STRUCTURES & MECHANICS

Permanent Underwater Adhesion: Lessons from Marine Byssus Chemistry

How mussels achieve permanent wet adhesion without surface preparation

5	3	1–3	5
convergent strategies	principle clusters	TRL range	featured strategies

PROBLEM FRAMING

Water contamination reduces adhesion by orders of magnitude — water displaces adhesives from surfaces before curing. Marine foulers achieve permanent adhesion to wet, dynamic surfaces without surface preparation or controlled temperature. The mechanism involves DOPA-mediated chemistry operating at the wet interface.

Application domains: medicine, materials, water_management

Principle cluster: adhesion, gradient materials, elasticity

Physics & Mechanism

Underlying physics

[DRAFT] Mussel adhesion plaques contain a gradient of five mussel foot proteins (mfp-1 through mfp-5) with increasing DOPA (3,4-dihydroxyphenylalanine) content toward the substrate interface. DOPA binds to oxide surfaces (TiO■, FeOOH, SiO■) through bidentate coordination with exposed metal ions — bond energy ~40–80 kJ/mol, comparable to covalent bonds. Critically, DOPA is maintained in the reduced (catechol) state at the adhesive interface by mfp-6 anti-oxidation proteins; oxidised DOPA (quinone) forms cohesive crosslinks in the bulk of the plaque. The byssus thread implements a mechanical gradient: stiff distal region ($E \approx 500$ MPa) grades to compliant proximal region ($E \approx 16$ MPa) over 2 cm, dissipating hydrodynamic loading energy. Engineering analogues: polydopamine (PDA) coatings achieve broad-spectrum adhesion on wet surfaces; DOPA-modified PEG hydrogels achieve surgical tissue adhesion. Key limitation: DOPA oxidation in ambient oxygen reduces binding efficiency; anaerobic deposition conditions required for maximum performance. [END DRAFT]

Biological Strategies

Modify Material Characteristics Animals

Fibulins function as structural proteins within the extracellular matrix, the material surrounding and supporting cells in animal tissues. Such proteins possess multiple calcium-binding domains arranged in tandem, which allow them to sequester calcium ions and form cross-linked networks with other matrix components including elastin, fibrillin, and fibronectin. This calcium coordination strengthen…

Design principle: Fibulin-based tissue architecture demonstrates a composite material strategy where reinforcing elements are strategically cross-linked to balance competing mechanical requirements. The calcium-binding

Attach Temporarily Octopus sucker · TRL 3/9 · 22 genera

The octopus generates switchable adhesion through muscular control of its suckers, which are specialized structures composed of concentric layers of muscle tissue, a flexible acetabulum (cup), and an intricate sensory epithelium. When an octopus sucker makes contact with a surface, radial and circular muscle fibers contract to deform the flexible cup into a domed shape, creating a sealed chamber. …

Design principle: Engineer switchable adhesion systems using active pneumatic-muscular deformation rather than passive suction alone. Design bilayer or multilayer soft structures with embedded muscle-like actuators tha

Prevent Fracture/Rupture Golden silk spider · TRL 1/9 · 25 genera

In all cases, the advances in understanding how biology uses hierarchical design to create failure and defect-tolerant materials with emergent properties lays the groundwork for engaging into these topics. Biological mechanical materials are particularly inspiring for their unique combinations of stiffness, strength, and toughness together with lightweightness, as assembled and grown in water from…

Design principle: Bioinspired materials engineering impacts the design of advanced functional materials across many domains of sciences from wetting behavior to optical and mechanical materials. In all cases, the advan

Move in/Through Gases Leafcutter ant · TRL 3/9 · 31 genera

The versatility of the fish to adapt to diverse swimming requirements has attracted the attention of researchers in studying bioinspired propulsion for developing efficient underwater robotics. The tail/caudal fin is a major source of thrust generation and is believed that the fish modulates its fin stiffness to optimize the propulsive performance. Inspired by the stiffness modulation of fish fins…

Design principle: Yet, replicating and scaling the balance between the structural and fluid-dynamical parameters of unsteady membrane wings for engineering applications remains challenging. In this study, we introduce

Manage Tension Australian frog

When provoked, Notaden bennetti frogs secrete an exudate which rapidly forms a tacky elastic solid ("frog glue"). We conducted macroscopic tests in air to assess the tensile strength of moist glue (up to 78 +/- 8 kPa) and the shear strength of dry glue (1.7 +/- 0.3 MPa). We also performed nanomechanical measurements in water to determine the adhesion (1.9-7.2 nN or greater), resilience (43-56%), w…

Design principle: This protein-based material acts as a promiscuous pressure-sensitive adhesive that functions even in wet conditions. We conducted macroscopic tests in air to assess the tensile strength of moist glue

Combination Intelligence

Strategies that address different aspects of the same problem and are not redundant when combined.

Prevent Fracture/Rupture + Move in/Through Gases

Shared principles: adhesion, elasticity, gradient materials, self organization

These strategies share 4 underlying principles including adhesion and elasticity and gradient materials. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

Attach Temporarily + Prevent Fracture/Rupture

Shared principles: adhesion, elasticity, gradient materials

These strategies share 3 underlying principles including adhesion and elasticity and gradient materials. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

Attach Temporarily + Move in/Through Gases

Shared principles: adhesion, elasticity, gradient materials

These strategies share 3 underlying principles including adhesion and elasticity and gradient materials. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

EXPLORE THE INTERACTIVE VERSION

This report is a static synthesis. The interactive version includes live strategy cards, the Design Brief generator, Combination Intelligence engine, and filtering by TRL, scale, and principle.

`https://atlasofnature.org/challenge/underwater-adhesion`

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