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MECHANICAL PROPERTIES OF A CRAB SHELL

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Abstract—1. The mechanical behaviour of crab shell is similar to that of prawn solid cuticle, especially in the occurrence of a low strain discontinuity in their bulk tensile stress–strain curves.

2. Although isolated crab chitin breaks in tension by the progressive failure of individual lamellae and exhibits post-fracture delamination, whole crab cuticle fails in an entirely brittle manner.

3. The mechanical properties of isolated crab chitin are highly susceptible to the effects of hydration as is typical of other animal chitins.

4. It is suggested that crab solid cuticle is a composite material, the properties of which are closely analogous to those of pre-stressed concrete.

INTRODUCTION

VERY few mechanical studies have been made on the hard shells (solid cuticle) characteristic of the arthropod integument and it is therefore not yet possible to provide a general model for the mechanical behaviour of the exoskeletons of this phylum. However, recent studies on insect solid cuticle (Jensen & Weis-Fogh, 1962; Hepburn & Ball, 1973; Hepburn & Joffe, 1974a, b) and prawn shells (Joffe *et al.*, 1975) indicate a number of similarities in the mechanical behaviour of insect and prawn solid cuticle as well as differences apparently due to the fact that the former are two-phase composite materials consisting of chitin fibres in a protein matrix while the latter include another phase, namely inorganic salts, resulting in a three-phase material.

In the present study, the mechanical behaviour of the solid cuticle and the isolated chitin of the crab, *Scylla serrata*, were investigated in order to determine their fracture behaviour, micro-hardness properties and general mechanical behaviour as composite materials. This crustacean was also studied in order to define more closely what might be peculiarly crustacean (i.e. three-phase dependent behaviour) as opposed to insectan (i.e. two-phase behaviour) and finally to provide additional evidence for generalizations about arthropod solid cuticle.

MATERIALS AND METHODS

All test specimens were taken from live crabs, *Scylla serrata*, caught on the southern Mozambique coast. Test specimens were cut from the inner and outer flat areas of the meropodites of the larger walking legs. Specimens were tested in fresh condition and in the dehydrated state. Wet and dry specimens of pure crab chitin were also tested. These samples were obtained from whole crab legs by treatment in 20% KOH at 293 K for 8 hr, rinsing until neutral pH, followed by 24 hr steeping in a 5% HCl solution. These procedures remove the protein matrix and inorganic salt phase respectively. The pure chitin specimens thus obtained were thoroughly washed and retained in distilled water until mechanical testing.

Uniform specimens of conventional dumb-bell shape were used in all tensile mechanical tests using a tensometer especially designed for delicate bio-materials (Joffe & Hepburn, 1974). The rate of extension used was 33 μm/min which corresponded to actual strain rates of about 0·7%/min. In addition to tensile testing, dynamic measurements were also made of the elastic modulus by means of a vibrational resonance technique (Worsnop & Flint, 1961) and the torsional rigidity modulus was determined from measurements of the frequency of torsional vibrations (Hearmon & Barkas, 1941). Full details of the above procedures are described elsewhere (Joffe *et al.*, 1974). Micro-hardness measurements were performed on whole crab shell with a Reichert Universal Camera Microscope "MeF" Microhardness Tester fitted with a diamond pyramidal indenting device.

RESULTS AND DISCUSSION

Chitin

The general tensile stress–strain behaviour for wet and dry crab chitin is shown in Fig. 1. It can be seen that both wet and dry crab chitin are non-Hookean and that neither exhibits a clear proportional limit. Whereas dry crab chitin shows a sharply defined failure point immediately beyond the ultimate stress, wet chitin does not have a clearly defined failure point. This results from the repeated observation during tensile testing that wet specimens break by progressive failure of individual successive lamellae so that what would have appeared as extensive plastic deformation beyond the ultimate

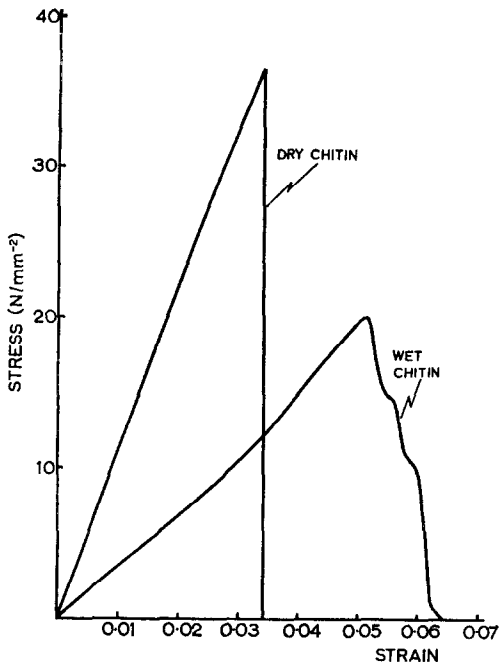

Fig. 1. Typical tensile stress–strain curves for wet and dry isolated crab chitin.

stress is in fact a result of inter-lamellar shear as failure progresses.

As will be seen from Fig. 1, isolated crab chitin shows markedly different mechanical properties depending upon the state of hydration. While the breaking stress for wet chitin was $19{\cdot}96 \pm 1{\cdot}6$ N/mm², that of dry chitin was $36{\cdot}24 \pm 2{\cdot}2$ N/mm² or about twice the wet strength. The elastic modulus increased from a wet chitin value of 330 to 1095 N/mm² when dry. The strain at breaking decreased from 6·1 per cent in the wet state to 3·4 per cent on drying. These results are consistent with the qualitative observations that wet crab chitin feels "rubbery" while dry chitin is stiffer and somewhat brittle.

Dynamic measurements of the torsional rigidity modulus exhibited a similar dependence on the state of hydration. The rigidity modulus for wet crab chitin was $27{\cdot}84 \pm 4{\cdot}7$ N/mm² which is considerably lower than that of 183 ± 26 N/mm² obtained for dry chitin. The increased value of the torsional rigidity modulus, the higher elastic modulus, the strength and the decreased value of the breaking strain for dry chitin are results of the consideralbe influence water has on the general properties of chitin structures. These results are entirely in keeping with those reported for other arthropod chitins (Hepburn, 1972; Hepburn & Ball, 1973; Joffe *et al.*, 1975). This water–chitin interaction also manifests itself in large changes in the damping of elastic oscillations of crab chitin strips. The damping coefficient of dry crab chitin (0·023) is an order of magnitude lower than that of wet crab chitin (0·120) and together with the increased strain at breaking suggests a role for water that is more active than merely filling the gaps left behind on removal of the protein and salt phases. This is reminiscent of the role of water in the mechanical behaviour of wood as well (Barkas, 1953).

Comparisons of the results of mechanical studies made on chitins of different species are somewhat difficult for a number of reasons. For example, under highly controlled and uniform testing conditions, standard deviations of 10 per cent reflect unusually good reproducibility for bio-materials which are notoriously variable, especially with regard to specimen thickness along the test axis. Added to this are such species-specific differences as density and arrangement of inter-lamellar chitin linking fibrils as well as distribution and average diameter of

Table 1. Mechanical properties of chitin taken from difference sources*

Source	Ultimate strength (N/mm²)	E (N/mm²)	ε (%)	G (N/mm²)	Damping coefficient	Reference
Crab						
Wet	20	330	6·1	28 ± 5	0·12	This paper
Dry	36	1095	3·4	183 ± 26	0·023	This paper
Prawn						
Wet	13	475	2·8	247 ± 28	0·036	Joffe *et al.* (1974)
Dry	21	1220	1·8	682 ± 75	0·023	Joffe *et al.* (1974)
Beetle						
Wet	26	630	2·0	~30	—	Hepburn & Ball (1973)
Dry	80	2900	0·6	—	—	Hepburn & Ball (1973)
Regenerated prawn						
Dry	47	2050	10·0	—	—	Joffe & Hepburn (1973)

* E, Elastic modulus; ε, elongation at breaking; G, torsional rigidity modulus. The values listed for regenerated prawn chitin are averages based on results from tests made on specimens of two distinct orientational types each of which exhibits exceptional anisotropy due to the manufacturing process.

pore canals, factors which may appreciably affect calculations of the real cross-sectional areas of these test specimens and hence the stress. Bearing these limitations in mind, a number of useful comparisons can however still be made.

As can be seen from Table 1, wet crab chitin is about as strong as both wet prawn and beetle chitin cut in the same plane as well as regenerated prawn chitin. This more or less uniform value for the strength of wet chitin persists despite the grossly different architectural arrangements seen in the examples cited. Regarding the elastic modulus for wet chitin (Table 1), the effects of dehydration are virtually the same and there is a characteristic ratio of about 3 : 1 for the increase in the elastic modulus on drying. However, a consideration of the changes in the values for the torsional rigidity moduli of these same materials on drying shows that crab chitin changes considerably more than does prawn chitin but at the same time the prawn values are an order of magnitude higher than are the former. This probably stems from the fact that there is a dense distribution of inter-lamellar chitin linking fibrils in prawn shells while inter-lamellar cross-linking in crab shells is predominantly proteinaceous. This is confirmed by the observation that slabs of crab chitin left soaking in water for long periods delaminated with no mechanical interference. The loose nature of the chitin lamellae has also been observed in another crab species (Dennell, 1973).

Whole crab shell

The experiments described above were repeated on specimens of untreated whole crab shell. Wet shell has a breaking stress of $30{\cdot}14 \pm 5$ N/mm^2 and an elastic modulus of 481 ± 75 N/mm^2 while dry crab has a breaking stress of $23{\cdot}01 \pm 3{\cdot}8$ N/mm^2 and a modulus of 640 ± 89 N/mm^2. The elastic modulus values differ greatly in magnitude from the isolated chitin values and while there is a suggestion of hydration dependence, the changes on dehydration of whole crab shell were by no means as significant as those occurring in the pure chitin case.

A typical tensile stress–strain curve for both wet and dry crab is shown in Fig. 2. A comparison of these curves with those for chitin (Fig. 1) demonstrates that both wet and dry whole crab shell exhibits a unique discontinuity in the region of low strain that does not occur in the chitin curves. This same discontinuity has been observed for whole prawn shells (Joffe *et al.*, 1975). However, the bulk tensile stress–strain behaviour of isolated crab chitin, prawn chitin (Joffe *et al.*, 1975), regenerated chitin (Joffe & Hepburn, 1973), beetle chitin (Hepburn, 1972; Hepburn & Ball, 1973) as well as from various insect solid cuticles (Hepburn & Ball, 1973; Hepburn & Joffe, 1974a, b) is completely free even of any suggestion of such a discontinuity. As in the case of whole prawn shell (Joffe *et al.*, 1975) the occurrence

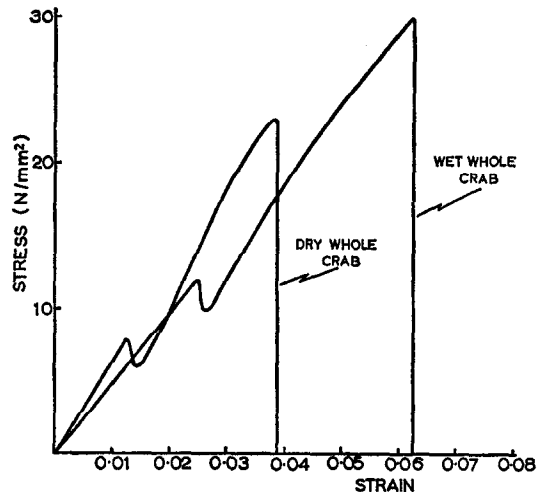

Fig. 2. Typical tensile stress–strain curves for wet and dry whole crab cuticle with low strain discontinuities.

of this discontinuity is associated with the tensile failure of the inorganic salt phase of the skeletons. This salt matrix is extremely brittle and consequently, when specimens of whole shell are stretched, brittle failure of the salt phase occurs at low strain resulting in the characteristic discontinuity and leaving the still intact chitin and protein phases to bear the load. This interpretation gains additional support from the fact that torsional rigidity measurements could not be carried out due to the extreme brittleness of this material.

Interpretations of the properties of bio-materials are hampered by a number of parameters that cannot be measured by currently available technology, such as inter-lamellar binding strengths and friction, Poisson's ratio and interactions between the various phases, etc. Hence the possible influence of many factors remains unknown. Similarly, other parameters which can be measured are biologically obscure. Such is the case with indentation micro-hardness, an index of the material's resistance to plastic indentation. Micro-indentations of about 25 μm depth were made and measured on the external surfaces of samples of dry whole cuticle taken from the outer and inner sides of the meropodites after it was noticed during handling that the two sides of the segment were tangibly different. The outer portion of the leg yielded an average value of $81{\cdot}06 \pm 16{\cdot}6$ while the inner leg cuticle was $82{\cdot}21 \pm 18{\cdot}8$, values which are not significantly different. The relative micro-hardness is therefore the same on both external surfaces of the leg despite differences in cuticular thickness and apparent tangible rigidity.

Failure of both wet and dry whole crab shell occurs sharply at the ultimate breaking stress and there is no detectable plastic deformation of these

materials. Figure 3 shows a scanning electron micrograph typical of a crab shell specimen failing in tension. The uniformity of the fracture edge indicates that this shell has failed in an entirely brittle manner and that no delamination of the lamellae occurs. In contradistinction to this, Fig. 4 shows the fracture edge of pure crab chitin. It will be seen that extensive delamination occurred and the various lamellae appear to have broken almost independently of each other. This observation is entirely consistent with the previous conclusion on the extreme paucity of chitinous inter-lamellar linkages in crab shell. Thus, in the whole shell, inter-lamellar linkages must be predominantly proteinaceous and the role of the binder is to give the whole crab shell its integrity as a composite material. Crack propagation from one lamella to the next is mediated through what would appear to be a brittle binder phase. The tensile failure of crab shell differs substantially from the fracture behaviour of prawn shells in which there is a clear delamination of the exocuticle from the endocuticle as well as endocuticular sub-delamination (Joffe *et al.*, 1974) and insect cuticles (Hepburn & Ball, 1973; Hepburn & Joffe, 1974a).

Since there is a sharp increase in the elastic moduli of crab shell and isolated crab chitin on drying, as in other arthropod shells, it is concluded that under normal functional use during life, cuticular water considerably reduces the en-brittling effects of the inorganic salt phase. It would appear then that a live wet cuticle is a composite material which exhibits both reasonable flexibility and adequate strength and toughness. One might speculate on the role of the three phases as they operate in the composite shell. Such a composite would have been designed for great compressive strength and the role of the inorganic salt phase would be to supply this compressive strength as a sort of concrete. The chitinous skeleton would supply tensile strength (useful in bending) while the protein phase is probably present as a reinforcement for the inorganic phase and possibly giving rise to a pre-stressed type of material once sclerotization of the protein is complete. Since the operational criteria for these shells are not known, it is not possible to state to what extent the actual shell represents an optimization of design; however, the evolutionary longevity of arthropod cuticle suggests that this construction is a more than adequate solution to skeletal design.

CONCLUSIONS

The results of the present paper show that the tensile behaviour, elastic modulus and deformation properties of isolated crab chitin are completely consistent with those of other arthropodan chitins. Under tensile loading conditions it is seen that whole crab shell exhibits a mode of fracture which does not include the delamination of lamellae common to the other arthropods thus far studied. Whole crab shell does, however, show the low strain discontinuity previously seen for prawn cuticle but absent from insect cuticle. The inference is that the three-phase crustacean cuticles which share the discontinuity in the bulk tensile stress–strain curve are uniquely different from the insect cuticles which lack the third, inorganic salt phase. However, once the crustacean cuticle is stretched beyond the point at which the inorganic salt phase fails, the load-bearing properties and behaviour of the remaining two phases of the crustacean shells are virtually identical to those of the insects.

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REFERENCES

BARKAS W. (1953) *Mechanical Properties of Wood and Paper*. North-Holland, Amsterdam.

DENNELL R. (1973) The structure of the cuticle of the shore-crab *Carcinus maenas* (L.). *Zool. J. Linn. Soc.* **52**, 159–163.

HEARMON R. F. S. & BARKAS W. (1941) The effect of grain direction on the Young's moduli and rigidity moduli of beech and sitka spruce. *Proc. Phys. Soc.* **53**, 674–680.

HEPBURN H. R. (1972) Some mechanical properties of crossed fibrillar chitin. *J. Insect Physiol.* **18**, 815–825.

HEPBURN H. R. & BALL A. (1973) On the structure and mechanical properties of beetle shells. *J. mat. Sci.* **8**, 618–623.

HEPBURN H. R. & JOFFE I. (1974a) Hardening of locust sclerites. *J. Insect Physiol.* **20**, 631–635.

HEPBURN H. R. & JOFFE I. (1974b) Locust solid cuticle—a time sequence of mechanical properties. *J. Insect Physiol.* **20**, 497–506.

JENSEN M. & WEIS-FOGH T. (1962) Biology and physics of locust flight—V. Strength and elasticity of locust cuticle. *Phil. Trans. R. Soc., B***245**. 137–169.

JOFFE I. & HEPBURN H. R. (1973) Observations on regenerated chitin. *J. materials Sci.* **8**, 1751–1754.

JOFFE I. & HEPBURN H. R. (1974) A simple low-cost tensometer for bio-materials testing. *Experientia.* **30**, 113–114.

JOFFE I., HEPBURN H. R., NELSON K. J. & GREEN N. (1975) Mechanical properties of a crustacean exoskeleton. *Comp. Biochem. Physiol.* **50A**, 545–549.

Worsnop B. L. & Flint H. T. (1961) *Advanced Practical Physics*, 9th edn). Methuen, London.

Key Word Index—Scylla serrata; chitin; cuticle; elastic modulus; torsional modulus; hydration effects; mode of fracture; pre-stressed concrete.

Fig. 3. Brittle fracture of whole crab cuticle that has failed in tension.

Fig. 4. Fracture of isolated crab chitin that failed in tension. Note the extensive delamination of the lamellae.