Effect of Loading Rate on the Ultimate Tensile Strength of a Soft Polydimethylsiloxane

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Abstract

This study investigates the effect of loading rate on the ultimate tensile strength of a commercial soft polydimethylsiloxane. Uniaxial tensile tests were performed at 10, 50, 100, and 1000 mm/min, and the results were analyzed using non-parametric statistical methods. The Kruskal–Wallis test revealed a significant effect of loading rate on UTS ($p < 0.0001$), with the mean strength increasing from 1.240 MPa at 10 mm/min to 1.927 MPa at 1000 mm/min. Post hoc analysis showed that the tensile strength at 1000 mm/min was significantly higher than at all lower rates, while no significant differences were found among the 10, 50, and 100 mm/min groups. These findings provide a statistically validated dataset that supports the design and reliability assessment of soft devices operating under dynamic loading conditions.

Keywords: Polydimethylsiloxane, Ultimate Tensile Strength, Rate-dependent behavior, Uniaxial tensile test.

1 Introduction

Polydimethylsiloxane (PDMS) is a widely utilized organosilicon polymer, recognized for its rubbery characteristics and versatile mechanical properties that can be tailored for specific applications [1, 2, 3]. The tensile strength, in particular, is dependent on the material's formulation and curing conditions [4, 5]. This versatility, coupled with its biocompatibility and thermal stability, makes PDMS a material of interest in diverse fields, including biomedical engineering, soft robotics, and microfluidics [2, 6].

For many of these high-performance applications, devices are subjected to dynamic loading conditions. Therefore, understanding the material's mechanical response as a function of the applied *loading rate* is critical for predicting performance, reliability, and failure of PDMS. While the rate-dependent behavior of polymers is a well-known phenomenon, there is a need for reliable, statistically-validated data on the failure properties of specific commercial formulations used in practice. Such data is essential for the robust design of components that must withstand varying operational speeds without fracturing.

This study presents an experimental investigation into the effect of loading rate on the ultimate tensile strength (UTS) of a soft, platinum-cured PDMS elastomer. Uniaxial tensile tests were performed at four distinct loading rates (10, 50, 100, and 1000 mm/min). The material for this study was sourced from 3-mm-thick commercial sheets intended for use as dermal phantoms for testing procedures involving needles, such as tattoo practice.

The resulting failure data was analyzed using non-parametric hypothesis tests to identify statistically significant differences between groups. The aim is to provide a quantitative dataset and a statistical analysis of the material's tensile strength, offering useful data for researchers working with this material.

2 Materials and methods

In this study, uniaxial tensile tests were performed on a platinum-cured PDMS to determine the effect of loading rate on its UTS. The resulting UTS data were grouped by loading rate and analyzed using non-parametric statistical methods to identify significant differences. The experimental procedure and methods of analysis are detailed in the following subsections.

2.1 Experimental setup and material data acquisition

The material selected for this investigation was commercially available *Smooth-On Dragon Skin*™20, a two-part, platinum-cured silicone elastomer [7, 8]. This material is characterized by a Shore A hardness of 20-25, classifying it as a soft elastomer. In accordance with the ASTM D638 standard [9], Type V tensile specimens were die-cut from pre-cured, 3 mm thick sheets of this material, which are marketed as dermal phantoms for procedural training. Representative specimens before testing and after failure are shown in Figure 1.

A total of 39 specimens were tested to failure across four distinct loading rates: 10, 50, 100, and 1000 mm/min. The number of specimens evaluated for each loading rate is detailed in Table 1. All tests were carried out using a Mark-10 model F305-EM universal testing machine, equipped with an FS05-300 load cell (1500 N capacity and 1 N resolution) and G1061 grips, as shown in Figure 2, adhering to the environmental conditions specified in the ASTM standard (tests were conducted at $23 \pm 2\,^{\circ}\mathrm{C}$ and $50 \pm 10\,\%\,\mathrm{RH}$).

From each load-displacement curve, the maximum load F_{max} was identified. The UTS, corresponding to the nominal stress at maximum load, was calculated using the recorded maximum load and the undeformed cross-sectional area of the specimen A_0 as follows:

$$UTS = \frac{F_{max}}{A_0} \tag{1}$$

where F_{max} is the maximum measured force and A_0 is the initial cross-sectional area. The resulting UTS values were then grouped by loading rate for statistical comparison.

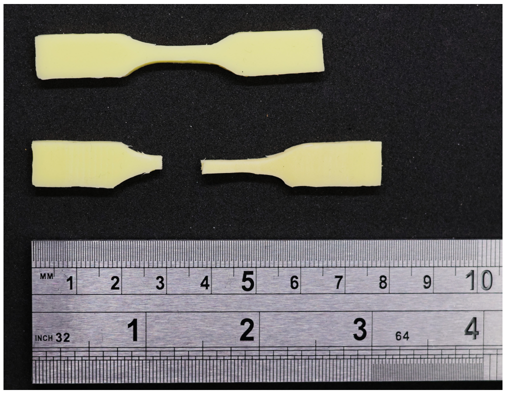

Figure 1: Representative ASTM D638 Type V specimen before testing and after failure. Note: The top part of the scale is given in millimeters.

2.2 Statistical analysis

A non-parametric statistical approach was chosen due to the small sample sizes in some experimental groups (as low as $n = 5$). With small samples, the assumption of data normality required for parametric tests like ANOVA cannot be reliably verified, as normality tests (e.g., Shapiro-Wilk) lack sufficient statistical power. The non-parametric Kruskal-Wallis test was therefore used to determine if the loading rate had a significant effect on the UTS ($\alpha = 0.05$). Subsequently, a Dunn's post-hoc test with Bonferroni correction was performed to conduct pairwise comparisons and identify which specific groups differed statistically from each other.

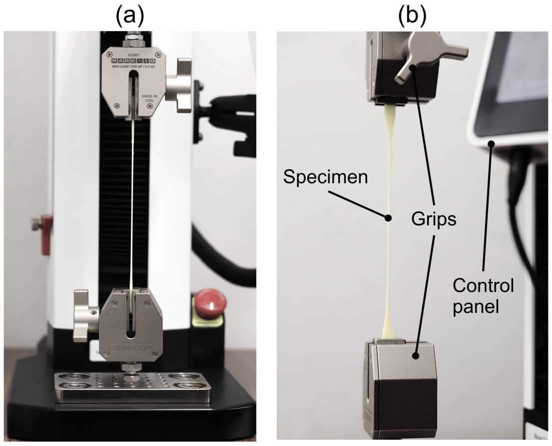

Figure 2: Experimental setup: (a) testing apparatus, and (b) detail of a specimen during testing.

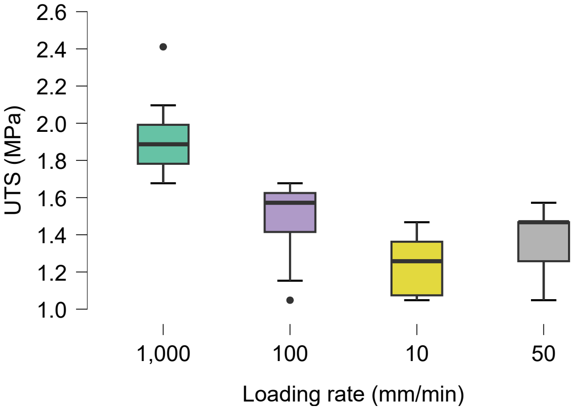

Figure 3: Boxplot distribution of Ultimate Tensile Strength as a function of loading rate for the PDMS elastomer. The central line indicates the median, the box represents the interquartile range (IQR), and the whiskers extend to 1.5 times the IQR. Outliers are shown as individual points.

3 Results

The results demonstrate a clear positive relationship between the loading rate and the material's tensile strength. A comprehensive summary of the descriptive statistics for each group is provided in Table 1, while the distribution of the data is visually represented in Figure 3. All raw UTS values are provided in Appendix A.

As shown in the data, the mean UTS increased monotonically from 1.240 ± 0.181 MPa at a loading rate of 10 mm/min to a maximum of 1.927 ± 0.199 MPa at 1000 mm/min. The boxplots in Figure 3 visually confirm this trend, illustrating a progressive increase in the median UTS with higher loading rates. Additionally, the figure suggests that the data dispersion tends to increase at higher speeds, indicating greater variability in the material's failure behavior under faster loading conditions.

The Kruskal-Wallis test confirmed that the effect of loading rate on UTS was significant ($H = 27.87$, $p < 0.0001$). This indicates that at least one experimental group differed significantly from the others.

The Dunn's post-hoc test with Bonferroni correction was performed to identify the specific pairwise differences, with the results summarized in Table 2. The analysis revealed that the UTS at 1000 mm/min was significantly higher than the UTS at 10 mm/min ($p < 0.0001$), 50 mm/min ($p = 0.0021$), and 100 mm/min ($p = 0.0015$). In contrast, no statistically significant differences were found among the lower loading rate groups of 10, 50, and 100 mm/min ($p > 0.45$ for all comparisons).

In summary, the statistical analysis provides evidence that *a high loading rate significantly increases* the material's ultimate tensile strength. This effect is primarily driven by the performance at the highest loading rate, as the UTS at 1000 mm/min was found to be significantly greater than all other groups. Conversely, while a positive trend is apparent, the differences in tensile strength among the lower to moderate loading rates of 10, 50, and 100 mm/min were not statistically significant.

4 Discussion

The experimental results demonstrate a clear influence of the loading rate on the UTS of the platinum-cured PDMS elastomer. The observed increase in UTS with increasing loading rate, particularly pro-

Table 1: Descriptive statistics for Ultimate Tensile Strength (UTS) at each loading rate.

Loading rate (mm/min)	**Number of specimens**	**Mean UTS (MPa)**	**Median UTS (MPa)**	**Std. Dev. (MPa)**
10	6	1.240	1.258	0.181
50	5	1.363	1.468	0.210
100	15	1.495	1.572	0.192
1000	13	1.927	1.887	0.199

Table 2: Pairwise p-values from the Dunn-Bonferroni post-hoc test. Significant differences ($p < 0.05$) are marked with an asterisk (*).

	Loading rate (mm/min)		
Comparison	**50**	**100**	**1000**
10 vs.	1.0000	0.4550	< 0.0001*
50 vs.	–	1.0000	0.0021*
100 vs.	–	–	0.0015*

nounced at the highest rate of 1000 mm/min, is a characteristic feature of *viscoelastic materials*. This behavior arises because, at higher deformation rates, the polymer chains have less time to reorient and disentangle in response to the applied stress, a well-established phenomenon in polymer science (see, e.g., [10]). Consequently, the material exhibits a stiffer response and a greater resistance to fracture, requiring a higher force to induce failure. This finding aligns well with the established understanding of polymer mechanics, where such rate-dependency is a fundamental aspect of their mechanical performance [11].

Comparing the results to existing literature, the measured UTS values for this soft PDMS (ranging from approximately 1.24 MPa to 1.93 MPa) are consistent with the spectrum reported for various PDMS formulations. For instance, studies on softer PDMS variants, typically report UTS values in the range of 0.1 to 4 MPa, with harder formulations achieving higher strengths [12, 13]. The results in this study therefore provide valuable quantitative data for a specific commercial formulation commonly utilized in practical applications, confirming its mechanical characteristics within the expected range for soft elastomers.

The statistical analysis, particularly the significant result from the Kruskal-Wallis test and the specific pairwise differences identified by the Dunn's post-hoc test, provides a robust confirmation of the observed trend. The lack of statistically significant differences among the lower loading rates (10, 50, and 100 mm/min) suggests that within this range, the material's viscoelastic relaxation times might still be sufficiently short to accommodate the deformation, leading to similar failure strengths. However, this should be studied further using more direct viscoelastic characterization techniques, such as Dynamic Mechanical Analysis, to precisely determine the material's relaxation time spectrum (see, e.g., [14]).

The practical implications of these findings are relevant for applications where this type of PDMS is subjected to dynamic loading. For materials used as *dermal phantoms for procedural training* (e.g., in tattoo practice or surgical simulation), understanding this rate-dependent behavior is crucial. For instance, rapid needle insertion or high-speed tool interactions may experience a material response that is effectively stronger than what would be predicted from slow, quasi-static tests. In *soft robotics*, where actuators can operate at various speeds, or in *biomedical devices* subjected to rapid tissue movements, accounting for this rate-dependency is essential for design, reliable prediction, and ensuring the structural integrity of the components under operational conditions.

However, this study has several limitations. The investigation was confined to uniaxial tensile loading at room temperature, focusing only on the UTS of the PDMS. The material's Young's modulus was not characterized due to instrumentation constraints for direct strain measurement. Therefore, future work should explore other loading modes (e.g., compression and shear), and the effect of temperature or aging conditions.

Although ASTM D412 [15] is the standard method for tensile testing of elastomers, the present study employed ASTM D638 Type V specimens due to the sheet format of the commercial PDMS material and die availability. The results should therefore not be interpreted as normative reference values, but rather as internal comparisons under a consistent specimen geometry. This choice does not affect the main conclusion of the study, namely the clear influence of loading rate on the ultimate tensile strength.

A further limitation concerns measurement resolution. The load cell's resolution, in conjunction with the inherently small cross-sectional area of the Type V specimens, dictates the minimum detectable stress increment. This results in a discretization of the stress data, which can generate tied ranks in the non-parametric analysis and potentially inflate the apparent data dispersion. Nevertheless, the magnitude of the rate-dependent effect on UTS is substantially larger than this instrumental limitation, ensuring the validity of our main conclusions. Future work could benefit from higher-resolution load cells or larger specimen geometries to enhance data precision.

5 Conclusions

This study characterized the effect of loading rate on the ultimate tensile strength of a soft, platinum-cured polydimethylsiloxane elastomer. The results demonstrated a clear positive relationship, where the material's mean UTS increased from 1.240 MPa at 10 mm/min to 1.927 MPa at 1000 mm/min. This rate-dependent behavior was confirmed by a Kruskal-Wallis test ($p < 0.0001$), validating that the observed trend is a genuine material response and not a result of random experimental variation.

A detailed post-hoc analysis revealed that the increase in strength was primarily driven by the highest loading rate. The UTS at 1000 mm/min was found to be significantly higher than at all lower rates (10, 50, and 100 mm/min), while no statistically significant differences were found among these lower to moderate rate groups. The quantitative data and statistical analysis presented in this work provide characterization of this specific PDMS formulation, offering essential information for the analysis of soft robotics, biomedical devices, and dermal phantoms. Future work should expand on these findings by investigating the material's behavior under other loading modes, such as compression and shear, and by studying the influence of temperature or aging on its mechanical failure properties.

Declaration of generative AI and AI-assisted technologies in the writing process

The author confirms that a commercial Large Language Model was employed solely for language editing and grammar refinement during the preparation of this manuscript. All scientific content, data analysis, interpretation, and conclusions were developed independently by the author. The final manuscript was thoroughly reviewed and edited, and the author assumes full responsibility for its content.

Data availability statement

All data supporting the findings of this study are included within the article.

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A Raw experimental data

Table A. Raw values of Ultimate Tensile Strength (UTS) for each specimen grouped by loading rate.

Loading rate (mm/min)	UTS (MPa)	Loading rate (mm/min)	UTS (MPa)
1000	1.6771	100	1.5723
1000	2.0964	100	1.5723
1000	1.8868	100	1.3627
1000	2.0964	100	1.3627
1000	1.8868	100	1.6771
1000	1.8868	100	1.6771
1000	1.7820	100	1.5723
1000	2.4109	100	1.5723
1000	1.7820	100	1.1530
1000	1.9916	100	1.4675
1000	1.9916	100	1.6771
1000	1.8868	100	1.4675
1000	1.6771	100	1.6771
10	1.3627	100	1.5723
10	1.4675	100	1.0482
10	1.3627	50	1.4675
10	1.0482	50	1.4675
10	1.1530	50	1.0482
10	1.0482	50	1.2579
		50	1.5723