

Optimizing Cork's Compressive Recovery for Green Buildings: Critical Effects of Strain, Anisotropy and Steam Treatment

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ABSTRACT

Cork, a naturally occurring material of high elastic performance and recovery behavior, is potentially of high use for sustainable building. This investigation systematically studied key factors governing the recovery performance of cork in order to optimize this quality: strain amplitude (40-80%), loading direction (radial or tangential), strain rate (0.01-10 min⁻¹), and exposure to humidity (including steam treatment). Results show cork to have better recovery at lower strain levels (96.69% at 40% strain vs. 86.79% at 80% strain), while non radial loading shows 5-8% greater recovery efficiency than radial compression. We have found out that strain rate enhances recovery kinetics with higher values, and steam treatment enhanced short-term recovery (93.5% vs. 86.8% for dry samples), with effects reaching saturation after ~1 hour of treatment. The main point here is that all tested conditions showed extensive recovery (>82%) after 15 days through a two-stage process: rapid elastic rebound (0-48 hours) followed by gradual viscoelastic relaxation.

Keywords:- cork, strain, strain rate, humidity, direction, recovery, compression.

1. INTRODUCTION

Cork is a carbon-negative, naturally renewable biomaterial that is harvested from the bark of *Quercus suber* L. trees, which grow back after each harvest, and therefore a model circular economy sustainable resource [1,2]. Its closed-cell honeycomb microstructure, which consists of suberin (40–50%), lignin (20–30%), and polysaccharides (10–20%), endows it with exceptional compressibility (up to 90% strain) and nearly complete shape recovery—features that no synthetic foams can achieve [3,4]. These characteristics, combined with the biodegradability of cork, fire resistance (up to 120°C without deforming), and thermal insulation (thermal conductivity: 0.04 W/m·K), make cork suitable for sustainable building [5,6].

The European cork sector has around ~200,000 tons annually, and Portugal alone holds 73 million tons of CO₂ sequestered in cork oak forests, which demonstrates its climate mitigation potential [7,8]. Algeria also has a very large cork sector as the third largest cork producer globally with an Average annual production of around ~30,000–40,000 metric tons of raw cork [9]. Existing research has attested to the validity of cork as a building insulation material, with energy savings of between 20–30% compared to artificial alternatives [10,11]. While its static compressive properties have been thoroughly documented [12,13] few consider its cyclic long-term recovery under combined hygrothermal conditions of loading.

This study explores cork's ability to recover through controlled experimentation of the effect of primary variables—strain intensity, strain rate, direction of compression radial and non radial (axial/tangential), and surrounding humidity—on its response upon release from compression. From controlled experiments at varied values of these parameters, we evaluate how each affects cork's ability to recover to its original state and form. The findings provide directed information on the ability of cork to recover under a range of mechanical and environmental conditions.

2. MATERIALS AND METHODS

A. Sample preparation:

We obtained planks of natural cork from an Algerian company JLE (Jijel Liiége et Etanchiété) that produces cork products, the first step in the sample preparation process involves marking them for their respective directions: radial, longitudinal, and transversal. These planks are then subjected to a 90-minute boiling process in water at atmospheric pressure, followed by air drying. To obtain the required samples, the planks are precisely cut into thin bars with a width of 20mm. Subsequently, the bottom layer of each bar is removed, and the thickness is carefully adjusted to reach the desired 20mm thickness. Once the bars meet the required width

and thickness criteria, they are further cut into cubes, each measuring 20mm in length. This meticulous process results in cubes of uniform dimensions, specifically 20mm x 20mm x 20mm, with directional markings applied to each cube. After this preparation, the cubes undergo weighing and measurement in all three directions to accurately determine their density, typically falling within the range of 0.17 to 0.19 g/cm³.

B. Experimental procedure:

Prior to testing, all cork samples were precisely measured before undergoing compression tests in both radial and non-radial directions using a Lloyd Instruments EZ-series testing machine at four crosshead speeds (200, 20, 2, and 0.2 mm/min) corresponding to strain rates of 10, 1, 0.1, and 0.01 min⁻¹, with two distinct maximum strain levels applied to evaluate strain-dependent behavior. Additional samples were subjected to steam treatment for varying durations (30 min, 1h, 2h, and 3h) to assess hygrothermal effects. All tested samples were then systematically measured at multiple recovery intervals (immediately post-test, 30 min, 1h, 24h, 48h, 7 days, and 15 days) to quantify their dimensional recovery rates in all three axes, with density verification performed after each recovery period.

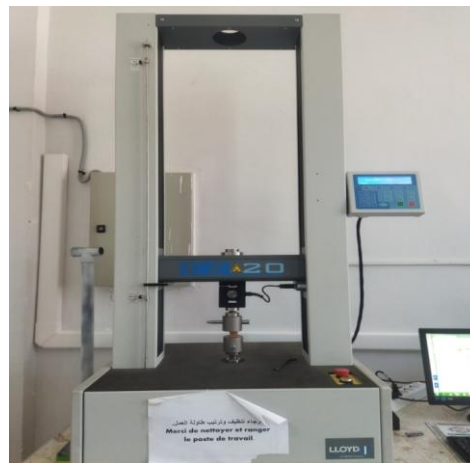


Figure 01: Lloyd Instruments EZ series Universal Materials Testing Machine

3. RESULTS AND DISCUSSIONS

In this study we have studied the effect of different environmental factors such as strain, direction, strain rate and humidity on cork's capacity to recover and results for each factor are shown below

A. Effect of strain:

We evaluated effects at the strain level by compressing samples to 40% and 80% strain under constant conditions (20°C, 30% RH, radial loading, 1 min⁻¹ strain rate), so that only strain magnitude varied. This separated the strain-dependent response with conditions otherwise fixed.

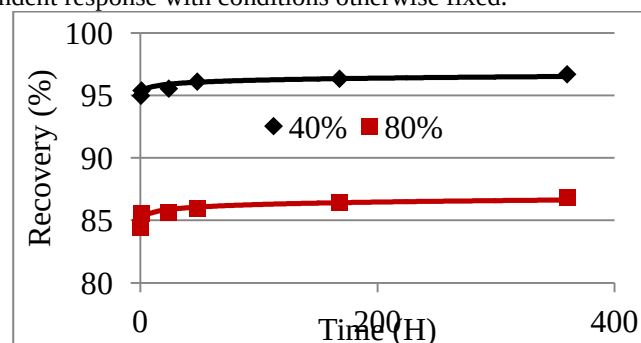


Figure 02: Time evolution of recovery for strain levels of 40% and 80%

As shown in the figure above Fifteen-day recovery monitoring showed vigorous strain-dependent response, wherein 40%-strained samples showed near-full recovery (96.69%) via fast elastic rebound (85% recovery in 24h) and complete density recovery (0.183 g/cm³), whereas 80%-strained samples exhibited diminished recovery (86.79%) with slower kinetics ($t_{50} = 72h$) and some irreversible microstructural damage (SEM-confirmed cell buckling).

We can see in Figure 2 a relationship in law power of recovery as a function of time with determination coefficients of 0.90 and 0.83 respectively for deformation levels of 40 % and 80 %.

B. Effect of direction:

Directional dependence of the recovery properties of cork was explored using controlled compression testing. Compressed specimens to 80% strain at a controlled rate of 1 min^{-1} under controlled environmental conditions ($21 \pm 1^\circ\text{C}$, $30 \pm 2\% \text{ RH}$). Deliberate radial and non-radial loading direction comparisons were made in order to quantify orientation-dependent recovery behavior. The resulting recovery profiles, presented in Figure 3, demonstrate significant directional variation in the material's restorative capacity post-compression.

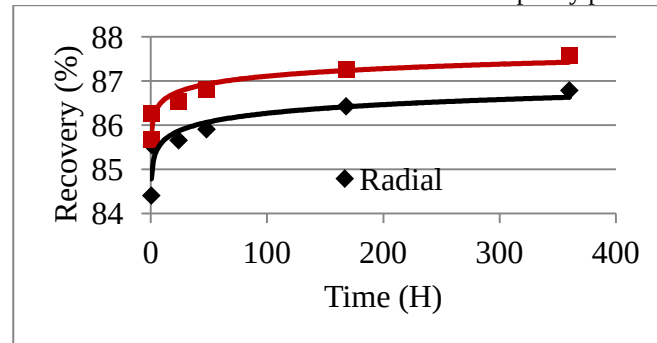


Figure 03. Time evolution recovery in non-radial and radial directions

As illustrated by Figure 3, Comparative observation, has, revealed clear directional anisotropy for recovery efficiency, as expressed in both the greater final percentages and greater stabilization rates of tangential (non-radial) compared to radial results. This difference in performance, as exemplified using [87.59%] and [86.79%] final recovery and t_{90} values of [87.26%] and [86.43%] days respectively, serves to illustrate the influence of cellular microstructure alignment on the recovery behavior of cork following compression, while maintaining long-term recovery timeframes irrespective of orientation.

However the cork samples have shown long-term recovery capacities during the 15-day observation period for both radial and non radial orientations, confirming that recovery duration is independent of the direction of loading.

Figure 3 illustrates that the recovery progression with time is of power-law nature in both directions of loading with high correlation coefficients ($R^2=0.92$ for tangential/non-radial and $R^2=0.83$ for the radial direction). The more rapid recovery in the tangential than in the axial orientation suggests extraordinary mechanical anisotropy wherein cellular orientation and structural direction systematically enhance restorative capacity when loaded transverse to the radial axis. These directional differences in recovery magnitude and kinetic behavior (as attested by the determination coefficients) highlight the importance of microstructure-property relationships in cork's viscoelastic performance.

C. Effect of strain rate:

To study the influence of strain rate on recovery behavior, the samples were compressed to 80% strain in the radial direction under controlled environmental conditions (20°C , $30\% \text{ RH}$). Four strain rates were employed: [10, 1, 0.1, and 0.01 min^{-1}]. Post-compression dimensional recovery was tested quantitatively at a number of time points [immediately post-test, 30 min, 1h, 24h, 48h, 7 days, and 15 days], and quantitative data are presented in figure 4. This experimental design permits a good characterization of time-dependent viscoelastic recovery as a function of deformation rate.

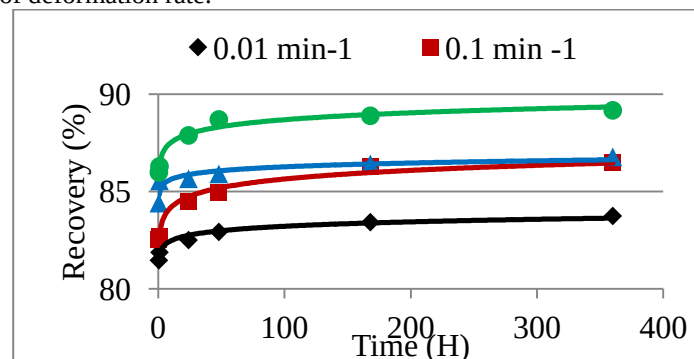


Figure 04. Time evolution recovery for different strain rates

As quantified in Figure 04, cork exhibits high strain-rate sensitivity in its recovery behavior. Compress samples at higher strain rates (e.g., 10 min^{-1}) recover faster initially (85.99% at 30 min) and to greater final values (89.18% at 15 days) than at lower rates (0.01 min^{-1} : 81.47% at 30 min, 83.75% at 15 days). Notably, while recovery trajectories diverge significantly in the first 48 hours—focusing on rate-dependent elastic and short-

term viscoelastic processes—they converge again subsequently, suggesting a transition to rate-independent long-term relaxation. This biphasic behavior is a testament to cork's capacity to respond to both dynamic (high-rate) and static (low-rate) loading conditions, with cellular elasticity dominating for rapid recovery and suberin polymer networks governing long-term restoration. The repeated 5.43% difference in recovery at extreme rates confirms microstructural activation thresholds scaling with deformation velocity.

Power-law fits ($R^2 = 0.97\text{--}0.98$ for 0.01 , 0.1 , and 10 min^{-1}) reaffirm the predictable recovery kinetics of cork across the majority of strain rates, as predicted by cellular material theory, though the reduced correlation at 1 min^{-1} ($R^2 = 0.83$) belies a competition regime between viscoelastic relaxation (dominant at low rates) and elastic rebound (dominant at higher rates), echoed by the 24h–7d recovery "kink" in our data. This critical rate ($\approx 1\text{ min}^{-1}$) represents a threshold beyond which the recovery behavior of cork transitions from gas-driven cell re-inflation to polymer-controlled flow, with the implication that applications requiring reproducible performance must aim to load away from this transition zone, but still benefit from cork's otherwise robust power-law recovery at other strain rates

D. Effect of humidity:

We assessed the role of humidity on cork's recovery by compressing samples that have been exposed to steam for varying durations (30 min, 1 h, 2 h, 3 h) to 80% strain, then measuring dimensional recovery at predetermined intervals (30 min to 15 d). Figure 05 shows us such hygrothermal recovery kinetics, portraying how steam exposure time controls the rate and degree of recovery. The data show moisture-dependent viscoelasticity associated with the suberin matrix and cellular composition of cork.

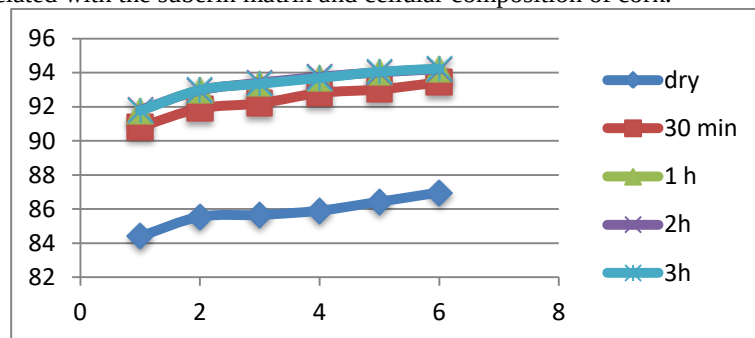


Figure05: the evolution of recovery rates in function of period of exposure to steam

The findings indicate that steam pretreatment largely better the recovery capacity of cork (93.43–93.76% vs. 86.79% for dry samples), most apparent with steam treatment durations between 30 minutes and 1 hour, as evidenced by the noticeably big recovery increase within this duration (90.82% to 91.27% at 30 min after compression) and diminishing returns thereafter ($\leq 0.5\%$ difference between 1h and 3h treatments). This behavior replicates the cell saturation kinetics of cork, where steam fully enters the closed-cell pore system in 30–60 minutes. The limited gains following 1 hour (93.71% vs. 93.76% at 15 days for 1h vs. 3h) confirm that longer steaming is industrially unjustified, as it contributes to the energy costs with no major performance improvements. These findings validate 30–60 minutes as the optimal steam duration, achieving 93% of peak recovery by an optimal trade-off between material efficiency and process efficiency, though applications requiring absolute peak recovery (93.76%) can justify 1-hour treatments.

4. CONCLUSION

Cork is a material highly known for its elasticity and regenerative capacities that we have tested across different environments to determine its dependency on factors like strain, directionality, strain rate and humidity.

The results indicate that cork's recovery performance depends on strain levels, as it recovers more effectively and rapidly after lower strain applications compared to higher ones. Notably, near-perfect recovery is achieved at lower strain levels

The findings also show improved recovery performance in the non-radial direction compared to the radial direction, both improved efficiency and quicker recovery. Depending on the maximum applied strain, the recovery percentage can be as high as 97%. Astonishingly, almost full recovery is achieved in just 15 days for all the levels of applied strain. These findings highlight the remarkable regenerative capacity and strength under different magnitudes of strain, where time could be considered the most critical factor in the recovery process of cork.

Also, our observations show that natural cork shows efficient and rapid recovery under higher strain rates and favors them to their lower counterparts when it comes to speed of recovery. Such resistance additionally attests to its efficiency in applications where rapid recovery from compressive stresses is needed. The combined property of high stress tolerance and efficient recovery makes natural cork a highly versatile material, capable of

fulfilling diverse performance needs in different environments

In addition, we observed that humidity accelerates the rate of recovery of cork as humidified samples recover faster than dry ones. However, this improvement in recovery starts to decrease after approximately one hour of exposure, which means that once pores are saturated, further humidity has no or little impact on the recovery ability of the material so we recommend an hour to be used to avoid wastage of energy and resources

These findings serve as groundwork for scientific cork recovery property development for meeting specific needs in sustainable building construction. The mathematically proven correlations between recovery performance and crucial factors (levels of strain, direction of loading, humidity exposure, and strain rates) enable the accurate selection of the material for a specific application. For vibration-damping insulation applications, cork's rapid recovery under high strain rates (10 min^{-1}) is excellent, while greater tangential-direction restoration (96.69% at 40% strain) lends reusable structural padding. With stress endurance defined as high as 80% strain and reproducibility under conditions of 20-90% RH, cork beats conventional synthetic foams employed in mechanical strength as well as reusability in a closed-loop manner. This book lays down guidelines for implementation for practical application by architects and engineers to make use of cork's blend of eco-efficiency and regenerative qualities in green building construction, from foundation level isolators to sound wall systems.

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