生物策略表

類別	生物策略 (Strategy)
生物策略 STRATEGY	堅硬而可延展的線 (Threads have hard flexible coating)
生物系統 LIVING SYSTEM	淡菜 *Mytilus edulis* (Common mussel)
功能類別 FUNCTIONS	#應付機械磨損 #應付張力 #改變材料特性 #防止變形 #Manage mechanical wear #Manage tension #Modify material characteristics #Prevent deformation
作用機制標題	淡菜的足絲透過角質層外犧牲性交叉鏈接而同時具備堅硬性及可伸展性 (The byssal threads of mussels display both hardness and extensibility thanks to sacrificial cross-links in the outer cuticle.)
生物系統/作用機制示意圖	

作用機制摘要說明 (SUMMARY OF FUNCTIONING MECHANISMS)

淡菜 (mussel) 吸收的能量中高達 70%會被足絲 (byssal thread) 所消耗，這些細絲可是可以讓淡菜依附在堅硬表面的彈性纖維。

「Matthew Harrington 是一位負責此計劃的研究員…解釋了研究足絲角質層 (byssus cuticle) 的動機：「保護性塗層 (protective coating) 可以延長物質或工具的使用壽命，但在設計聚合物及複合材料時很少會同時考慮其堅硬度及伸展性，透過個案瞭解如何保護可延展性基質變得十分重要。」足絲的角質層佈滿突起 (knobby)，是由於在連續的表面基質中包裹了很多亞微米大小 (submicron-sized) 的顆粒狀構造，在拉長角質層時會在基質中形成亞微米大小的裂縫，相信能防止更大的裂縫形成而導致斷裂。

要瞭解角質層奇特的機械特質，重點是角質層中含有高濃度的鐵離子，以及胺基酸中的不常見的酪胺酸 (tyrosine) 修飾物，通常稱為多巴 (dopa)，在角質層組成的淡菜足蛋白-1 (mfp-1) 中有高濃度含量。多巴因為與過渡金屬離子尤其鐵離子有驚人的親和力，而與典型的胺基酸區分開來。普朗克研究院中研究膠體 (colloid) 及接合劑 (interface) 的科學家 Admir Masic 解釋：「當 2-3 個多巴殘基 (residue) 與單個鐵離子結合，會製造出一種非常穩定而且可以與結構蛋白相互連結的複合物」這些金屬-蛋白複合物有著非常高的破斷力（差不多是共價鍵的一半），但與共價鍵 (covalent bond) 不同的是有著可破碎性，

使這種物質成為理想的犧牲性交叉鏈接 (sacrificial cross-links) 物料。」(Science Daily 2010)

The marine mussel's byssal threads can dissipate up to 70% of the energy it absorbs. These threads are elastomeric fibers that enable the mussel to attach to hard surfaces.

"Matthew Harrington, a researcher who worked on the project…explains the motivation for studying the byssus cuticle: 'Protective coatings are important for prolonging the lifetime of materials and devices. However, considering that hardness and extensibility are seldom coupled in engineered polymers or composites, understanding how one protects a flexible substrate becomes quite important.' Byssal cuticles have a knobby appearance due to inclusions of submicron-sized granular structures in an apparently continuous matrix. Submicron-sized tears that form in the matrix during stretching of the cuticle are believed to hinder the formation of larger cracks that could lead to material failure.

Central to understanding the peculiar mechanical behaviour of the cuticle are the high concentration of iron ions in the cuticle and the presence of an uncommon modification of the amino acid tyrosine known commonly as dopa. Dopa is found at high concentrations in the main cuticle component, mussel foot protein-1 (mfp-1). Dopa is distinguished from typical amino acids due to its impressive affinity for complexing with transition metal ions, particularly iron. As Admir Masic, a scientist at the Max Planck Institute for Colloids and Interfaces who worked on the project, explains, 'when 2-3 dopa residues complex with a single iron ion, they create an incredibly stable complex that can be utilized to cross-link structural proteins.' These metal-protein complexes have a high breaking force (nearly half that of covalent bonds), but unlike covalent bonds they are reversibly breakable, making them ideal for creating sacrificial cross-links." (Science Daily 2010)

文獻引用 (REFERENCES)

「結構性分子及複合材料中的犧牲性鍵結及隱匿長度 (hidden length)，被證實能透過分子層面的可逆性能量消耗機制 (energy-dissipation mechanism)，大幅增加生物材料的斷裂韌性。這種機制依靠 100 eV 的能量降低熵 (entropy) 及提高焓 (enthalpy)，令被稱為犧牲性鍵結的弱鍵結斷開時釋放出來的分子小塊能夠延展。這種能量相比打破聚合物骨架的能量要大數個 eV。在很多生物案例中，犧牲性鍵結被發現是可逆的，因此為物料額外提供了『自癒』的特性。」(Fantner 2006:1411)

「淡菜可延展的足絲，因為有充滿蛋白質的角質層外層，使其在海浪沖刷的棲息地中免被磨損，足絲的表層甚至比中心要堅硬大約五倍。數個物種中的足絲有著顆粒狀的角質層表面，其中含有豐富的兒茶酚胺 3,4-dihydroxyphenylalanine（多巴）以及無機離子，尤其是三價鐵離子。顆粒狀角質層有著特別高的硬度及延展組合特性。我們以原位共振拉曼光譜儀 (in situ resonance Raman spectroscopy) 探究了足絲角質層的化學組成，並證實了角

質層是一個被有著不尋常群集分佈兒茶酚胺-鐵螯合物所固定的聚合物支架。我們展示了一個與足絲角質層的化學及機制相符的模型，顆粒透過密集的交叉鏈接提高了堅硬度，而較稀疏的交叉鏈接則加強了延展性。」(Harrington et al. 2010:216)

"Sacrificial bonds and hidden length in structural molecules and composites have been found to greatly increase the fracture toughness of biomaterials by providing a reversible, molecular-scale energy-dissipation mechanism. This mechanism relies on the energy, of order 100 eV, needed to reduce entropy and increase enthalpy as molecular segments are stretched after being released by the breaking of weak bonds, called sacrificial bonds. This energy is relatively large compared to the energy needed to break the polymer backbone, of order a few eV. In many biological cases, the breaking of sacrificial bonds has been found to be reversible, thereby additionally providing a 'self-healing' property to the material." (Fantner 2006:1411)

"The extensible byssal threads of marine mussels are shielded from abrasion in wave-swept habitats by an outer cuticle that is largely proteinaceous and approximately fivefold harder than the thread core. Threads from several species exhibit granular cuticles containing a protein that is rich in the catecholic amino acid 3,4-dihydroxyphenylalanine (dopa) as well as inorganic ions, notably $Fe3^{+}$. Granular cuticles exhibit a remarkable combination of high hardness and high extensibility. We explored byssus cuticle chemistry by means of in situ resonance Raman spectroscopy and demonstrated that the cuticle is a polymeric scaffold stabilized by catecholato-iron chelate complexes having an unusual clustered distribution. Consistent with byssal cuticle chemistry and mechanics, we present a model in which dense cross-linking in the granules provides hardness, whereas the less cross-linked matrix provides extensibility." (Harrington et al. 2010:216)

參考文獻清單與連結 (REFERENCE LIST)

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延伸閱讀
生物系統延伸資訊連結 (LEARN MORE ABOUT THE LIVING SYSTEM/S)
https://en.wikipedia.org/wiki/Blue_mussel
撰寫/翻譯/編修者與日期
譚國鋈翻譯 (2020/04/07)；許秋容編修 (2020/11/25)；紀凱容編修 (2020/11/25)
AskNature 原文連結
https://asknature.org/strategy/threads-have-hard-flexible-coating/