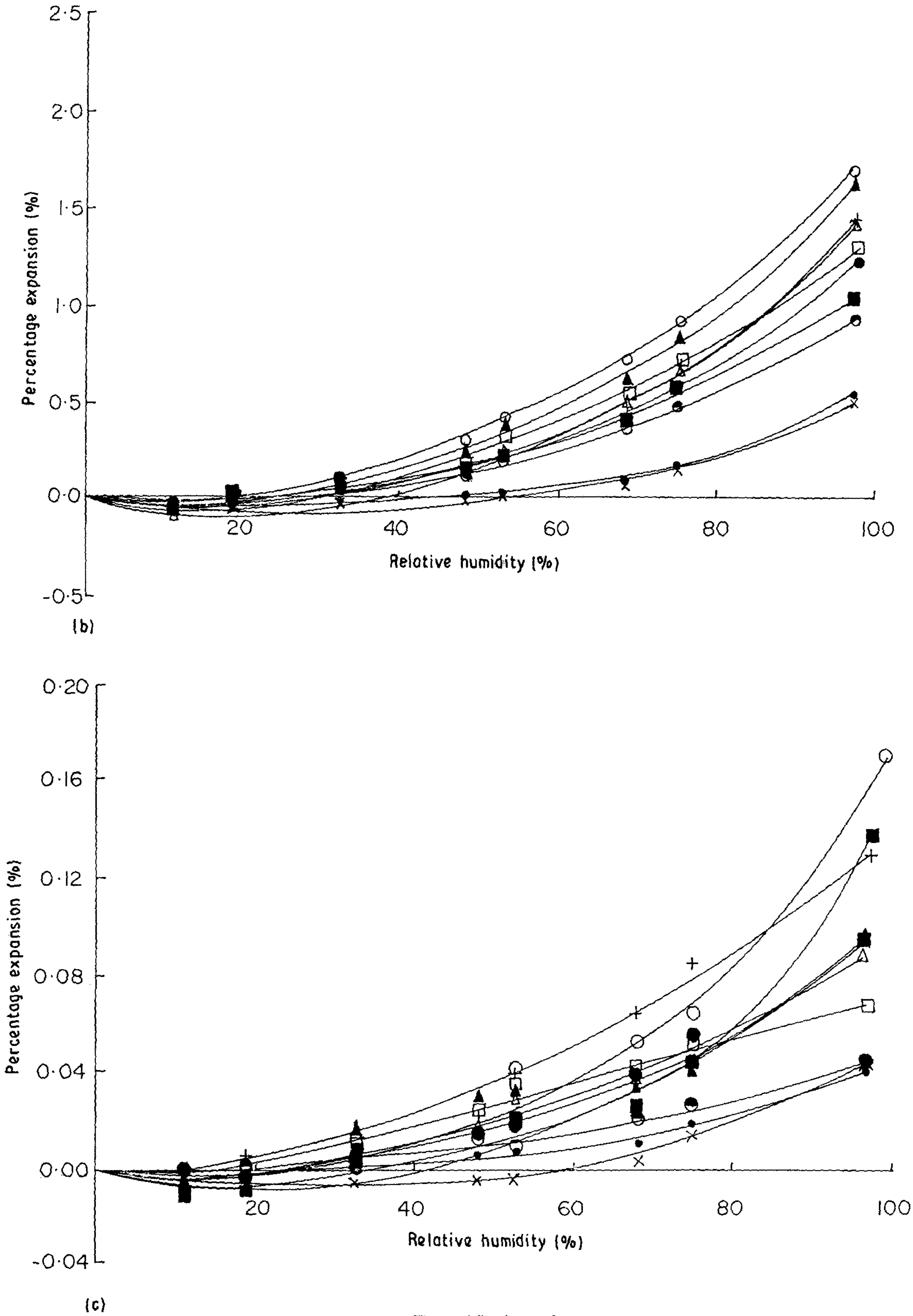


Figure 4 (b–c) contd.

4. Discussion

4.1. Adsorption and desorption with changes in relative humidity

The results of the experiments show that, in general, adsorption of moisture due to the increase in relative humidity leads to expansion of wood samples and desorption due to reduction in relative humidity leads to contraction. These results are in agreement with the findings of other workers for temperate species [2, 8] and are attributed to either the addition or loss, respectively, of water molecules to hydroxyl sites on the cellulose molecules [6]. The expansion and contraction properties are both species and direction dependent.

4.2. Expansion due to moisture adsorption

For changes of relative humidity from 0% (oven-dry condition) to 97% under our experimental conditions, expansion reaches a maximum varying between 0.8%

(*Manilkaran bidentata*) and 2.2% (*Carapa guianensis*) in the tangential direction; 0.5% (*Manilkaran bidentata*) and 1.7% (*Carapa guianensis*) in the radial direction and 0.04% (*Manilkaran bidentata*) and 0.17% (*Carapa guianensis*) in the longitudinal direction. Thus, in general, expansion is greatest in the tangential direction followed by the radial and the longitudinal directions. This general trend is consistent with that observed by other workers for temperate species [9]; however, our values are lower.

The lower values obtained under our experimental conditions are attributed to several factors; firstly, because the samples were subjected to RH changes for short periods (12 h), they did not attain equilibrium conditions with the environment [10]; secondly, internal stresses of the wood samples were probably different to those of other workers [11, 12]; thirdly, differences in the methods for obtaining data and finally the structural differences between the temperate and tropical species [13].

As indicated above, expansion is observed to be greatest in the tangential direction and least in the longitudinal direction for our data as well as those of other workers. To date there is no clear explanation

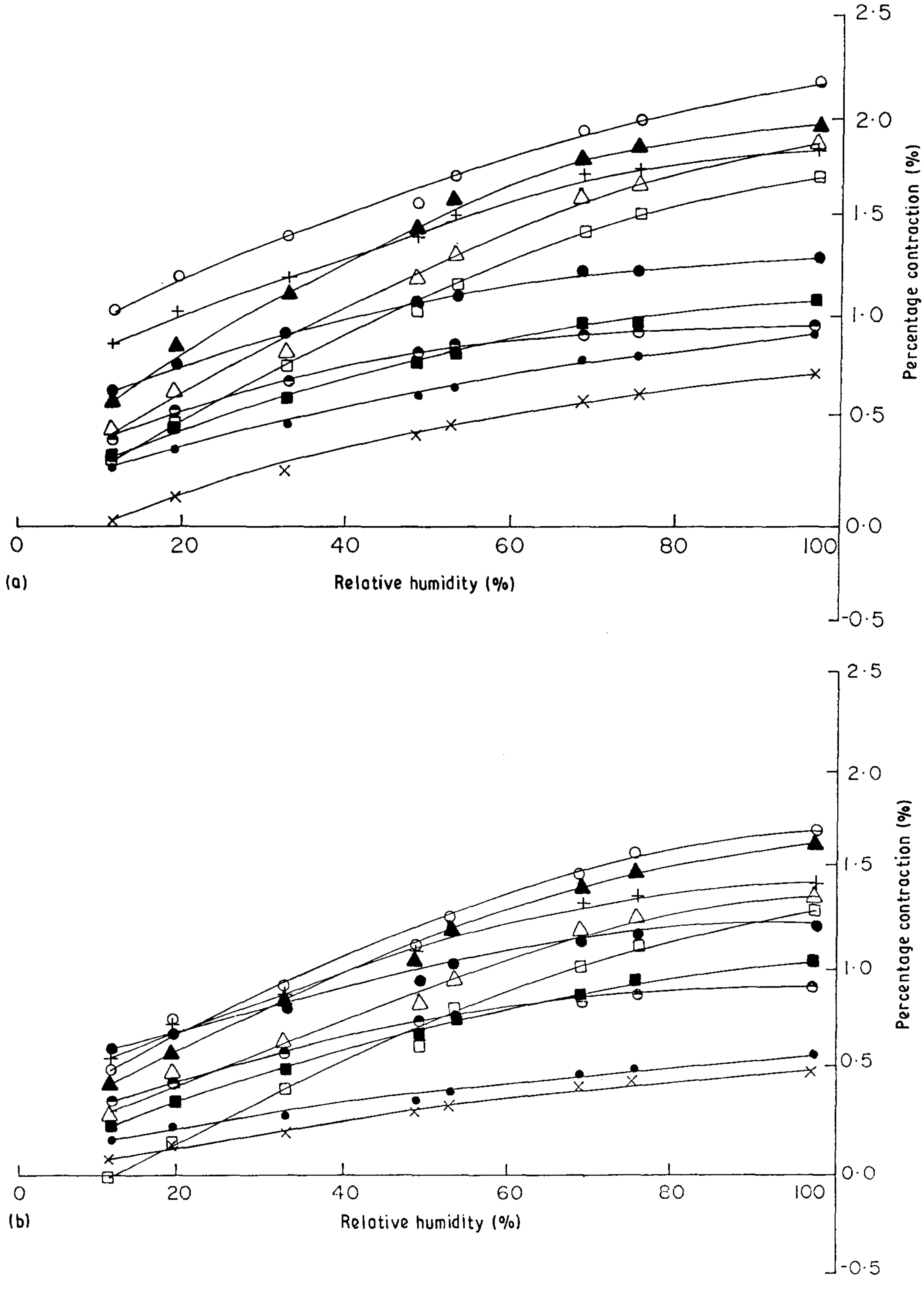


Figure 5 Graphs of percentage contraction, (a) tangential, (b) radial and (c) longitudinal, versus relative humidity for the ten species of tropical wood. For key, see Fig. 4.

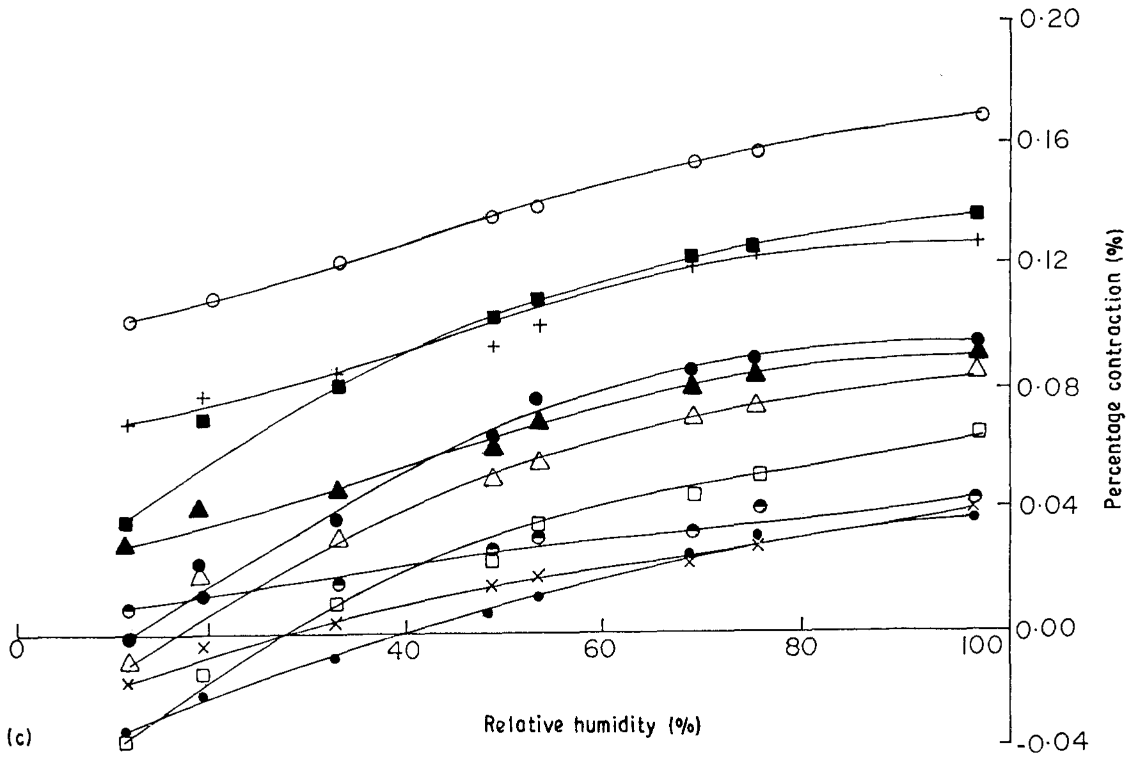


Figure 5 (c) contd.

for this anisotropy of wood in the literature. According to Cousins [4] anatomical characteristics may be responsible for tangential swelling being approximately double that in the radial direction. However, it has been reported [14] that the reason for this anisotropy in wood was not yet completely clear. On the basis of light and electron microscopical evidence [15], we believe that anatomical characteristics affect the relative magnitude of expansion of wood in the three directions as well as differences between the various species.

4.3. Anomalous contraction

Although the general trend for our expansion results is similar to those of other workers, a detailed study reveals a significant difference which has not been observed by other researchers. The adsorption curves for all the species (see Fig. 4) show an initial contraction at low humidities below the range usually examined [2]. A contraction of up to 0.074% at 11.3% RH in the case of *Cordia alliodora* (see Fig. 8a) and extending up to 48.2% RH as in the case of *Manilkaran bidentata* (see Fig. 8b) are evidence of this anomalous contraction. This initial contraction occurs in spite of an increase in MC (see Fig. 8). The adsorbed water molecules which attach themselves to hydroxyl sites on cellulose molecules "normally" produces an expansion [2].

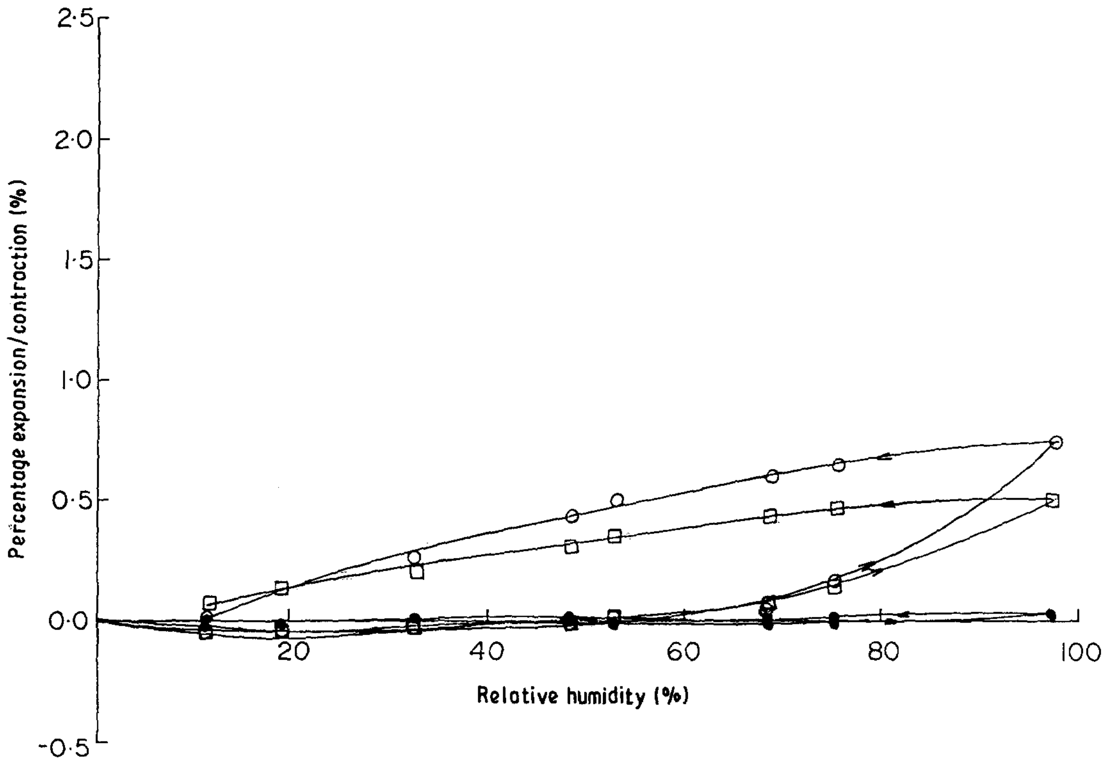
4.4. Contraction due to moisture desorption

On changing the RH between 97% and 11.3% RH, the percentage contraction (shrinkage) varies between 0.58% (*Peltogyne prophyrocardia*) and 1.43% (*Cedrela odorata*) in the tangential direction; 0.43% (*Tectona grandis*) and 1.37% (*Cedrela odorata*) in the radial direction and 0.05% (*Peltogyne prophyrocardia*) and 0.10% (*Cedrela odorata*) in the longitudinal direction. In analogy with expansion, greatest shrinkage occurs in the tangential direction and least in the longitudinal direction. This general trend is consistent with that reported by other workers for temperate species [9, 10, 16], but our values are lower.

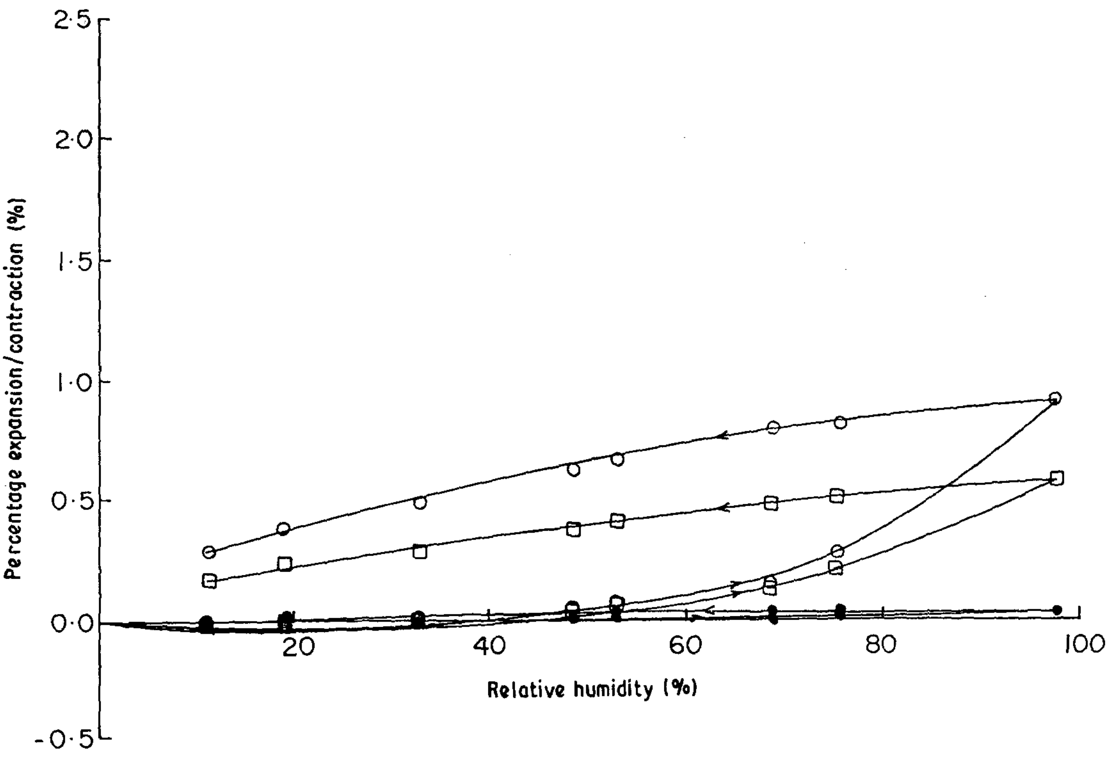
The difference between our results and those of other workers can be accounted for by the fact that shrinkages were measured by different methods, our experimental data being obtained by subjecting samples to decrease in RH from 97% to 11.3% while data of many other workers [9, 16] were obtained by bringing the samples from green to oven-dry condition and computing the shrinkage. In addition, our data address short-term effects of RH changes and as such the samples were only subjected to specific RH changes for a relatively short period (12 h) whereas in the experiments of other workers, samples were brought to equilibrium. In Hart's experiments [10], for example, the wood samples (*Quercus* sp.) were left for 20 days to attain equilibrium moisture content (EMC) at each RH. A further reason is that the nature of internal stresses may differ for temperate and tropical species and hence influence the shrinkage values.

4.5. The shell–core model

The general trend of the adsorption/desorption curves, can be explained in terms of internal stresses [11, 17]. Essentially, there are two types of internal stresses which may occur in wood, firstly, tensile stress which results from an increase in EMC and leads to expansion, and secondly, compressive stress which results from a decrease in EMC and leads to contraction [18]. Whenever a tensile stress is present in one part of a sample, as a reaction, a compressive stress

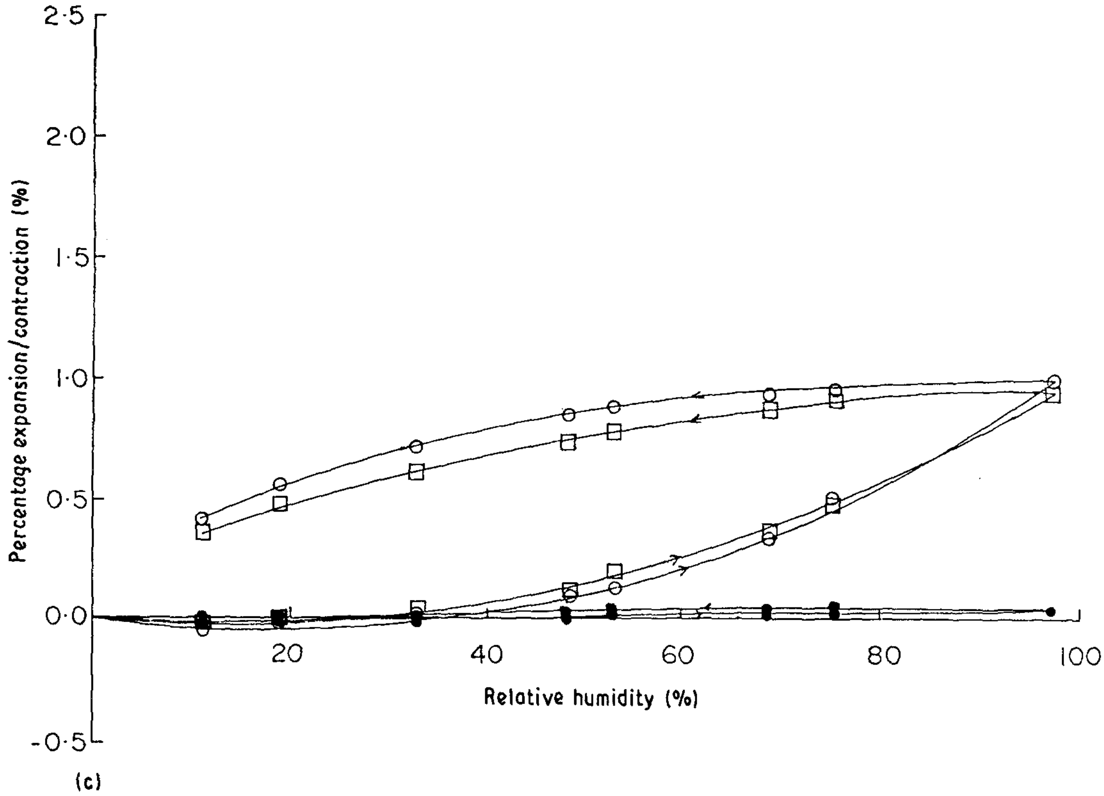


(a)



(b)

Figure 6 Graphs of percentage expansion/contraction versus relative humidity for (a) *Manilkaran bidentata*, (b) *Tectona grandis*, (c) *Peltogyne prophyrocardia*, (d) *Swietenia macrophylla*, (e) *Mora excelsa*, (f) *Cedrela odorata*, (g) *Cordia alliodora*, (h) *Terminalia amazonia*, (i) *Hieronyma caribaea*, and (j) *Carapa guianensis*, in the three directions of wood: (○) tangential, (□) radial, (●) longitudinal.



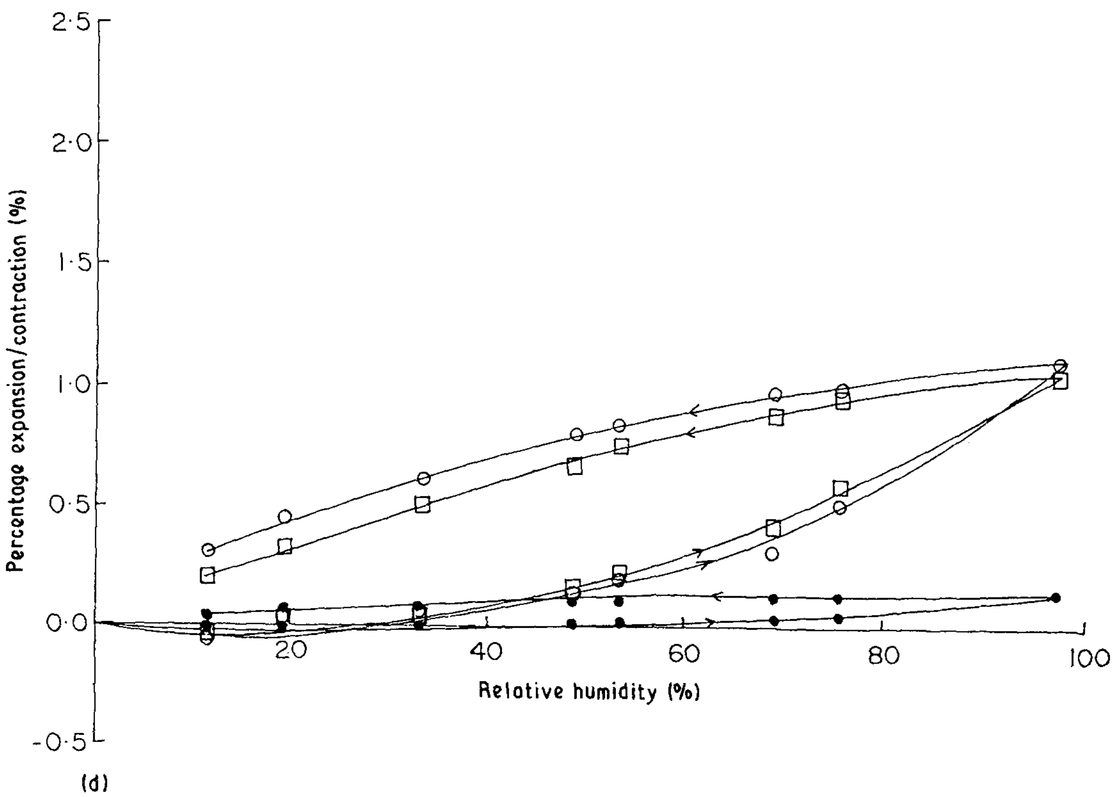
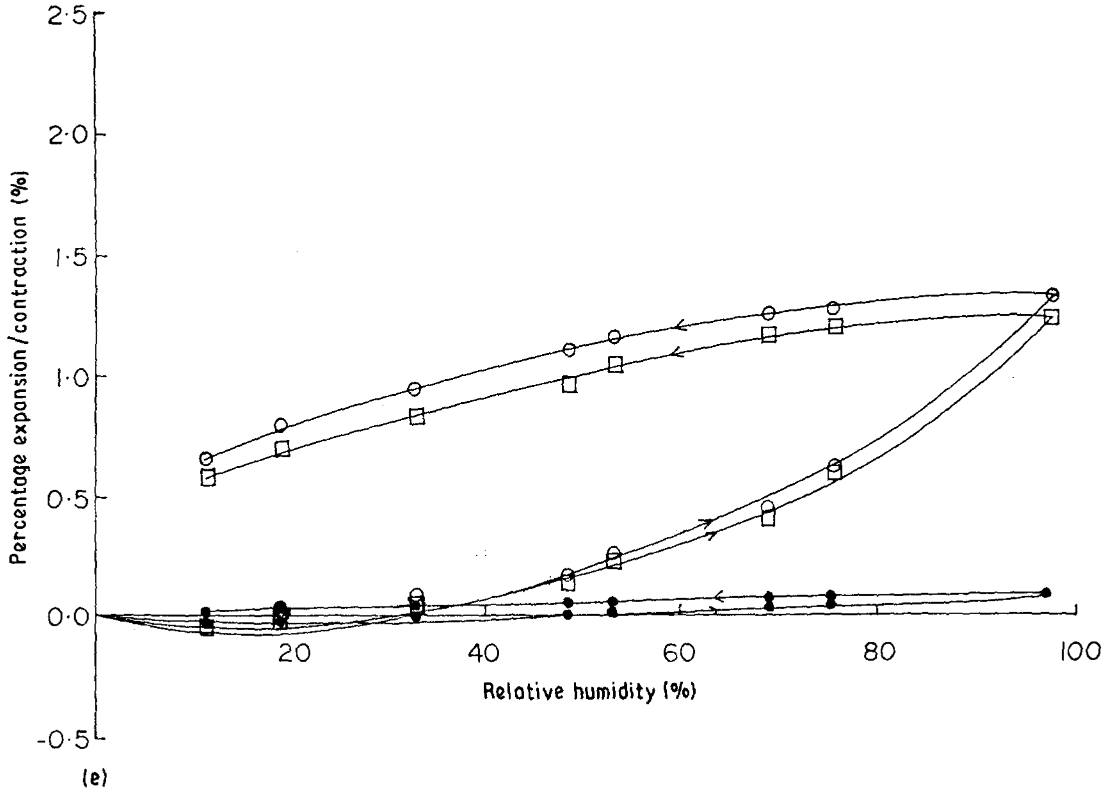


Figure 6 (c–d) contd.



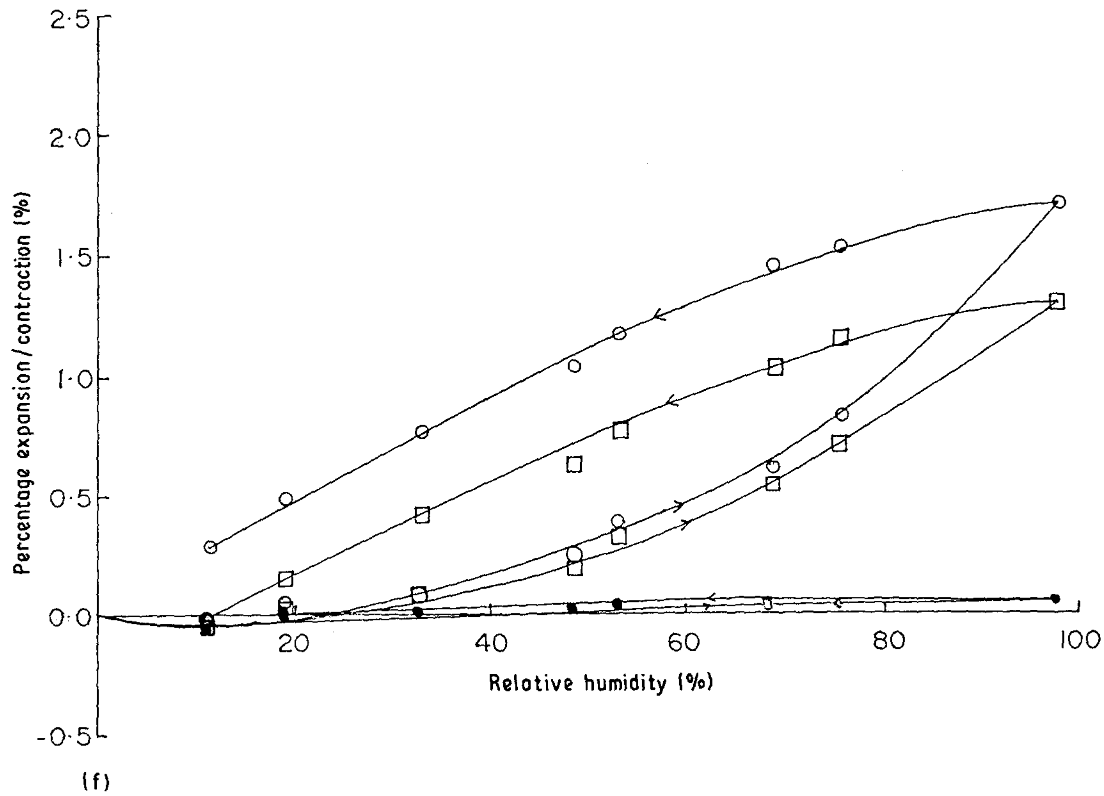
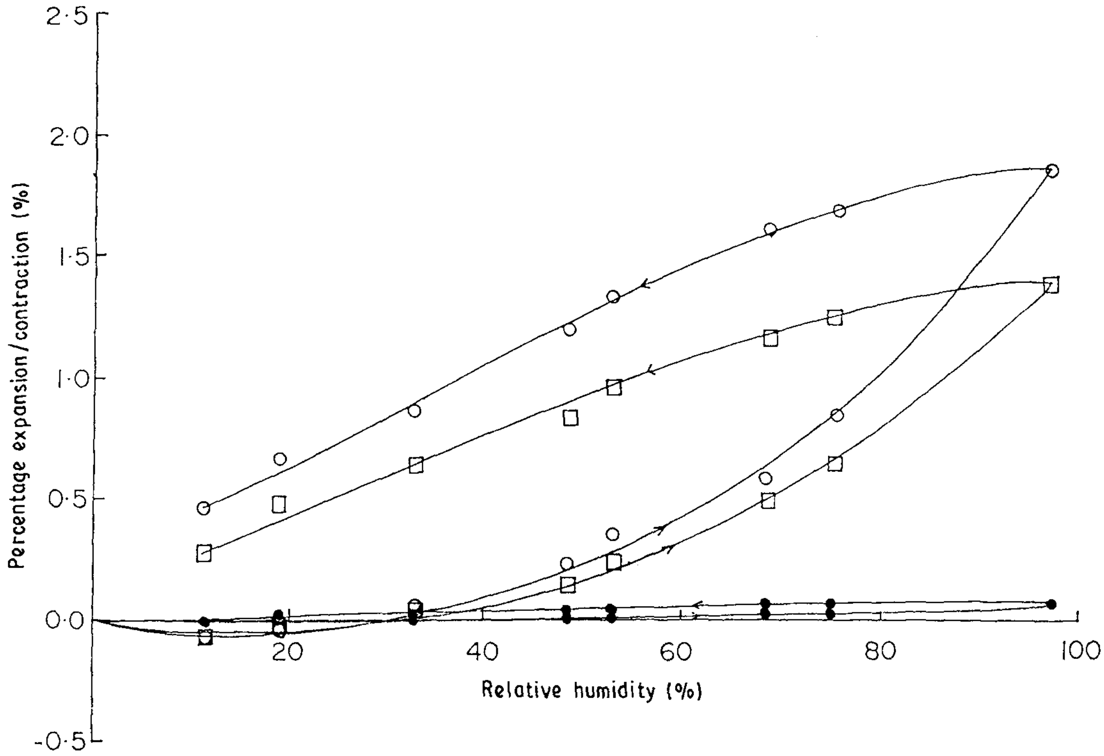
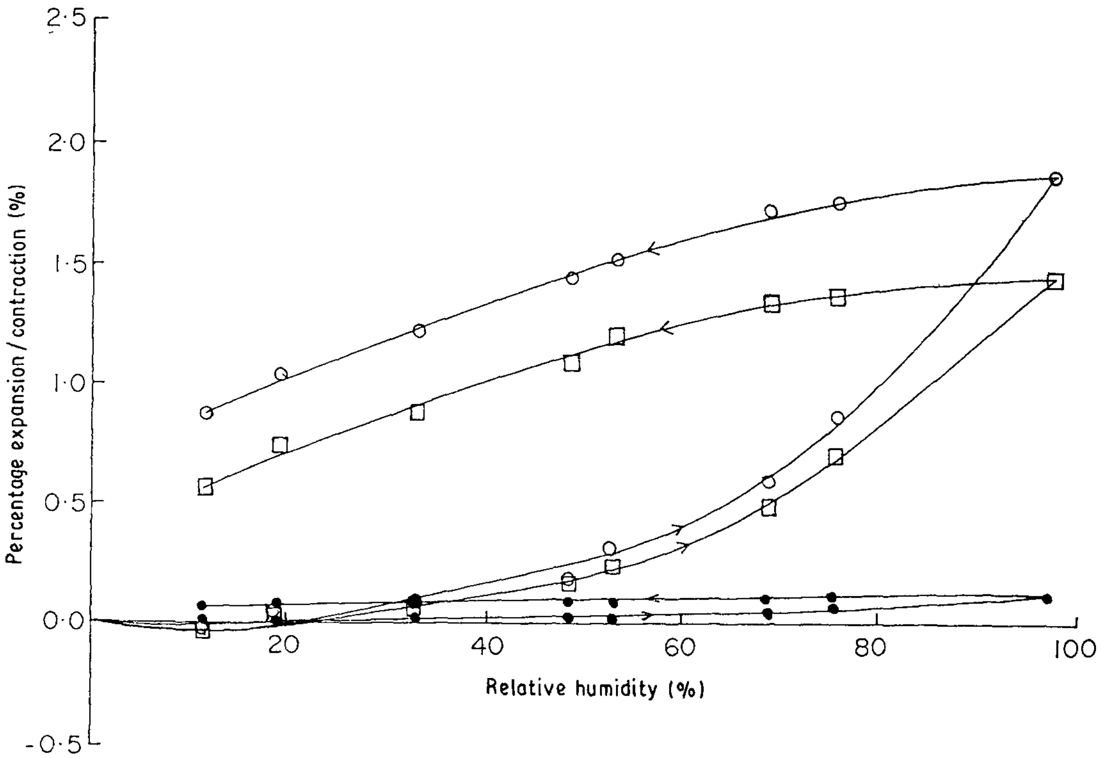


Figure 6 (e–f) contd.

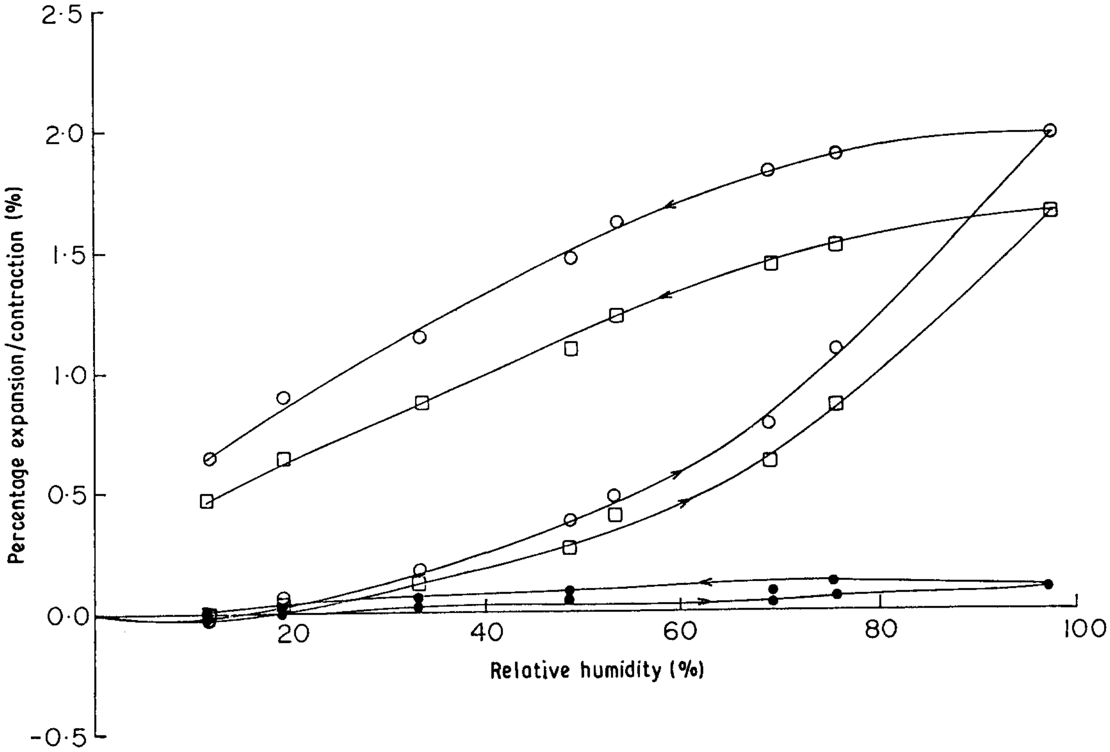


(g)

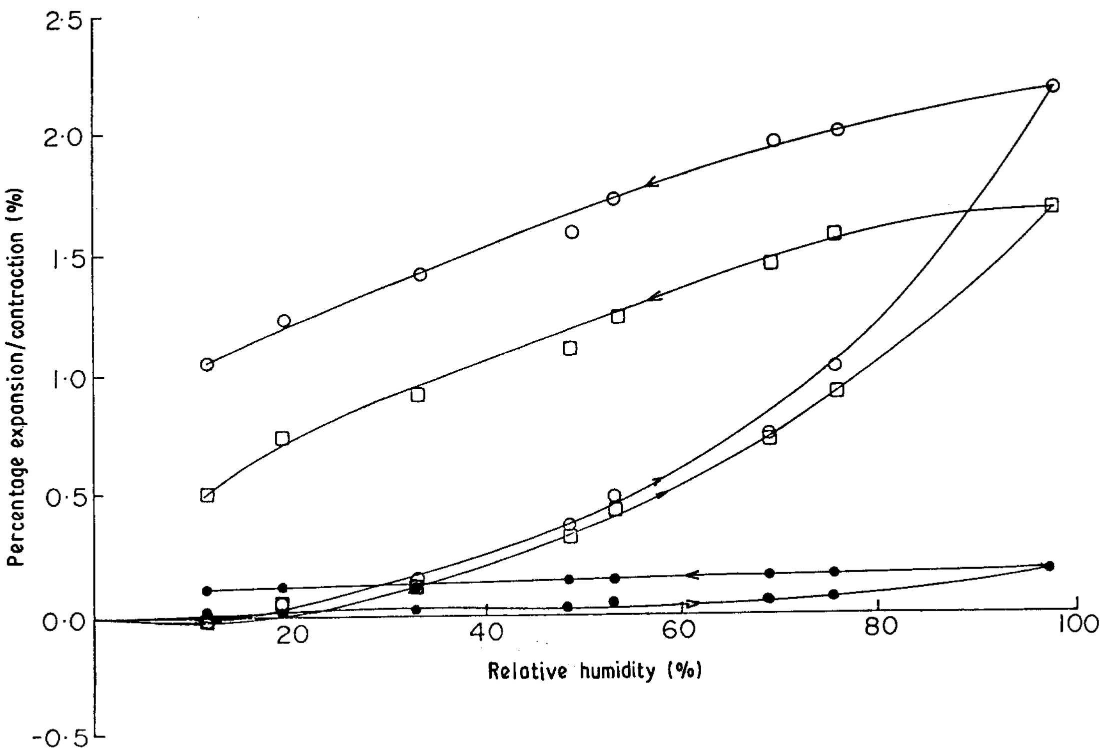


(h)

Figure 6 (g–h) contd.



(i)



(j)

Figure 6 (i–j) contd.

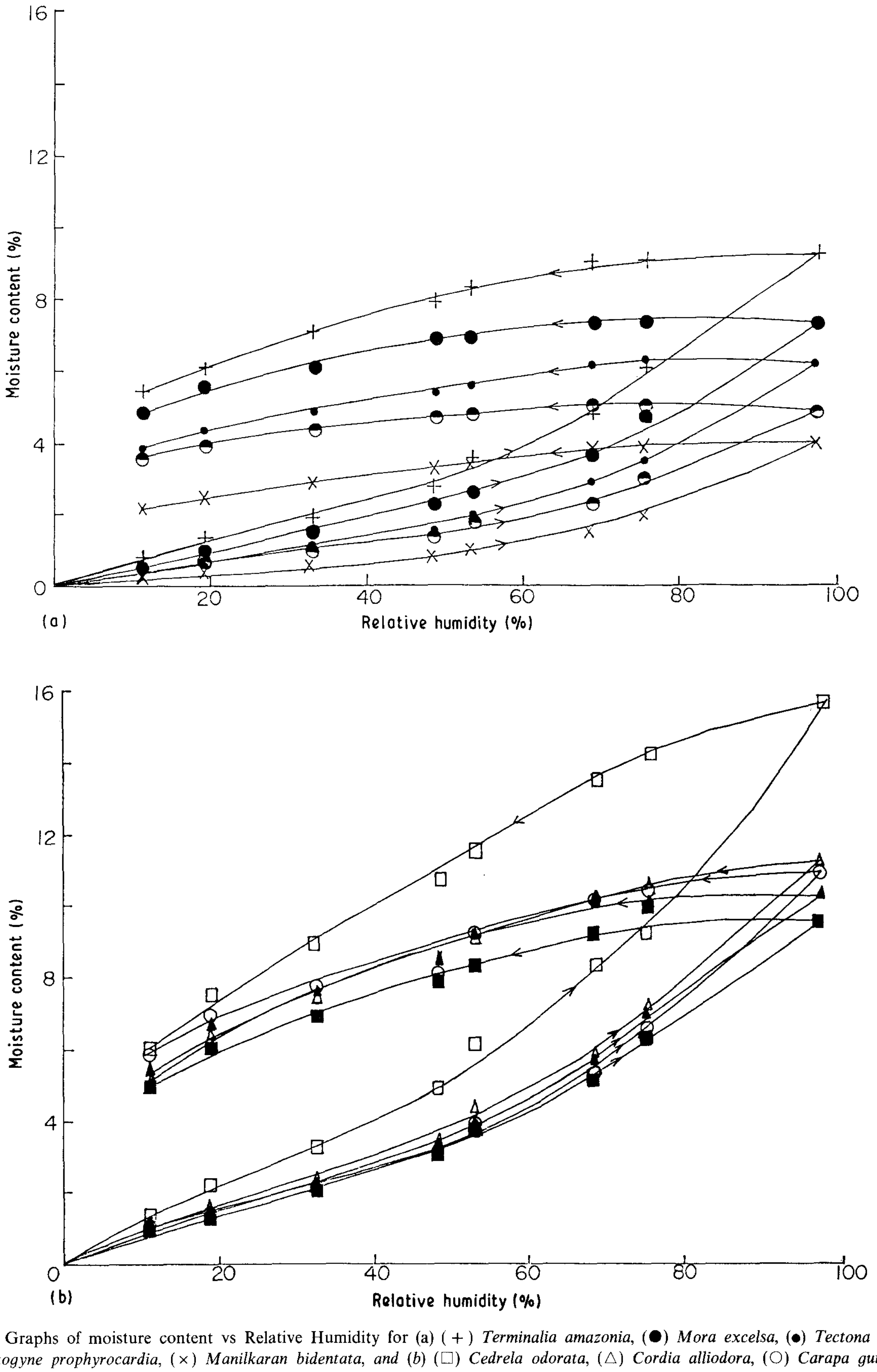


Figure 7 Graphs of moisture content vs Relative Humidity for (a) (+) *Terminalia amazonia*, (●) *Mora excelsa*, (•) *Tectona grandis*, (○) *Peltogyne prophyrocardia*, (×) *Manilkaran bidentata, and* (*b*) (□) *Cedrela odorata*, (△) *Cordia alliodora*, (○) *Carapa guianensis*, (▲) *Hieronyma caribaea*, and (■) *Swietenia macrophylla*.

occurs in another part. For example, if the outer region or "shell" of a piece of wood is subjected to tensile stress, the inner region or "core" is subjected to a compressive stress. Some ways in which these stresses may arise are through moisture gradients, mechanical restraints, macroscopic tissue, swelling anisotropy, and microscopic and submicroscopic anisotropy within the cell wall itself. It is impossible in practice to eliminate completely stresses during moisture changes in wood, particularly those associated with macroscopic tissue and swelling anisotropy [11]. In addition, it has been pointed out [11] that even in the

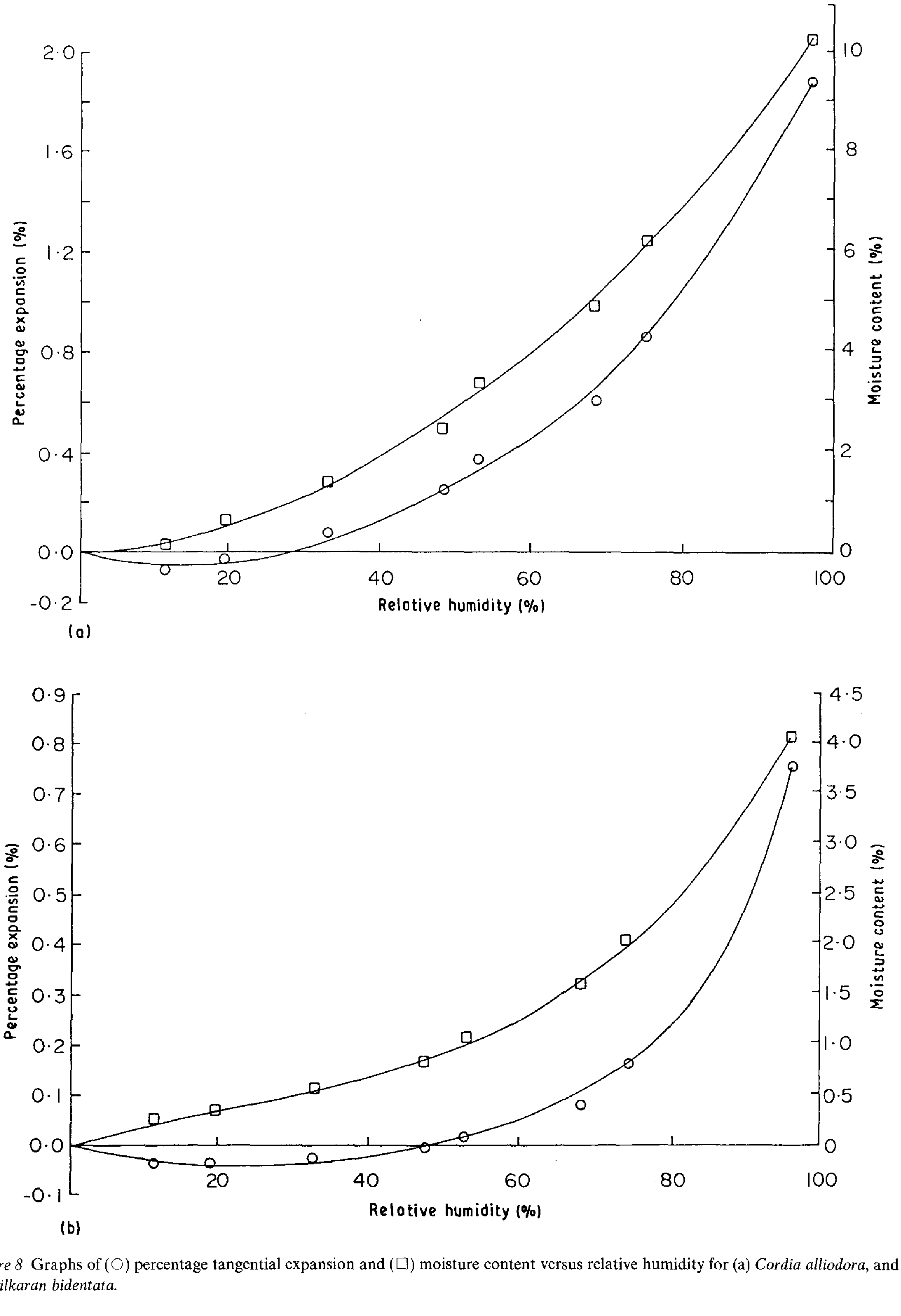


Figure 8 Graphs of (○) percentage tangential expansion and (□) moisture content versus relative humidity for (a) *Cordia alliodora*, and (b) *Manilkaran bidentata*.

absence of external restraint there is an internal restraint to swelling because of the nature of the cell wall structure itself.

In terms of our data, the samples were initially baked to constant weight (0% RH) thereby removing moisture from the sample. Although it is usual for the initial state of the stresses in a sample (shell in tension and core in compression state) to be reversed during drying [17], it seems improbable that this has occurred for our samples because reversal occurs only after prolonged heating. Stress reversal may take up to 50 days [12]. In our experiments samples were heated for 12 h which is insufficient time for stress reversal to occur. Hence, it can be assumed that at the start of the RH cycling each sample has its shell in a state of tensile stress and its core in a state of compression.

The anomalous contraction observed during the initial exposure of samples to low levels of RH for MC less than 2% is most likely a surface phenomenon. We now propose the following mechanism for the observed contraction. Water molecules entering the surface are held by the wood as bound water, the adsorbed molecules being attached to hydroxyl sites thereby increasing the number of hydrogen bonds in a zone just under the surface. In this zone of adsorbed water and of increased bonding, the wood contracts under the action of increased cohesion (see Fig. 9).

As the RH increases, the adsorbed water diffuses further into the bulk of the wood destroying the cohesion effect in the surface zone and the contraction gives way to expansion. This will occur slowly at first as moisture begins to enter the core. Eventually, stress reversal will occur with increase in RH as the core gradually goes into tension and the shell into compression. The increase in tensile stress of the core is manifested as a sharp rise in the adsorption curves (see Fig. 4).

The gradual decrease in size on decreasing RH manifested by the desorption curves is consistent with results obtained by other workers [19]. This part of the cycle is a continuation of the adsorption process within the core, hence at the start of the desorption process, the core of the samples is in a state of tensile stress. During this part of the cycle the tensile stress is being relieved as the samples continue to lose moisture. Eventually, the core goes into compression and the shell into tension with a consequent contraction of the samples. Thus, a decrease in RH results in a gradual contraction as the compressive stress of the core increases.

5. Hysteresis

Inspection of Fig. 6 shows that the expansion and contraction curves follow different isotherms. This is indicative of a hysteresis effect. These results are consistent with those of other workers [9, 20] for temperate species. They suggest that the expansion process employs mechanisms in wood that are different from those of the contraction process.

5.1. Curve fitting ("Best" fit curve)

The algorithm employed for the analysis of these data was formulated to produce "best" fit curves. Curve fitting was accomplished by determining a function $f(x)$ for the p data points $(x_1, y_1) \ldots (x_p, y_p)$ such that

$$f(x_j) \sim y_j \qquad j = 1, 2, 3, \ldots p \qquad (1)$$

For this study, polynomials were fitted separately to the results for the adsorption and desorption curves for dimensional changes and MC. Using this algorithm, it was found that for good fits to be obtained simultaneously for all directions, a cubic polynomial was required for the adsorption data and a fifth degree polynomial for the desorption data. This supports the suggestion that the adsorption and desorption processes are mediated by different mechanisms.

The "best" fit algorithm was also used to compute area enclosed by hysteresis loops. This was achieved by finding the areas under the adsorption (expansion) and desorption (contraction) curves and subtracting these values. Using this method, the area enclosed by hysteresis loop was found for both dimensional changes and moisture content data.

The results of area enclosed by hysteresis loop due to dimensional changes for the ten species studied in the tangential, radial and longitudinal directions are listed in Table II. This table shows that these species undergo the greatest expansion/contraction hysteresis in the tangential direction and least in the longitudinal direction. This type of hysteresis effect is smallest for *Manilkaran bidentata* and greatest for *Carapa guianensis*.

For moisture content hysteresis, the areas enclosed by the hysteresis loops were computed and are listed in Table III in order of increasing area. The table shows that the species which experiences the greatest moisture content hysteresis is *Cedrela odorata* and the species with the least is *Manilkaran bidentata*.

Differences in the extent of hysteresis between species is evident from the DC and MC hysteresis data (see Tables II and III). As before these differences are attributed to anatomical differences between the species.

5.2. Correlation between dimensional changes and moisture content hysteresis

As a measure of hysteresis for our experimental conditions the area enclosed by hysteresis loops (the hysteresis area) was used for both moisture content (MC) hysteresis and dimensional change (DC) hysteresis. In

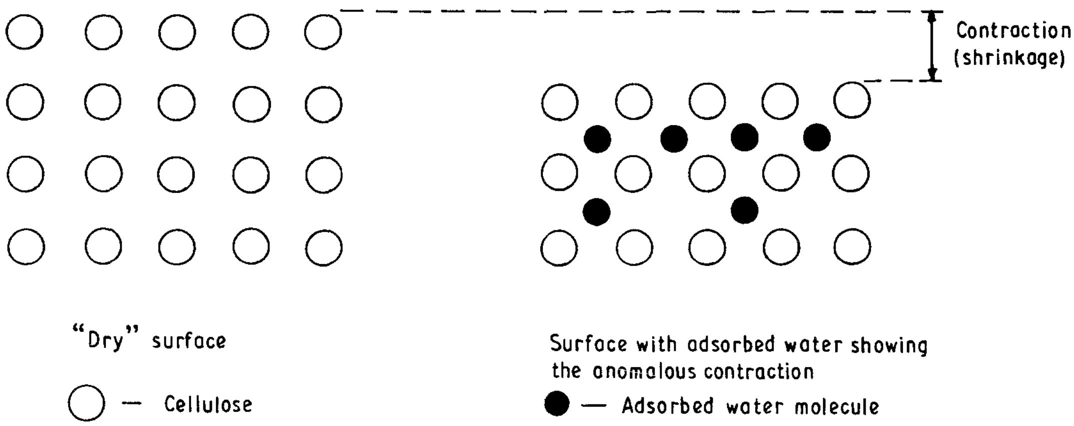


Figure 9 Schematic diagram of surface adsorption of water molecules.

TABLE II Area enclosed by hysteresis loops for dimensional changes (average of 12 samples per direction per species)

Species	Area (arb. units)		
	Tangential	Radial	Longitudinal
Manilkaran bidentata	29.35	29.66	0.95
Tectona grandis	41.17	24.87	0.01
Cedrela odorata	55.71	27.93	− 0.16
Swietenia macrophylla	44.35	34.29	6.79
Peltogyne prophyrocardia	49.27	41.42	1.16
Cordia alliodora	68.29	49.87	1.99
Mora excelsa	63.93	57.57	3.39
Hieronyma caribaea	72.28	59.06	2.46
Terminalia amazonia	87.41	64.30	5.23
Carapa guianensis	95.48	59.93	8.57

TABLE III Area enclosed by moisture content hysteresis loops

Species	Area enclosed by hysteresis loops (arb. units)
Manilkaran bidentata	180.9
Peltogyne prophyrocardia	237.8
Tectona grandis	280.2
Mora excelsa	322.6
Swietenia macrophylla	352.3
Terminalia amazonia	363.0
Cordia alliodora	365.3
Hieronyma caribaea	371.3
Carapa guianensis	417.9
Cedrela odorata	430.2

order to compare DC hysteresis with MC hysteresis it is necessary to compute a resultant area for DC hysteresis. This was done by finding the sum of the area enclosed by hysteresis loops obtained in the three directions of wood, i.e. {tangential area + radial area + longitudinal area}. The hysteresis areas for DC and MC are listed in Table IV in order of increasing MC hysteresis area.

The correlation coefficient between these data sets is 0.61, indicating that MC and DC hysteresis have some influence on each other. Thus, in general, as MC hysteresis increases, DC hysteresis also increases. It should, however, be noted that whereas an increase in RH is always accompanied by an increase in MC, it can produce either an increase or decrease in size depending on the nature of internal stresses. Consequently, better correlation between the DC and MC hysteresis areas should not be expected.

TABLE IV Moisture content (MC) and dimensional change (DC) hysteresis areas

Species	MC hysteresis area (arb. units)	DC hysteresis area (arb. units)
Manilkaran bidentata	180.9	59.96
Peltogyne prophyrocardia	237.8	91.85
Tectona grandis	280.2	66.04
Mora excelsa	322.6	124.89
Swietenia macrophylla	352.3	85.43
Terminalia amazonia	363.0	156.94
Cordia alliodora	365.3	120.15
Hieronyma caribaea	371.3	133.80
Carapa guianensis	417.9	163.98
Cedrela odorata	430.2	83.48

6. Conclusion

Our study on the ten species of tropical wood has shown that increases in relative humidity (RH) generally lead to an expansion of samples and increase in moisture content while decreases lead to contraction and decrease in moisture content. Under certain conditions, however, increases in RH can lead to a decrease in size although the moisture content is increased. This anomaly is explained by the shell–core model of internal stresses.

On cycling the RH from adsorption to desorption conditions, hysteresis effects are observed both for dimensional changes and moisture content. These effects are anisotropic and species dependent. The curve fitting technique applied to the moisture content and dimensional changes data show that the adsorption and desorption processes are mediated by different mechanisms and are therefore distinctly different processes.

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