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MPA & DVS Case Study 627

Measuring importance of humidity control on healing in bio-based wound dressings

Sean McIntyre [1], Marilou Vinot [2], Paul Iacomi [1]
[1] Surface Measurement Systems Ltd. Unit 5, Wharfside, London HA0 4PE, United Kingdom
[2] Polytech Nantes, Rue Christian Pauc, 44300 Nantes, France

Wound dressings regulate healing by controlling fluid uptake, moisture retention, and gas exchange at the wound interface. These functions arise from intrinsic material–water interactions and the resulting transport pathways. Here, the hygroscopic and barrier properties of two commercially available wound dressings, representing distinct polymer architectures, were investigated using Dynamic Vapor Sorption (DVS Resolution) and membrane permeation analysis (MPA Horizon). A dense hydrocolloid composite exhibited diffusion-limited hydration, negligible water uptake below high relative humidity, pronounced sorption hysteresis, and very low water vapor transmission rates, consistent with slow swelling and restricted transport pathways. In contrast, a porous calcium alginate fibrous network showed strong water affinity across the full humidity range, rapid swelling, large sorption capacity, and high vapor and oxygen transmission dominated by open porosity. Sorption and permeation measurements using a 50:50 ethanol–water vapor mixture demonstrated enhanced early-stage wetting without substantially altering permeability. Together, the results highlight swelling-controlled transport as a unifying mechanism linking sorption kinetics and permeability, providing a materials-based framework for interpreting dressing performance under dynamic hydration conditions.

Introduction

Effective wound management and healing depend on maintaining a balanced local micro-environment that supports tissue regeneration while protecting the wound bed from external contamination. Central to this process is the regulation of wound exudate, a complex aqueous fluid containing water, electrolytes, proteins, and cellular components that mediates inflammation, nutrient transport, and tissue remodeling (healing). An optimal dressing must therefore balance fluid absorption with moisture retention, as excessive fluid accumulation can cause peri-wound maceration, whereas uncontrolled evaporation leads to desiccation and impaired wound repair.[1] These competing requirements are governed by the intrinsic interactions between the dressing material and water, and by the resulting transport pathways for vapor and gases.

From a materials science perspective, wound dressings span a broad range of polymer architectures that differ fundamentally in how they interact with water. Two widely used but mechanistically distinct classes are dense hydrocolloid composites and open, hydrophilic polymer networks. In hydrocolloid composites, hydrophilic components (cellulose, gelatine, pectin) are embedded within a continuous, often elastomeric matrix and frequently coupled to an external polymeric backing layer,[2] An example hydrocolloid structure is shown below, Figure 1.

Water uptake in such hydrocolloid composite systems is diffusion-limited and typically occurs only once sufficient hydration allows swelling of the embedded domains. These systems remain impermeable to bacteria and viruses, making them suitable for low to moderately exuding wounds[3].

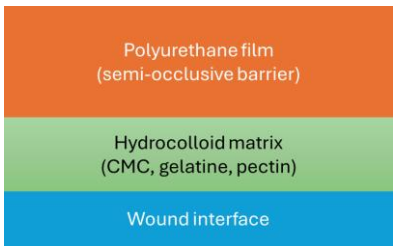

Figure 1: An example hydrocolloid composite structure

In contrast to hydrocolloid composites, hydrophilic polymer networks, such as ionically crosslinked calcium alginates and polysaccharides supplied in fibrous or nonwoven form, interact strongly with water through rapid polymer–solvent association and network expansion. In these materials, fluid uptake is governed by swelling and capillary infiltration within an open pore structure rather than by diffusion through a continuous barrier phase[3]. Example structure shown in Figure 2.

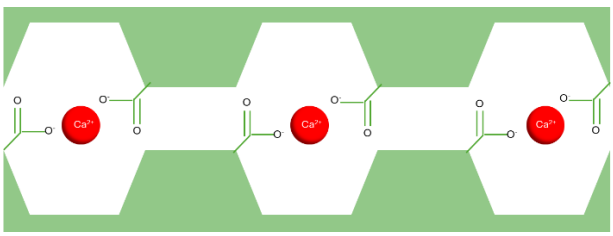

Figure 2: An example ionically crosslinked network

These intrinsic differences in polymer chemistry and morphology strongly influence sorption kinetics, water vapor transmission rate (WVTR), and oxygen transmission rate (OTR), which together determine the ability of a dressing to regulate moisture and gas exchange at the wound interface. Sorption capacity reflects the extent to which a material can absorb and retain wound fluid, while vapor and gas transmission rates govern evaporative losses and oxygen availability, both of which are critical to healing. Although these parameters are routinely reported, they are often measured using static or end-point methods that do not capture hydration kinetics or the dynamic evolution of transport pathways as the material swells.

In this study, two commercially available wound dressings were selected as representative examples of these contrasting material classes: DuoDERM, a hydrocolloid composite and Cutiderm, a fibrous calcium alginate hydrogel network. Rather than treating these materials purely as clinical products, they are examined here as model systems to elucidate how intrinsic material structure governs water sorption, swelling behavior, and coupled vapor and gas transport. These parameters are critical in predicting a wound dressings' performance.

Dynamic Vapor Sorption (DVS) was employed to quantify the kinetics and magnitude of water uptake under controlled humidity and temperature, providing insight into hydration thresholds, swelling behavior, and hysteresis. Complementary measurements of WVTR and OTR were conducted using the MPA Horizon, a dynamic membrane permeation analyzer, allowing direct assessment of vapor and gas flux under controlled humidity gradients. To bridge the gap between idealized water vapor measurements and physiological relevance, sorption and permeation experiments were also performed using a 50:50 v/v ethanol–water vapor mixture[4], selected as a regulatory-accepted blood simulant based on its polarity and solvation characteristics (FDA, ISO 10993-18:2020).

By directly linking gravimetric sorption behavior with dynamic permeability measurements, this work aims to clarify how swelling-controlled transport emerges from intrinsic polymer–water interactions and material architecture. The comparative analysis highlights how dense hydrocolloid composites and open hydrophilic polymer networks respond differently to humidity and fluid exposure, and how these responses translate into distinct moisture-management functions. Such insights provide a mechanistic framework for interpreting dressing performance and for rational selection of materials according to wound exudate level and healing requirements, while also illustrating the importance of dynamic measurement methodologies in evaluating moisture-responsive biomaterials.

Methods

The materials of study were the commercially available DuoDERM and Cutiderm wound dressings. HPLC grade water was used to generate humidity, ethanol (97%), oxygen (99.99%), dry N_2 was used as the carrier gas in both MPA and DVS experiments.

Uptake measurements at controlled humidity and temperature were monitored in-situ using a DVS Resolution instrument. During the experiments an average 70 ± 10 mg of sample material was cut into the sample pan, Figure 3.

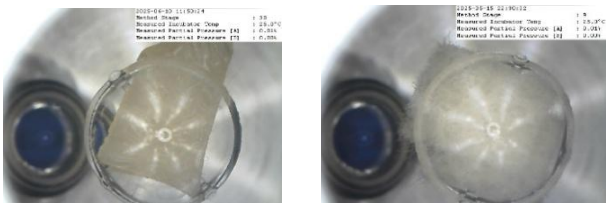

Figure 3. Samples of a hydrocolloid composite (left) and a fibrous hydrogel network (right) in the DVS sample chamber.

Humidity or a blood-simulant (water/ethanol)[4] was introduced in steps to the sample until mass equilibrium was achieved at each step, which was changed between 0 – 95 %RH, as shown in Figure 4. The temperature was set to 25 or 37 ˚C to simulate both room and body temperature.

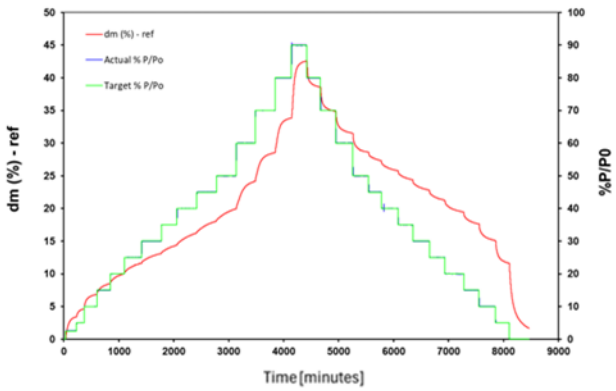

Figure 4. Example DVS water sorption experiment.

Water vapor, water/ethanol vapor, and oxygen permeation was measured using the Membrane Permeation Analyzer (MPA Horizon). A cross-flow membrane permeation device where humidity (using a nitrogen carrier gas) or pure oxygen was introduced to the top of the membrane and a sweep gas (helium) was used to carry permeating humidity to the outlet sensors. Similar to the DVS, WVTR and OTR measurements were carried out at 25 and 37 °C using a flow rate of 20 sccm above and below the membrane.

Results

Water sorption isotherms

Water sorption measurements at 25 and 37 °C were first used to probe the intrinsic interactions between the wound dressing materials and humidity, and to establish how hydration evolves with relative humidity and temperature. From Figure 5, the two materials exhibit markedly different sorption isotherms, reflecting fundamental differences in polymer chemistry, morphology, and transport pathways.

From Figure 5a, the hydrocolloid composite displays minimal water uptake over a broad range of relative humidity, with sorption remaining negligible below approximately 60–70 %RH at both 25 °C and 37 °C. Only at high humidity does a sharp increase in uptake occur, and even then the total mass gain remains below 2 % at 90 %RH. This behavior is characteristic of diffusion-limited hydration in dense composite systems, where hydrophilic domains are embedded within a continuous, low-permeability polymer matrix and further constrained by an external backing layer. Water vapor must first diffuse through this continuous phase before interacting with the hydrophilic components, resulting in a pronounced humidity threshold for measurable uptake.

A clear hysteresis between adsorption and desorption is observed, indicating that once water has penetrated the composite, it is partially retained during drying. This hysteresis is consistent with slow relaxation and incomplete de-swelling of the hydrocolloid domains, leading to trapped moisture within the material.

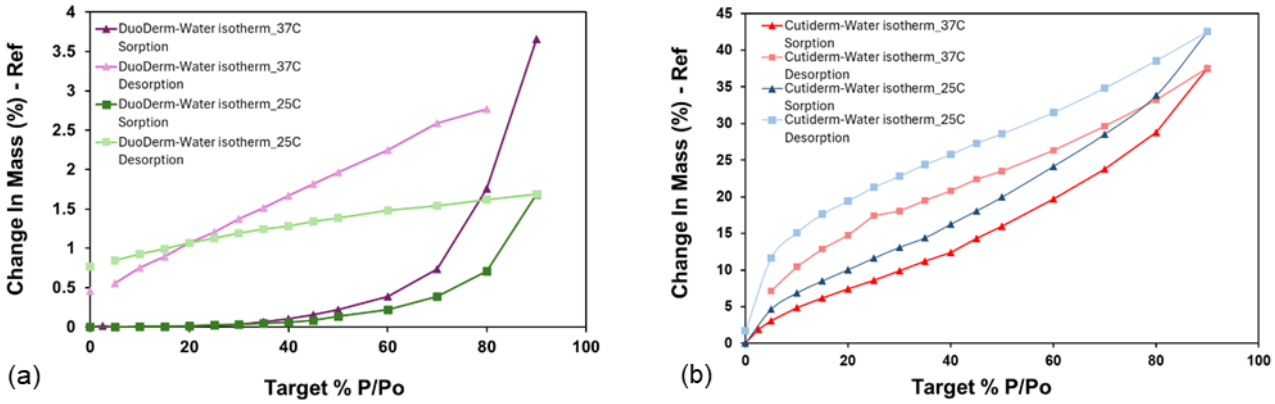

Figure 5. Water sorption isotherms of (a) hydrocolloid composite and (b) fibrous hydrogel network (25 and 37 °C).

Increasing the temperature from 25 °C to 37 °C results in a modest increase in total uptake, reflecting enhanced molecular mobility and slightly faster diffusion, although the overall hydration remains limited. Importantly, the small magnitude of the temperature effect confirms that the material does not transition to a highly swollen or permeable state under the conditions explored.

In contrast, from Figure 5b, the calcium alginate fibrous network exhibits strong water affinity across the entire humidity range. Sorption begins at very low relative humidity and increases continuously with increasing water activity, reaching mass gains of approximately 40–45 % at high relative humidity. This behavior reflects the intrinsically hydrophilic nature of alginate polymers, whose carboxylate groups readily form hydrogen bonds with water, combined with an open, fibrous morphology that facilitates rapid vapor access to the polymer surface. Hydration in this system is governed by swelling and network expansion rather than by diffusion through a continuous barrier phase.[5]

The alginate network also shows pronounced hysteresis, with substantial water retained during desorption. This indicates that absorbed water becomes incorporated into the swollen polymer network and is released only slowly upon drying. Such behavior is consistent with the gel-forming mechanism of calcium alginate dressings, in which ionically crosslinked chains partially reorganize upon hydration. In contrast to the hydrocolloid composite, slightly lower water uptake is observed at 37 °C than at 25 °C, consistent with the exothermic nature of polymer-water interactions in ionically crosslinked polysaccharides. Although the temperature dependence is modest, it further highlights the distinct thermodynamic drivers of hydration in the two materials.

Sorption of blood simulants

Sorption experiments using a 50:50 v/v% ethanol–water vapor mixture provide additional insight into early-stage wetting and surface interactions under physiologically relevant conditions.

For the hydrocolloid composite, Figure 6a, the presence of ethanol leads to measurable uptake at lower relative humidities than observed with pure water vapor (~1% at 50% RH). Ethanol reduces surface tension and improves wetting of the otherwise diffusion-limited surface, enabling limited penetration at lower partial pressures. However, the overall uptake remains small, and the total sorption capacity is not substantially increased. The persistence of hysteresis indicates that once absorbed, the simulant is partially retained, but the material remains largely resistant to bulk hydration. Clinically, this reinforces the hydrocolloid composite's role as a barrier dressing with slow hydration kinetics, while highlighting that its interaction with biological fluids may differ slightly from that with pure water.

From Figure 6b, the alginate fibrous network shows similar qualitative behavior for pure water and the ethanol-water simulant, with rapid uptake and strong hysteresis in both cases. The simulant promotes early-stage sorption at lower partial pressures but does not significantly alter the total uptake capacity. This similarity reflects the dominant role of swelling and network expansion in controlling sorption, with surface wetting effects playing a secondary role once the polymer network is hydrated.

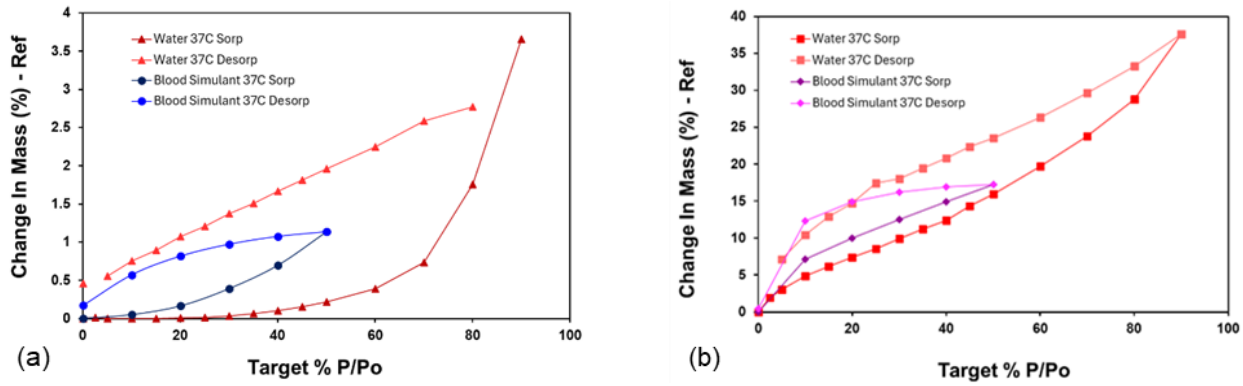

Figure 6. DVS measurements of blood-simulant sorption by (a) hydrocolloid composite and (b) fibrous hydrogel network.

Water and oxygen transmission rates

To link sorption behavior with transport properties, dynamic permeation measurements in the MPA Horizon were performed to determine water vapor and oxygen transmission rates (WVTR and OTR). The transmission rates for both the hydrocolloid composite and the calcium alginate fibrous network are displayed in Table 1. The hydrocolloid composite exhibits an exceptionally low water vapor transmission rate under the dynamic conditions employed. This low WVTR (23 g m^{-2} day^{-1}) indicates that, in the hydration states accessed during the experiment, diffusion pathways through the composite remain largely closed, and vapor transport is strongly restricted. The result is consistent with the sorption data, which show that significant swelling does not occur except at very high humidity.

By contrast, the alginate fibrous network displays a very high apparent WVTR (3020 g m^{-2} day^{-1}), reflecting continuous vapor transport through an open, percolating pore structure. In this case, vapor transmission is dominated by gas-phase diffusion and convective transport through interconnected voids rather than by solution–diffusion through a polymer phase. As a result, the measured WVTR is primarily a function of material architecture rather than intrinsic polymer permeability. This distinction is critical when interpreting permeability data for highly porous fibrous networks.

Oxygen transmission measurements further highlight the role of swelling in modulating transport pathways. From Figure 7, for the hydrocolloid composite, increasing humidity leads to a modest increase in OTR, up to 7 % at 75%RH, consistent with limited swelling that slightly increases free volume and enables additional gas transport. In the alginate network, oxygen transmission increases dramatically with humidity, reflecting extensive swelling and the persistence of open transport pathways. While absolute OTR values are reported, it should be noted that for highly open structures these values represent apparent transmission rates rather than intrinsic material constants.

Comparison with literature highlights important methodological and material considerations. Reported WVTR values for the hydrocolloid composite (~829 g/m²/day) are an order of magnitude higher than those obtained here, while

published values for the calcium alginate fibrous network (~1270 g/m²/day for a 12-layer gauze configuration) are substantially lower than our single-layer measurement[6,7]. These discrepancies underscore two key factors: (i) structural variability between products (e.g., thickness, porosity, layering) and (ii) methodological differences. Previous studies employed static gravimetric approaches that infer permeability from mass loss, whereas our dynamic setup directly quantifies vapor flux between controlled inlet and outlet humidity streams. The dynamic method may capture early hydration kinetics and barrier resistance more sensitively, particularly for hydrocolloid composites. Overall, the combined sorption and permeation results demonstrate that swelling-controlled transport provides a unifying framework for understanding moisture and gas regulation in these materials.

Table 1: Experimental transmission rates of water and oxygen through DuoDERM and Cutiderm.

Material	WVTR [g m^{-2} day^{-1}]	OTR [cc m^{-2} day^{-1}]
Hydrocolloid composite	23	5312
Fibrous network	3020	N/A

Dense hydrocolloid composites resist hydration and maintain low permeability until sufficient swelling occurs[7,8], whereas open hydrophilic polymer networks hydrate rapidly and permit extensive fluid and gas exchange. These intrinsic differences in material behavior underpin their distinct functional roles in wound management and highlight the value of dynamic characterization methods in evaluating moisture-responsive biomaterials.

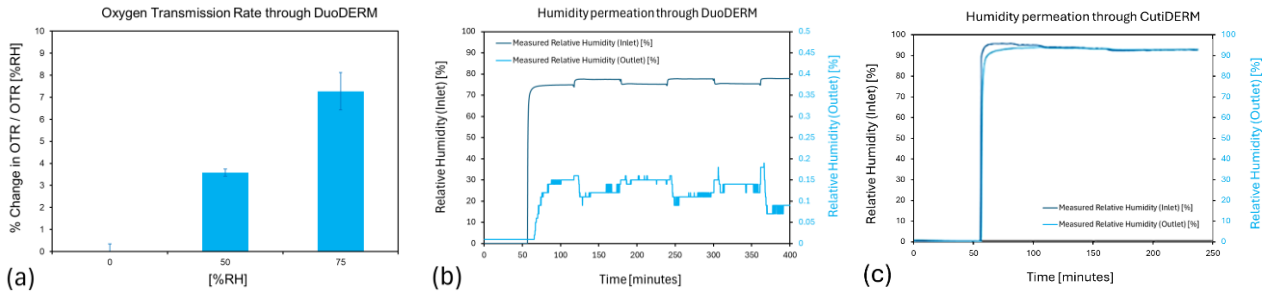

Figure 7. Permeability measurements of (a) oxygen with increasing humidity through a hydrocolloid composite (b) water through a hydrocolloid composite (c) water through the fibrous hydrogel network.

Conclusion

This study demonstrates a clear contrast in the hygroscopic and barrier properties of hydrocolloid composites and the calcium alginate fibrous network. The calcium alginate fibrous network exhibited high water uptake and strong affinity for both water vapor and blood simulant, confirming its role as a highly absorbent dressing. In contrast, the hydrocolloid composite displayed minimal fluid uptake under all conditions, reflecting the slow hydration and low permeability characteristic of hydrocolloid matrices designed to retain moisture.

These differences arise from the intrinsic interactions of the materials with water. Calcium alginate fibrous network-based dressings swell rapidly upon hydration, expanding their polymer network and enabling extensive fluid absorption and vapor exchange. The hydrocolloid composite, by contrast, resists initial hydration; only gradual swelling opens limited diffusion pathways, resulting in delayed sorption and very low WVTR. The strong link observed between fluid uptake and vapor permeability highlights swelling behavior as a key determinant of dressing performance.

Clinically, these findings underscore the complementary applications of the two dressings. Calcium alginate fibrous networks are best suited for heavily exuding wounds requiring rapid absorption, while hydrocolloid composites provide effective moisture retention and protection in low-

exudate contexts (burns, rashes). These findings highlight not only the intrinsic material differences between dressings but also the importance of test methodology in evaluating dressing performance.

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