

Original Article

Dual Ageing Mechanisms in UHMWPE Heart Valve Discs Revealed by Terahertz Time-Domain Spectroscopy

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UHMWPE heart valve discs undergo surface and bulk microstructural change during cyclic service, yet no single non-contact, non-ionizing, non-destructive method can simultaneously resolve both. This study asked whether THz-TDS could detect and distinguish these concurrent ageing processes in UHMWPE discs from the TTK Chitra heart valve TC2. Measurements were taken at six locations per disc across the 0.2–0.6 THz range, before and after 400 million cycles of accelerated durability testing. After testing, the refractive index fell by 2.38%, the extinction coefficient by 11.46%, and the absorption coefficient by 15.56% - against expectation, all three optical losses decreased rather than increased. Spatial variability roughly halved across all parameters, with the extinction coefficient CV dropping from 32.75% to 17.32% and the absorption coefficient CV from 37.00% to 19.13%. THz-TDS resolves two concurrent ageing mechanisms - surface polishing and bulk microstructural reorganisation - within a single non-contact measurement, establishing its value as an NDE tool for polymer prosthetic valve assessment.

Introduction

Mechanical heart valve prostheses are high risk implants in clinical use, which is required to open and close reliably over hundreds of millions of cycles during the lifetime of a patient. The TTK Chitra tilting disc valve is a long term clinically proven, developed and manufactured in India based valve that has been tested in varied populations of patients including paediatric cases [1, 2]. Its disc component, manufactured from Ultra-High-Molecular-Weight Polyethylene (UHMWPE) - absorbs impact loads, resist fatigue, and maintain dimensional stability over extended service [3]. The TC2 model has been specifically assessed for fatigue life and durability under accelerated cyclic loading [4], and the results point to a material that holds up well mechanically. What remains poorly understood is how cyclic loading modifies the internal microstructure and surface state of the UHMWPE disc at a level below what mechanical or gravimetric testing can detect. Conventional assessment methods available for polymer heart valve components [5,6] are largely limited to mechanical testing, dimensional and visual inspection — none of which can resolve the dual ageing mechanisms of surface conditioning and bulk microstructural change that accumulate during fatigue service. This gap in NDE capability is what the present

study sets out to address.

Terahertz waves lie in the intermediate band between microwave and infrared, 0.1 to 10 THz, and they have a spectral interaction with matter giving rise to spectral fingerprints [7]. These interactions make THz waves sensitive to material properties that conventional optical or X-ray methods cannot easily resolve, offering non-invasive, non-ionising and non-contact measurement. THz-based material characterisation has been applied across pharmaceuticals, composites, and coatings, driven by its ability to inspect bulk and near-surface properties simultaneously [8,9]. The technique has matured considerably as a practical NDE modality for engineering materials, with a well-established track record across industrial sensing applications [7,8].

Terahertz time-domain spectroscopy is the most widely used THz measurement technique for material characterisation [10,11]. A broadband THz pulse is transmitted through or reflected from a sample and the time-domain waveform is recorded. Fourier transformation gives the complex transmission function, from which the refractive index $n(\omega)$, extinction coefficient $k(\omega)$, and absorption coefficient $\alpha(\omega)$ are extracted as continuous functions of frequency [10]. These three optical parameters characterize the storage and dissipation of electromagnetic energy in a material. They also are physically interpretable signs

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of microstructural state and not merely transmission metrics. THz-TDS has been applied to thickness measurement and degradation detection across thermal barrier coatings [12], stealth coatings [13], polymer sheets [14], and PCTFE coatings over metallic seals [15] - establishing an NDE track record that directly motivates its application here to biomedical-grade polymers.

Despite this capability, its use for characterising ageing in UHMWPE heart valve components has not been explored. Existing NDE approaches for polymer valve discs rely on single-parameter or single-point measurements and do not account for spatial variability across the component surface. In a tilting disc valve, where contact mechanics vary across the disc face, single-point sampling risks missing localised ageing and misrepresenting overall material condition. Prior work from this group showed that THz-TDS picks up thickness-level degradation in UHMWPE heart valve discs after accelerated durability testing [16] and holds good promise for QA/QC of biocompatible implants [17]. Neither study attempted spatially resolved extraction of a full optical parameter set - that is the gap the present work takes up.

This study was undertaken to determine whether THz-TDS can non-destructively detect and separate durability-induced surface and bulk ageing in TC2 UHMWPE heart valve discs. The specific question was whether $n(\omega)$, $k(\omega)$, and $\alpha(\omega)$ - tracked across multiple disc locations - could act as physically grounded markers of the two ageing processes that cyclic loading drives in a polymer valve disc: surface wear at the contact face and microstructural reorganisation within the bulk.

Three optical parameters - $n(\omega)$, $k(\omega)$, and $\alpha(\omega)$ - were extracted from THz-TDS scans at six locations per disc across the 0.2–0.6 THz band, covering both as-received and durability-tested UHMWPE discs of the TTK Chitra heart valve TC2. Testing ran to 400 million cycles as per ISO 5840 [4]. Each location yielded an independent parameter set; these were averaged across the grid, and the coefficient of variation was used to track both the mean shift and the point-to-point spread across the disc surface.

THz-TDS is well suited for this task: each scan point gives three optical parameters together - $n(\omega)$, $k(\omega)$, and $\alpha(\omega)$ - without contact, without sample preparation, and without running separate tests for each. Deployed across the disc surface, this approach turns out to be enough to pull apart two ageing processes running in parallel and track how they are distributed spatially. For condition monitoring and quality assurance of polymer prosthetic valve components [16,17], that combination of spatial coverage and multi-parameter sensitivity is what makes the technique worth pursuing.

Method

UHMWPE disc specimens: Fresh and ADT conditioned

The TC2 model of the TTK Chitra heart valve is illustrated schematically in figure 1. Its construction includes a sewing ring of PET fabric, a disc machined from UHMWPE, and a Ti6Al4V alloy frame carrying a TiN surface coating. Two UHMWPE disc samples were selected for this investigation: one unused disc in its as-manufactured condition, and one retrieved from a valve assembly after 400 million cycles of accelerated durability testing conducted in accordance with ISO 5840. Disc thick-

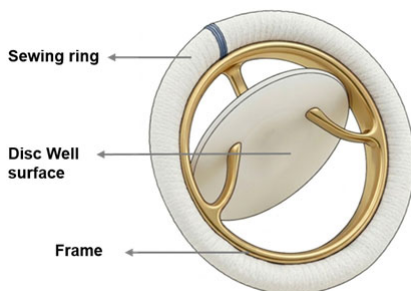


Figure 1: Schematic illustration of the TC2 heart valve sample under THz-TDS study

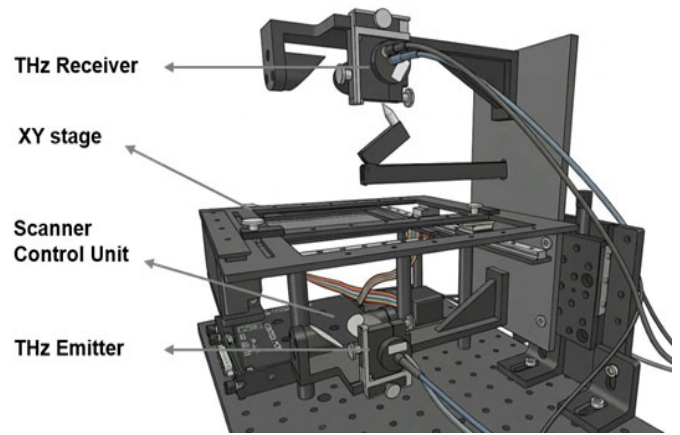


Figure 2: Schematic diagram of the transmission-mode THz-TDS experimental setup used in this study

ness was measured at the central region, and recorded as 0.923 mm for the unused disc and 0.880 mm for the durability-tested disc. To account for any spatial variation in optical response, six measurements were made across this central disc region.

THz-TDS through-transmission measurement setup

A TOPTICA TERAFLASH pro system was used for the THz TDS measurements. The experimental system has four main components: an emitter, a receiver, a scanner control unit, and an XY stage, arranged in the through-transmission mode as shown in figure 2.

Before the disc was placed in the THz wave path, a reference scan was collected. This baseline captures the THz pulse shape in free air and is needed to isolate the sample's effect on the transmitted signal. The UHMWPE disc was then placed on the XY stage platform, positioned between emitter and receiver, and the transmitted pulse was recorded. Both scans - the reference and the sample - were recorded as time-domain waveforms.

Six locations were scanned on each disc [16]. The distance between them on the surface was intentional: the disc does not wear or age in an even manner and individual points would not capture the difference. The six-point grid provides a spatially distributed image of the optical property distribution and how it alters following the ADT.

Extraction of THz optical parameters from time-domain signals

Raw time-domain waves from both the reference and sample scans were passed through a fast Fourier transform (FFT) to develop the frequency-domain representation:

$$E(\omega) = \text{FFT}[E(t)]$$

From this, a complex transmission function was assembled by dividing the sample spectrum by the reference:

$$T(\omega) = E_{\text{sample}}(\omega) / E_{\text{reference}}(\omega)$$

The phase was then extracted from the complex logarithm of $T(\omega)$:

$$\varphi(\omega) = \text{Im}[\log(T(\omega))]$$

Once the phase was unwrapped, the refractive index followed directly:

$$n(\omega) = c\varphi(\omega) / (2\pi f d) + 1$$

The extinction coefficient required an additional Fresnel correction to account for reflection losses at both air-sample boundaries:

$$k(\omega) = c / (2\pi f d) [\ln(4n/(n+1)^2) - \ln|T(\omega)|]$$

Finally, the absorption coefficient was recovered from $k(\omega)$ as:

$$\alpha(\omega) = 2\omega k(\omega) / c$$

All symbols are listed in table 1.

The scan coverage was made in six locations marked on the surface of the disc (A1- A6). The values of n , k , and α at each location were obtained independently, and averaged over the six locations to give a representative per-disc result. The averaging 0.2 to 0.6 THz window was chosen because signal quality beyond this frequency range was compromised by spectral noise at the spectral edges.

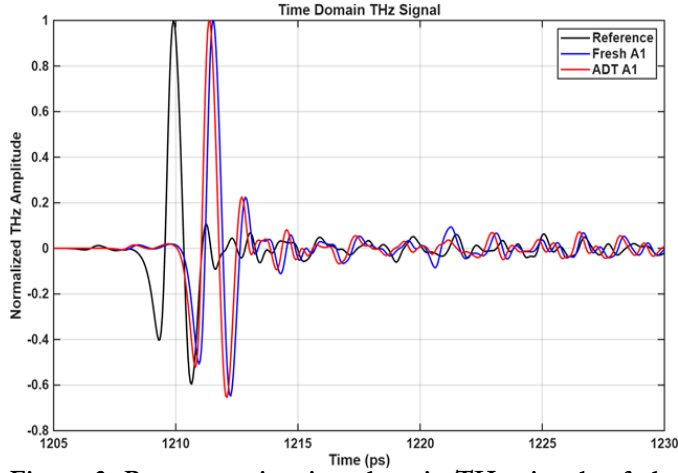


Figure 3: Representative time-domain THz signals of the reference, fresh sample, and artificially aged sample

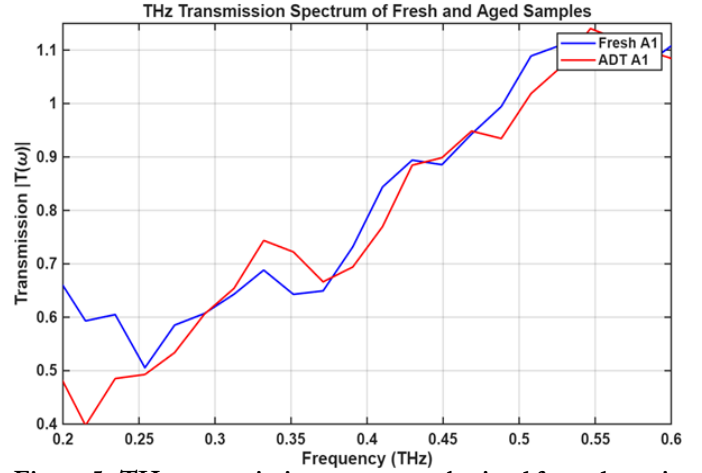


Figure 5: THz transmission spectrum obtained from the ratio of the sample and reference spectra in the frequency domain

Table 1: Symbol definitions for optical parameter extraction

Symbol	Definition	Unit
$E(t)$	Time-domain THz electric field signal	V/m
$E(\omega)$	Complex THz electric field in frequency domain	V/m
f	THz frequency	THz
ω	Angular frequency, $\omega = 2\pi f$	rad/s
$T(\omega)$	Complex transmission function	—
$E_{\text{sample}}(\omega)$	Frequency-domain spectrum through sample	V/m
$E_{\text{reference}}(\omega)$	Frequency-domain spectrum of reference scan	V/m
$\varphi(\omega)$	Unwrapped phase of $T(\omega)$	rad
$\text{Im}[\cdot]$	Imaginary part of complex argument	—
$n(\omega)$	Frequency dependent refractive index	—
c	Speed of light in the vacuum, 3×10^8 m/s	m/s
d	Sample thickness (0.923 mm fresh; 0.880 mm ADT)	mm
$k(\omega)$	Frequency-dependent extinction coefficient	—
$ T(\omega) $	Magnitude of complex transmission function	—
$\ln(4n/(n+1)^2)$	Fresnel reflection correction term	—
$\alpha(\omega)$	Frequency-dependent absorption coefficient	cm^{-1}

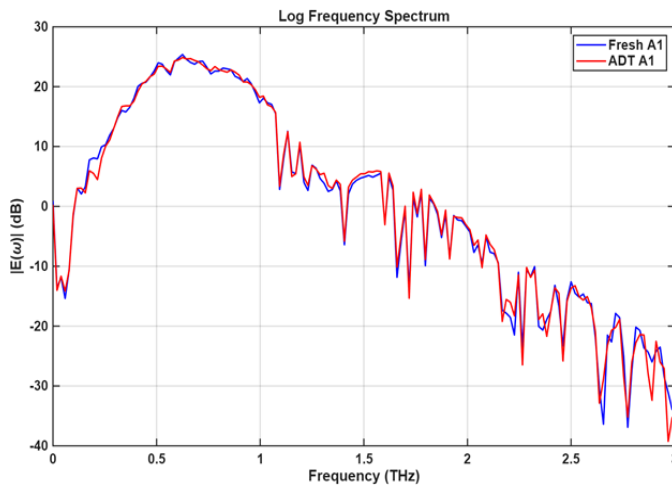


Figure 4: Logarithmic magnitude spectrum of the THz signal obtained from the FFT of the representative time domain measurement

Results

The time-domain signal, frequency spectrum, and transmission spectrum from a representative single-point measurement on the fresh and ADT sample are presented in figures 3-5 to demonstrate the THz signal characteristics. These plots provide a visual representation of the material's characteristic signature response. Quantitative optical parameters were derived from measurements at six spatial locations each for the fresh and artificially aged samples, with the $n(\omega)$, $k(\omega)$, and $\alpha(\omega)$ in the following figures and tables obtained via automated analysis and averaging over all positions

Time-domain THz response

Figure 3 shows the time domain THz signals for the reference, fresh sample of UHMWPE disc, and artificially aged sample of UHMWPE disc.

Frequency-domain spectral characteristics

The logarithmic magnitude spectrum of the THz time domain signal

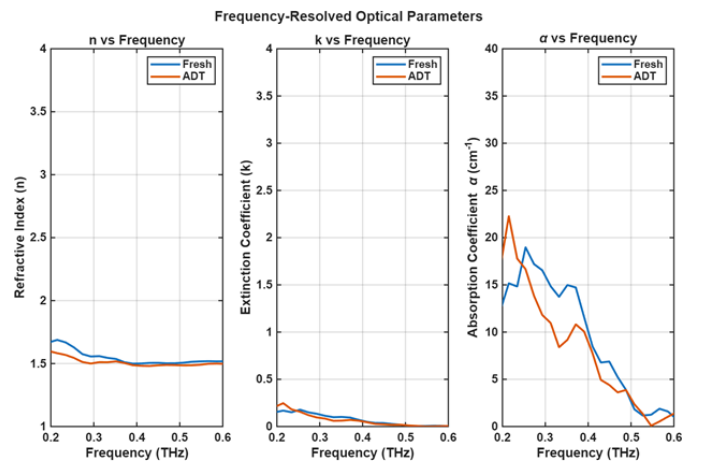


Figure 6: Frequency-dependent optical characteristics calculated based on the measurements of THz-TDS, i.e. (a) the refractive index, (b) the extinction coefficient, and (c) the absorption coefficient of fresh and ADT samples

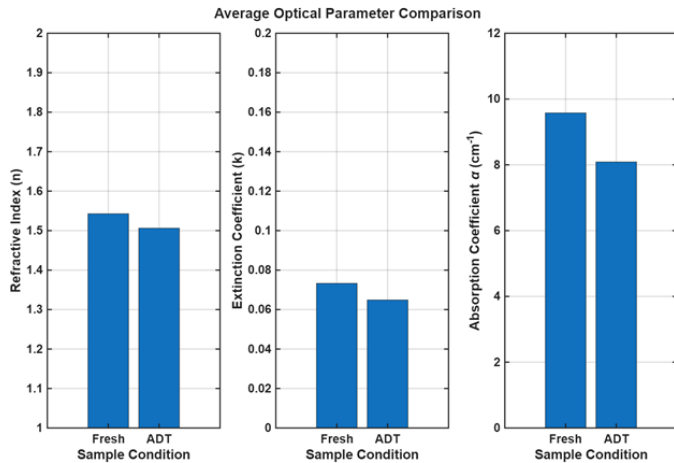


Figure 7: Comparison of the average $n(\omega)$, $k(\omega)$, and $\alpha(\omega)$ for fresh and ADT samples

obtained from the Fourier transform is shown in figure 4. The peak amplitude was observed around the lower frequency region of 0.5 THz, and a gradual decrease at higher frequencies due to variations in signal-to-noise ratio.

Figure 5 shows the transmission spectrum, obtained by dividing the sample spectrum by the reference spectrum. The transmission curves for the fresh and artificially aged UHMWPE disc samples exhibit comparable spectral trends across the frequency range examined.

Frequency-resolved optical properties

While figures 3–5 present THz responses from a single measurement position, comprehensive optical characterization requires data across multiple sites. Six positions at the disc well surface were therefore assessed for both fresh and aged samples using THz-TDS, and the resulting frequency-dependent optical properties are shown in Figure 6. In the 0.2–0.6 THz range, both fresh and ADT samples exhibit only slight variation in refractive index. The extinction coefficient, however, shows moderate frequency dependence, whereas the absorption coefficient shows more pronounced frequency dependence, accompanied by fluctuations across the band.

Spatial variation of optical parameters

Table 2 and table 3 summarize the optical parameters obtained from six measurement locations (A1 to A6) at the disc well surface for fresh and artificially aged samples. The refractive index values for fresh samples range between 1.5188 and 1.5579, while the extinction coefficient ranges from 0.0392 to 0.1102. Corresponding absorption coefficients vary between 4.59 cm^{-1} and 15.01 cm^{-1} . For artificially aged samples, the refractive index ranges from 1.4969 to 1.5153, and the extinction coefficient varies between 0.0443 and 0.0749.

Table 4 summarizes the mean optical parameters for fresh and artificially aged samples. The average refractive index drops from 1.5428 (fresh) to 1.5062 (artificially aged), the extinction coefficient from 0.0733 to

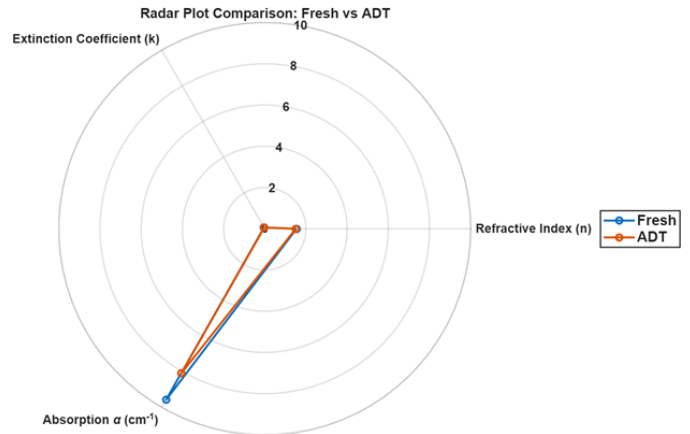


Figure 8: Radar plot showing a comparison of the average optical parameters of fresh and ADT samples within the 0.2–0.6 THz frequency range

0.0649, and the absorption coefficient from 9.58 cm^{-1} to 8.09 cm^{-1} . Figure 7 offers a graphical depiction of these average optical parameters.

Effect of accelerated aging

Table 5 presents the percentage changes in optical parameters due to aging. These variations are depicted in figure 8 through a radar chart comparison. Accelerated aging resulted in a 2.38% decrease in refractive index and a 15.56% reduction in the absorption coefficient, indicating reduced THz attenuation after aging. These changes emphasize the degradation nature of the material. Table 5 provides further details on the coefficient of variation, a measure commonly used to assess measurement stability. The refractive index has a very small variation, and the values of CV are less than 1%; hence, a very similar result is obtained by the refractive index at different spatial locations. However, the extinction and absorption coefficients vary significantly for both fresh and ADT samples.

Discussion

Effect of accelerated durability testing on THz optical properties

THz TDS measurements clearly distinguish between fresh and ADT UHMWPE disc samples. The refractive index decreases from 1.5428 to 1.5062, a drop of 2.38%, while the extinction and absorption coefficients decreased by 11.46% and 15.56% respectively. This trend remains consistent across all the six spatial measurement locations, and the spatial variability in absorption decreased from 4.59–15.01 cm^{-1} to 5.25–9.43 cm^{-1} .

The spectra profiles within the 0.2–0.6 THz range appear similar in shape for both sample conditions. This implies ageing has not altered the fundamental spectral signature of UHMWPE- it only changed the dielectric state of the material: lower effective density, smoother surface, and less molecular damping.

Table 2: Optical parameters of fresh samples

Location	Refractive Index (n)	Extinction Coefficient (k)	Absorption Coefficient α (cm^{-1})
A1	1.5489	0.0634	8.22
A2	1.5536	0.0880	11.90
A3	1.5368	0.0673	8.60
A4	1.5410	0.0716	9.15
A5	1.5188	0.0392	4.59
A6	1.5579	0.1102	15.01

Table 3: Optical parameters of ADT samples

Location	Refractive Index (n)	Extinction Coefficient (k)	Absorption Coefficient α (cm^{-1})
A1	1.5153	0.0749	9.43
A2	1.5073	0.0709	8.93
A3	1.4969	0.0443	5.25
A4	1.5048	0.0609	7.58
A5	1.5044	0.0660	8.19
A6	1.5086	0.0721	9.15

Table 4: Average optical parameters

Sample	Average n	Average k	Average α (cm ⁻¹)
Fresh	1.5428	0.0733	9.58
ADT	1.5062	0.0649	8.09

To our knowledge, THz-TDS has not previously been used to track accelerated durability-induced changes in UHMWPE heart valve discs. The optical parameters measured here reveal two ageing processes running in parallel - surface wear and internal microstructural change - and distinguish between them within a single non-contact THz TDS measurement, which is what makes the approach useful for condition assessment of polymeric valve components.

Refractive index changes and polymer microstructure

The average refractive index decreased from 1.5428 in fresh samples to 1.5062 after ADT, corresponding to a 2.38% drop. When THz radiation passes through a polymer, its phase velocity - captured by the refractive index - is governed by the equation:

$$n \propto \sqrt{\rho\alpha_m}$$

where ρ is density and α_m is molecular polarizability.

A reduced refractive index after ADT indicates that the effective dielectric density of the UHMWPE matrix has dropped. Cyclic loading can drive microstructural changes in UHMWPE disc - including micro void nucleation, chain scission, or reduced molecular packing - each of which reduces the volume of material available for polarization.

UHMWPE is well known for load-bearing and fatigue resistant biomedical applications. A shift of just 2.38% implies to quiet internal rearrangement within UHMWPE architecture rather than progressive structural failure.

Extinction coefficient and THz scattering behavior

The extinction coefficient decreased by 11.46% after ADT. The extinction coefficient represents energy losses due to absorption and scattering during THz wave propagation. Lower values indicate reduced THz wave attenuation: that is, the lower the k, the lower the scattering loss. A plausible mechanism is surface smoothing by wear due to cyclic loading. Repeated impact loading during ADT removes surface asperities, leading to surface polishing of the UHMWPE disc. This alteration of the disc surface would reduce the scattering component of k, thereby enhancing THz transmission.

An interesting observation is the reduction of spatial variability of extinction coefficient after ADT. The CV of the extinction coefficient (table 5) decreased from 32.75% to 17.32%. This implies that the point-to-point differences in THz attenuation have been reduced, and the shift is consistent with the wear induced surface polishing across the disc.

Reduced THz absorption after ADT and its molecular interpretation

Table 5 shows that the absorption coefficient decreases by 15.56%. The THz absorption in UHMWPE may arise from molecular vibration modes, dipole relaxation modes, and polymer chain dynamics. Hence the observed reduction indicates a decreased molecular energy dissipation.

Interestingly, polymer ageing is often associated with increased optical attenuation due to structural damage or increased scattering. In contrast, the present results show reduced THz losses after ADT. This behaviour suggests that cyclic loading may induce surface smoothing and partial polymer chain alignment, thereby reducing both scattering

losses and dipole relaxation processes within the measured THz frequency range.

Beyond the reduction in mean absorption shown in table 4, ADT produced a near-halving of the spatial variability of the absorption coefficient - the CV fell from 37.00% to 19.13% - indicating a progressive surface smoothing in ADT samples. Notably, this pattern of CV reduction is consistent across all three optical parameters measured, reinforcing the interpretation that ADT systematically homogenizes the disc surface rather than degrading it randomly.

Spatial variability of optical properties

Table 2 and table 3 show that fresh UHMWPE discs show wide point-to-point differences in optical properties across the six measurement locations. The absorption coefficient spans 4.59–15.01 cm⁻¹ in untested samples - a range that narrows sharply to 5.25–9.43 cm⁻¹ after ADT. The refractive index and extinction coefficient follow the same pattern, with CV values roughly halving across all three parameters.

Two factors likely account for this shift. Fresh components carry whatever surface heterogeneity the disc manufacturing process has introduced - local differences in molecular packing, surface finish, or crystallinity. Cyclic loading during ADT then works on this non-uniform starting surface, gradually wearing it toward a more consistent state. The optical parameters register this as reduced spatial scatter, not just lower mean values.

Identification of two concurrent aging mechanisms in ADT-conditioned UHMWPE

Three optical parameters - refractive index, extinction coefficient, and absorption coefficient - each shift in the same direction after ADT (table 5), but for different physical reasons. Reading them together indicates that two ageing processes are running concurrently in the UHMWPE disc.

The extinction coefficient and its spatial variability tell the surface story. Both drop after ADT, and the most straightforward explanation is mechanical wear: repeated disc contact during durability testing progressively removes surface asperities, smoothing the disc face and reducing scattering losses.

The refractive index and absorption coefficient tell a different story - one about what is happening inside the polymer. Their reductions point to internal reorganization, such as microvoid nucleation, chain scission, or shifts in molecular packing, that lower the effective dielectric density and reduce dipole relaxation.

UHMWPE fails clinically in two ways, depending on where degradation occurs - surface wear compromises disc geometry and contact mechanics, while bulk microstructural changes erode fatigue reserve. A technique that only signals "this sample has aged" cannot separate the two. THz-TDS does. Each optical parameter carries a distinct physical signature, and together they indicate where in the material ageing has taken hold - at the surface, in the bulk, or both simultaneously. For NDE of polymer valve components, that capability counts.

Conclusion

THz-TDS measurements on fresh and ADT-conditioned TC2 UHMWPE heart valve discs show clear, quantifiable differences across all three optical parameters. The refractive index fell by 2.38%, the extinction coefficient by 11.46%, and the absorption coefficient by 15.56% - shifts that held consistently across all six spatial measurement locations. CV values roughly halved for all three parameters, from 0.92% to

Table 5: Effect of ageing on optical parameters

Parameter	Fresh Mean	ADT Mean	Change in Mean (%)	Fresh CV (%)	ADT CV (%)
Refractive Index (n)	1.5428	1.5062	-2.38	0.92	0.40
Extinction Coefficient (k)	0.0733	0.0649	-11.46	32.75	17.32
Absorption Coefficient α (cm ⁻¹)	9.58	8.09	-15.56	37.00	19.13

0.40%, 32.75% to 17.32%, and 37.00% to 19.13% respectively, pointing to progressive surface smoothing as a defining feature of durability-induced conditioning.

Against expectation, THz optical losses decreased after ageing rather than increasing. This anomaly resolves when the parameter set is read as a whole: surface wear has polished the disc face and cut scattering losses, while internal reorganisation - microvoid nucleation, chain scission, shifted molecular packing - has reduced effective dielectric density and dipole relaxation. Two processes, running in parallel, each leaving a distinct optical fingerprint.

What THz-TDS offers here that no conventional NDE method does is the ability to separate these two mechanisms within a single non-contact measurement. Surface degradation and bulk microstructural change have different clinical consequences for polymer valve components, and distinguishing between them matters. These results establish the optical parameter set derived from THz-TDS as a physically interpretable, quantitative basis for condition assessment of UHMWPE prosthetic valve discs.

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