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A study of the effect of exposure in the reticulo-rumen of the cow on the strength of cotton, grass, hay and straw

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1. Changes in strength of cotton, Italian ryegrass leaf, hay stem and barley-straw stem on immersion in the contents of the reticulo-rumen, at two sites in the rumen and at one site in the reticulum, for periods of up to 56 h were measured using a cow on a hay diet. Specimens of the fibrous materials were immersed in the rumen digesta in such a way that they were not damaged by agitation or by rumination.

2. Load-to-fracture and elongation were measured on a machine using a constant-speed cross-head at a strain of about 10^{-3}/s. The ratio strength: density (breaking load/mass per unit length) was determined.

3. Leaf of Italian ryegrass and stem of hay and of barley straw had strengths of about 37, 150 and 210 MN/m². They lost strength at different rates when immersed in the rumen digesta, the times to half strength being in the ratio grass: hay: straw = 1:1·9:3·8. The similarity of this ratio to that for total time for eating and ruminating as given by Balch (1969), namely 1:2·0:3·5, for similar materials was noted.

Differences in the physical properties of fibrous foodstuffs and changes that such properties undergo in the reticulo-rumen are thought to affect intake and digestion. The usual approach is to measure voluntary intakes for foodstuffs of different chemical composition, the proportion of dry matter that is present as cell-wall constituent being generally held to be a significant factor affecting both intake and digestion (Colburn, Evans & Ramage, 1968; Welch & Smith, 1969*a*, *b*; Cammell & Osbourn, 1972).

It has been shown (Evans, 1964) that there is a correlation between strength and cellulose content in ryegrass and (Evans, 1967) that strength depends on position of leaf on the plant, on age of the plant, and on the position of the specimen along any one leaf. Smith, Goering, Waldo & Gordon (1971) found that the rate of digestion of cell wall was negatively correlated with the ratios lignin: acid-detergent fibre ($r = -0·60$) and lignin: cellulose ($r = -0·57$) and positively correlated with content of soluble material in the cell dry matter (DM) ($r = +0·77$).

Experiments have been carried out to determine the rates of loss of strength of fibrous foodstuffs, grass, hay and straw, in the reticulo-rumen (hereafter called rumen) of the cow. It was assumed throughout that change in strength in the longitudinal direction of the fibre was a measure of degradation of the foodstuff. One object of these experiments was to determine the extent to which a change in physical properties of fibre could occur in the rumen without involving mechanical damage due to chewing. The possibility that differences in the rate of degradation would be caused by differences in the foodstuff and by its immersion in different sites in the rumen was recognized.

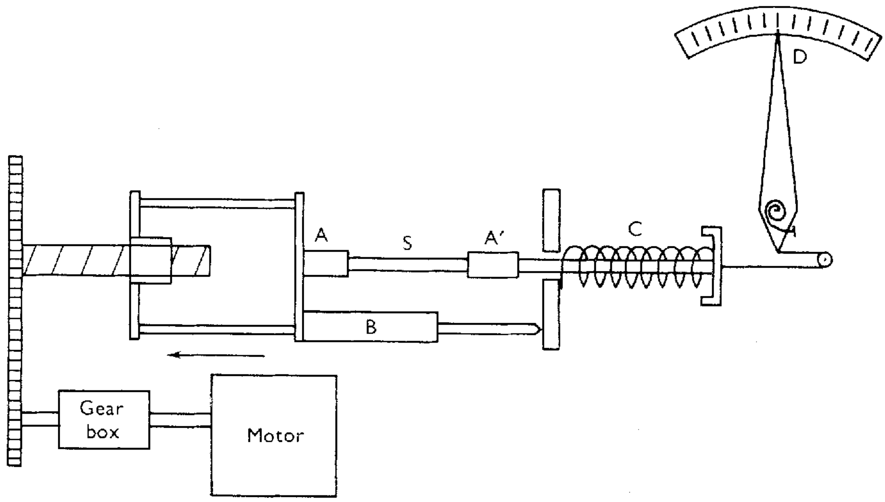

Fig. 1. Diagram of tensile test apparatus showing specimen, S, between grips A, A′. Load applied by spring C, indicated on scale D. Extension measured by transducer B.

EXPERIMENTAL

Measurement of strength

Degradation of fibrous material in the rumen was examined by means of a mechanical test in which the load-to-fracture was determined for specimens that had and specimens that had not been immersed in the rumen.

The load-to-fracture for a specimen was measured with the tensile testing machine (Fig. 1). Specimens, approximately 50 mm long, were held at each end by brass grips A, A′, the load being applied horizontally at A′ by means of a coiled spring. Pieces of fine emery cloth were stuck on to the surfaces of the grips to improve their hold on the specimen. The distance between the grips, defining the gauge length of the specimen, was adjusted to a constant value before each specimen was inserted into the machine, the output of a transducer (B) being used as an indicator of the separation.

A motor pulled the grip A, extending the specimen and applying a load to it by means of the spring C. The load on the specimen was indicated on the dial D, and changes in length of the specimen were measured by means of the transducer.

It was possible to change the strain rate by changing the gearing of the motor. The strain rate $(1/l) \times (dl/dt)$ was not constant; it decreased during a test because of an increase in length of the specimen and also varied because of the non-linear characteristics of the spring. Nevertheless the strain rate, which was about 10^{-3}/s and which varied by less than a factor of 2 during a series of tests, was considered to be sufficiently constant to have little effect on the load-to-fracture. Strain could be measured by means of the transducer, which was calibrated by relating electric current through the transducer circuit to the separation of the grips. The load scale was calibrated by applying known loads to the spring. The following quantities are used in the formulas for strength: M, mass of specimen (kg); l, length of specimen (m); A, area of cross-section of specimen (m^2); L, load-to-fracture (kg); ρ, density of specimen (kg/m^3); S, strength, (MN/m^2); R, proportion of DM that was load-bearing. The subscript 0 refers to conditions before immersion.

Strength was given by

$$S = \frac{L}{A} = \frac{Ll\rho}{M} \quad \left(\text{since } A = \frac{M}{l\rho}\right). \tag{1}$$

Also

$$\frac{S}{S_0} = \frac{L}{L_0}\frac{l}{l_0}\frac{M_0}{M}. \tag{2}$$

Where it was considered necessary to make an absolute measurement of strength, the density of dried stem or leaf was measured with a specific gravity bottle, and used for calculating strength by equation (1).

Adjustment of ratios for strength, required because not all DM *was load-bearing*

Comparison of strength after immersion in the rumen with the strength of fibre that had not been immersed seemed to indicate that all fibres increased in strength on immersion in the rumen, at least during the first few hours. The greatest degree of apparent strengthening occurred for hay, the least for straw. Even cotton showed some increase in strength.

This strengthening effect could be real, being caused by some chemical effect of immersion in the rumen liquor, or apparent, either because of changes in density that were not taken into account, or because not all of the DM in the fibre before immersion in the rumen was load-bearing. Tests on grass leaf agitated in water and tensile-tested indicated that the last explanation was the most likely. Grass, hay and straw lost DM rapidly to varying extents, because of the leaching out of soluble components, mainly carbohydrates, on agitation in water at room temperature. These observations may be compared with those of Hungate (1966), and of Sutherland, Ellis, Reid & Murray (1962). It was considered that solid matter that could be leached out of the fibre by agitation with water was not load-bearing.

If DM in fibre before immersion in the rumen = M_0, and a proportion (R) of this, assumed to be structural, is load-bearing, then structural DM in fibre = RM_0 and the strength of the leaf before immersion = $(L_0\rho_0 l_0/RM_0)$. Suppose that the strength of the fibre after non-structural DM has been leached out = $(L\rho l/M)$, then the ratio (strength after:strength before immersion) = $R \times$ (apparent strength after immersion:apparent strength before immersion). Application of this factor R to all ratios (strength after immersion:strength before immersion) reduced the ratio to unity, within the error of the experiment, for the shortest time of immersion in the rumen for each of the three types of fibrous material. Thus:

$$\frac{S}{S_0} = R\frac{L}{L_0}\frac{l}{l_0}\frac{M_0}{M}. \tag{3}$$

The factor R was determined as follows: the ratio of mass per unit length after, to that before, immersion in the rumen was available for all the specimens that were

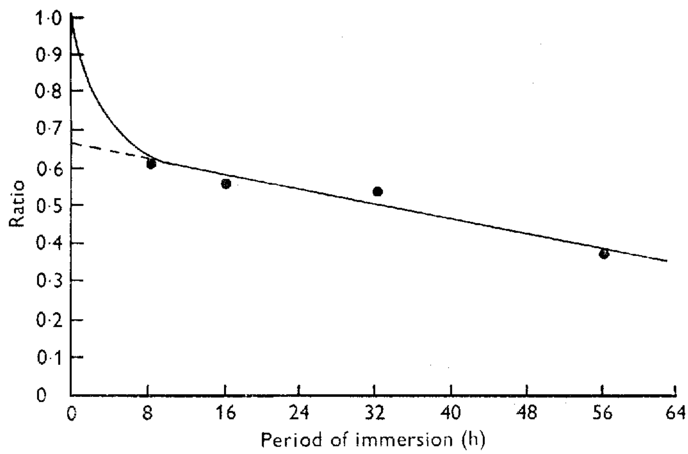

Fig. 2. Ratio of mass per unit length after immersion, to mass per unit length before immersion, of hay stem immersed in the reticulo-rumen of a cow for periods of up to 56 h.

placed in the rumen. Graphs of this ratio for each type of fibre against duration of the immersion indicated rapid decreases during the first few hours followed by much slower, linear decreases at longer times of immersion. Fig. 2 indicates the extent of this effect for hay. During the first 8 h about 40% of the DM was washed out of the fibre whereas during the subsequent 48 h only 23% of the DM was lost from the fibre. Beyond the first 8 h, loss of DM was linear with time. Extrapolation back to $t = 0$ gives an indication of the extent to which DM is readily removed from the fibre. The assumption is made that material that is so readily washed out of the fibre does not contribute to the strength of the fibre. The factor R for hay was 0·65; values of R for other fibres are given with the results.

Selection and preparation of materials

Cotton. White cotton (Coats 6 card, 36, 40 and 50 cottons) was found to have roughly the same breaking load as the fibrous foodstuffs. The 40 cotton had the most consistent strength and was used in all the rumen experiments.

Tests on cotton indicated that the moisture content of the fibre had an effect on its strength. The mean breaking loads together with the standard deviations were $1{\cdot}23 \pm 0{\cdot}03$, $1{\cdot}12 \pm 0{\cdot}03$ and $1{\cdot}11 \pm 0{\cdot}02$ kg for wet cotton, cotton taken off the reel, and cotton that was soaked in water for 4 h and freeze-dried, respectively. Variability due to differences in water content was avoided by testing in the freeze-dried condition.

For immersion in the rumen, lengths of cotton were loosely stretched on a light plastic frame and enclosed in a perforated container as described below. On retrieval from the rumen the short lengths required for testing were cut off between the points of contact of the cotton with the frame.

Grass. The main difficulty in determining the decrease in strength of fibrous foodstuffs in the rumen arises from variability in the strength of the starting material.

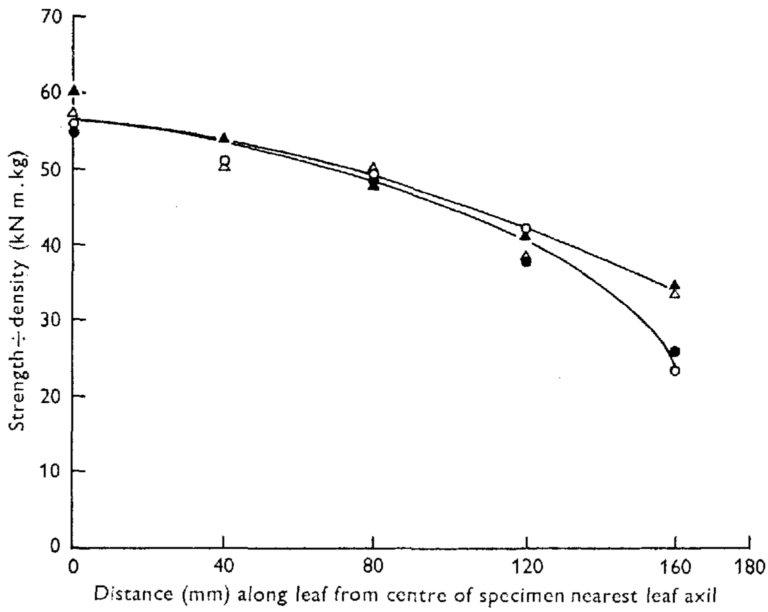

Fig. 3. Variation of strength ÷ density along four leaves of Italian ryegrass. The symbols refer to different leaves taken from one plant.

Italian ryegrass, which was used in this experiment because of its ready availability, was no exception, and many tests were made to find a way of sampling leaves to yield repeatability of the values of tensile strength.

Leaves were selected that were as free as possible from defects such as bends and tears, and the broad base and narrow tip were discarded. A linear relationship between load-to-fracture and cross-sectional area was observed for Italian ryegrass leaves removed from a single stalk. Three specimens were removed from each of five leaves from two stalks for this test. Mean values of the tensile strength (load-to-fracture ÷ area of cross-section of fresh leaf) for each leaf ranged from 48 to 57 MN/m^2 for nine of the leaves, the mean for one leaf being 75 MN/m^2. A more detailed study of the variation, along a leaf, in the quantity Ll/M related to strength (Fig. 3) indicated that it decreased from the base towards the tip.

In the light of these results it was decided to consider only ratios of strengths, specimens for immersion in the rumen being taken taken from positions on a leaf such that control specimens, not for immersion in the rumen, could be taken on both sides. In all tests on grass leaf, at least three specimens, five when possible, were taken from each leaf. If a leaf yielded three specimens, two were used as controls, the middle specimen being immersed in the rumen; if a leaf yielded five specimens, three were used as controls, the two intermediate specimens being immersed in the rumen.

Hay and straw. Consistent ratios for strength could not be obtained by testing specimens of straw and hay leaves prepared by the procedure used for grass. Leaves of hay and of straw were damaged so badly during conservation that it was not possible to take test pieces that were structurally sound. It was found that stems of hay and straw were less damaged and that they could be split longitudinally to give two test pieces that had the same tensile strength. One piece was tested for breaking load and the other placed at one of three sites in the rumen for one of four set times, 8, 16, 32 or 56 h. The piece that was immersed in the rumen was identified by notches cut at its ends, so that its strength could be related to that of the half, cut from the same piece of stem, that was not immersed. Pieces of hay and straw for immersion in the rumen were contained in a perforated plastic container (see below).

After immersion in the rumen, each piece of fibre was washed in water at 30° and dried for 16 h in an oven at 80°. Hay made from the summer's crop of Italian ryegrass was used for these experiments in December of the same year. Barley straw made from the summer's crop was tested in November of the same year.

Insertion of specimens in the rumen

It was necessary to prevent damage to the specimens by normal rumen movement and by rumination. Specimens were contained in perforated plastic tubes (hair curler tubes were satisfactory) which were enclosed in close-fitting and finely woven silk bags that allowed free access of rumen-liquor to the specimen. Specimens were positioned on the floor of the rumen by means of a 1 kg weight for the ventral and reticulum sites, and by suspension from the fistula plug for the dorsal site.

All experiments were done on a fistulated Friesian cow that was given 8 kg medium-quality hay daily as the sole food. The dorsal site was directly below the fistula, below the surface of the digesta at their lowest level. The ventral site was directly below the fistula, on the floor of the rumen. At the third site specimens rested on the bottom of the reticulum. Specimens were inserted at feeding times and withdrawn at intervals of up to 56 h later. On withdrawal, they were washed thoroughly in their containers to remove rumen liquor and to stop the reaction.

Three or four specimens of each fibre were placed at each site in the rumen for each of the immersion periods. Each type of fibre was immersed in the rumen in separate experiments. All of the specimens necessary for an experiment were put into the rumen at the start of the experiment and specimens were withdrawn after being immersed for periods as stated for the various fibres. The number of specimens that were put into the cow at the start of an experiment could therefore be up to sixty, withdrawing twelve (four from each of three sites) at the end of each of five periods.

RESULTS

All the fibrous materials were brittle, fracture occurring without measurable plastic deformation. Fracture occurred across the leaf or section of stem at right angles to the direction of the applied stress, with little or no tearing in that direction.

Cotton. Breaking loads, mass per unit length and the ratio stress:density at fracture are given in Table 1 for cotton immersed for 0, 8, 16, 32 and 56 h in the dorsal and ventral sites of the rumen and in the reticulum. Breaking load and mass

Table 1. *Effect on the load-to-fracture and strength of cotton thread of immersion in the reticulo-rumen of a cow for various periods at different sites*

(Mean values of eight determinations for fibres not immersed and of three for immersed fibres)

Site	Duration of exposure, t (h)	Breaking load, L (kg)	Mass/unit length, M/l (kg/m) × 10^4	Strength/density, Ll/M (m) × 10^{-3}	Ratio, breaking load at t: breaking load at t_0	Ratio, strength at t: strength at t_0	
						Value	Standard error of the mean
Not exposed	0	1·1	0·51	21·8	—	—	—
Dorsal	8	1·04	0·44	23·9	0·94	1·10	0·08
Ventral	8	1·10	0·47	23·6	0·99	1·08	0·04
Reticulum	8	1·09	0·55	19·6	0·98	0·90	0·08
Dorsal	16	0·95	0·37	25·6	0·86	1·17	0·04
Ventral	16	0·60	0·40	14·7	0·54	0·67	0·04
Reticulum	16	0·49	0·39	12·6	0·44	0·58	0·04
Dorsal	32	0·49	0·35	14·4	0·44	0·66	0·07
Ventral	32	0·12	0·23	5·9	0·11	0·27	0·07
Reticulum	32	0·03	—	—	—	—	—
Dorsal	56	0·07	0·23	3·2	0·06	0·15	0·02
Ventral	56	0	—	—	—	—	—
Reticulum	56	0	—	—	—	—	—

Table 2. *Ratios of strength of Italian ryegrass leaf immersed in the dorsal and ventral rumen and in the reticulum of a cow for periods of up to 20 h to that of leaf not immersed*

(The results are the means of three or four determinations, except for 7 and 17 h immersion when the results are means of six determinations, three from two separate experiments; SE of means are given in parentheses)

Duration of exposure (h)	Dorsal site	Ventral site	Reticulum site	Mean for the three sites
2	0·71 (0·18)	0·92 (0·10)	1·02 (0·25)	0·88 (0·11)
3	—	1·05 (0·06)	—	1·05 (0·06)
4	1·00 (0·14)	0·83 (0·10)	0·67 (0·15)	0·83 (0·09)
5	—	0·94 (0·02)	—	0·94 (0·02)
7	0·92 (0·17)	0·92 (0·11)	0·90 (0·09)	0·91 (0·07)
8	—	1·03 (0·04)	—	1·03 (0·04)
10	1·05 (0·20)	0·60 (0·15)	0·80 (0·15)	0·82 (0·12)
13	0·78 (0·15)	0·70 (0·25)	0·93 (0·20)	0·80 (0·11)
17	0·40 (0·10)	0·41 (0·09)	0·10 (0·06)	0·30 (0·10)
20	—	0·30 (0·11)	—	0·30 (0·11)

Table 3. *Ratios of strength of hay stem immersed for periods of up to 56 h in the dorsal and ventral rumen and in the reticulum of a cow to the strength of stem not immersed*

(Mean values for four determinations; SE of means given in parentheses)

Duration of exposure (h)	Dorsal site	Ventral site	Reticulum site	Mean for all sites
8	1·01 (0·11)	0·69 (0·14)	1·18 (0·06)	0·96 (0·07)
16	0·80 (0·26)	0·68 (0·17)	0·96 (0·37)	0·81 (0·14)
32	0·55 (0·10)	0·54 (0·09)	0·36 (0·13)	0·48 (0·05)
56	0·33 (0·02)	0·33 (0·04)	0·37 (0·13)	0·34 (0·04)

Table 4. *Ratios of strengths of straw stem immersed for periods of up to 56 h in the dorsal and ventral rumen and in the reticulum of a cow to the strength of stem not immersed*

(Mean values for four determinations; SE of means given in parentheses)

Duration of exposure (h)	Dorsal site	Ventral site	Reticulum site	Mean for all sites
8	1·04 (0·05)	0·91 (0·11)	0·76 (0·90)	0·90 (0·07)
16	0·71 (0·16)	0·89 (0·19)	0·87 (0·06)	0·82 (0·07)
32	0·81 (0·15)	0·87 (0·18)	0·61 (0·13)	0·76 (0·07)
56	0·68 (0·09)	0·47 (0·20)	0·69 (0·15)	0·61 (0·07)

per unit length decreased with duration of immersion at different rates for the three sites; specimens placed in the dorsal sac lost weight and strength most slowly whilst those placed in the reticulum were degraded at the fastest rate.

The ratio strength: density decreased more rapidly for fibre in the reticulum than in the ventral rumen, and most slowly in the dorsal rumen. These results indicated that differences in the rate of degradation of fibre should be expected from the siting of specimens at different positions in the reticulo-rumen.

If load-to-fracture were simply a function of cross-sectional area, i.e. if the cotton was homogeneous with regard to strength, the ratio strength after immersion in the rumen:strength of fibre not immersed in the rumen should remain equal to unity. The results indicated that this assumption was tenable only for short durations of immersion in the rumen, namely < 8 h for material in the reticulum, about 8 h for material at the ventral site and 16 h at the dorsal site. After longer times in the rumen the load-to-fracture of cotton decreased more rapidly than could be accounted for by decrease in area of cross-section. Strength decreased at roughly the same rate at each of the three sites in the rumen.

Italian ryegrass. Ratios of the strength of ryegrass leaf placed in the rumen for various times to the strength of the unexposed leaf are given in Table 2. This table has been assembled from the results of three separate experiments, each value being the mean of three, sometimes four, individual tests. Values given at 7 and 17 h are the means of six individual values, three from each of two experiments. The factor that was applied to compensate for the proportion of DM in the leaf that was not placed in the rumen and that was assumed not structural was 0·83. Leaf lost strength at the same rate at all three sites in the rumen. Load-to-fracture and mass per unit length both decreased as soon as leaf was placed in the rumen, but strength was unaffected, within the accuracy of the experiment, for times up to 10 h. Beyond this time the strength of the leaf decreased more quickly than could be accounted for by loss of structural DM, as was observed for cotton.

Hay. Ratios of the strength of hay stem, after various times of immersion at three different sites in the rumen, to the strength of stem that was not immersed are given in Table 3. The factor that was used to compensate for non-structural material in the hay was 0·65. There was no significant difference between rate of loss of strength of hay at the three sites. Hay lost half its strength after 30 h in the rumen.

Straw. The effect of immersing straw in the rumen on strength is given in Table 4, each site being considered separately. The factor that was used to compensate for non-structural material in the straw was 0·94.

The strength of straw decreased at the same rate at all three sites, within the accuracy of the measurements. The rate of decrease of strength was slower than that for any other materials that were tested, the half-strength value being reached after 68 h (extrapolated, on the assumption that the relationship between the strength ratio and time is linear for straw).

DISCUSSION

Nothing can be learned from this experiment about the mechanism of loss of strength of natural fibres on immersion in the rumen; their structure is too complex. The results for cotton, which is relatively much more homogenous in structure, indicate that this fibre is attacked, and so weakened, more at some points than others; enzyme action is not uniform over the entire surface of the fibre.

The results of these tests may be related to the times that cows take to eat and to ruminate when the different fibrous materials are given. Balch (1969) suggested that the total time spent eating and ruminating, per kg of DM eaten, would provide an

Table 5. *Comparison of times taken by fibrous foodstuffs to lose half their strength when immersed in the reticulo-rumen of a cow with the times spent eating and ruminating per kg of each type of fibre*

Foodstuff	Duration of immersion necessary to halve strength (h)	Ratio of time to half strength, relative to that for dried grass	Total time spent eating and ruminating* (min/kg)	Ratio of time spent eating and ruminating relative to that for dried grass
Italian ryegrass leaf	18	1	—	—
Dried grass (not ground)	—	—	48	1
Hay (stem)	35	1·9	—	—
Mean value for medium-and good-quality hay	—	—	98	2·0
Barley straw (stem)	68	3·8	—	—
Oat straw	—	—	168	3·5

* Values of Balch (1969).

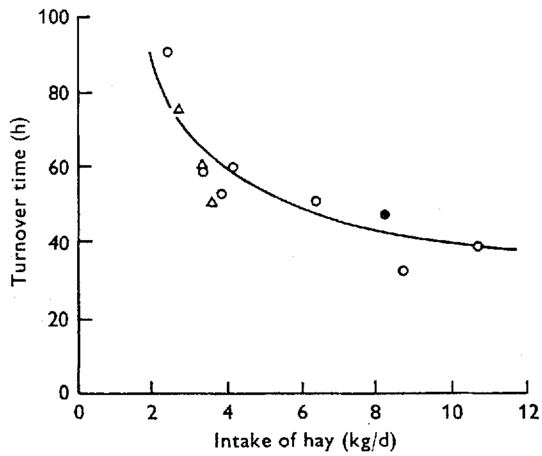

Fig. 4. Turnover times for hay (average times that particles of hay remain as digesta in the rumen) for cows and steers at different levels of daily intake. ○, Cows, timothy–clover hay (Makela, 1956); ●, cows, meadow-fescue–timothy–white clover hay (Balch & Line, 1957); △, 1-year Holstein-Friesian steers, Korean lespedeya, *Seriea lespedeya*, and prairie hays (Cason, Ruby & Stallcup, 1954).

index of fibrousness of diets for ruminants. Times of immersion in the rumen liquor necessary to cause a decrease in the strength of the fibre to half the strength of material that was not placed in the rumen, obtained from the present experiment, are given in Table 5. Ratios of each of these two times, relative to dried grass and to fresh ryegrass, 1:2·0:3·5 and 1:1·9:3·8 respectively (Table 5), were very similar. Total time spent eating and ruminating may therefore be proportional to the duration of immersion in the rumen necessary to halve the strength of the fibrous foodstuff.

The initial strengths of grass, hay and straw, 37, 150 and 210 MN/m^2 respectively (in the ratio 1:4·0:5·7) seemed unrelated to the total times of eating and ruminating. Periods of immersion in the rumen, required to reduce the strength of each type of fibre to zero, estimated by extrapolation, were 20, 73 and 140 h, i.e. in the ratio 1:3·6:7·0. Period of immersion in the rumen necessary to reduce the strength of fibrous foodstuffs to zero, may therefore be proportional to the initial strength of the fibre.

It would be of interest to establish what decrease of strength occurs before fibrous material passes out of the rumen but information on turnover times is sparse except for hay. For hay, Cason, Ruby & Stallcup (1954), Makela (1956), and Balch & Line (1957), give values for turnover times (Fig. 4), from which it seems reasonable to expect that the turnover time for hay (= average time that particles of hay remain as digesta in the rumen) in the present experiment, in which the cow was offered 8 kg/d, would be about 50 h. The results of this experiment indicate that hay stem would have lost almost two-thirds of its strength during this time, by immersion in the rumen, without mechanical deformation.

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