

Highlights

PDMS elastic properties: influence of fabrication protocol and test method

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- The stiffness of PDMS reported across literature is inconsistent
- Tension testing, a mechanical “best practice”, produces the widest variability
- False equivalencies arise when directly comparing different methods and cure schedules
- Cure schedules and testing protocols should be standardized in the field

PDMS elastic properties: influence of fabrication protocol and test method

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Abstract

Silicone rubbers have been integral to the rapid development of microfluidic devices and flexible electronics in recent decades. Polydimethylsiloxane, commonly abbreviated as PDMS and produced using the brand name Dow SYLGARD 184, is a ubiquitous such rubber that is renowned for its ease of manufacturing and biocompatibility. SYLGARD 184 is a soft polymer frequently used in the field of mechanics, microfluidics, and electronics given the straightforward ability to manipulate its material properties via tuning base to curing agent mix ratios and curing schedules. However, this tuning process largely occurs on a case by case basis via trial and error, without a comprehensive understanding of how composition, temperature, or mechanical test method may alter the measured elasticity. Here we compare the reported elastic response of PDMS SYLGARD 184 obtained using a range of mechanical testing methods and compositions to investigate the variability. We also include previously unreported experimental results obtained in our lab using Volume Controlled Cavitation Expansion (VCCE). Both testing method and cure schedule (time and temperature of curing) are found to strongly influence the measured elastic response resulting in shear moduli that range over 3 orders of magnitude for chemical compositions that are reported to be the same. While tension testing is a common test method in mechanical analysis, the wide ranging moduli for stiff PDMS and complete inability to measure softer PDMS compositions reveal the limits of this standard method. As researchers in the field of mechanics strive to quantify the properties of increasingly complex biological and composite materials, converging on a standardized measurement of PDMS is necessary, and is a necessary first step for the community.

Keywords: polydimethylsiloxane (PDMS), stiffness, SYLGARD 184

1. Introduction

Polydimethylsiloxane (PDMS) is widely used in microfluidics [1, 2, 3], medical devices, electronics [4, 5, 6], and engineering mechanics. As a two-part material system, the stiffness of the resulting silicone polymer can be easily tuned to suit the needs of an application. PDMS will cure at room temperature, or can have the curing accelerated with an oven cure. This flexibility of composition and cure is particularly useful in the context of biological research where PDMS has been proposed as a scaffold for muscle growth [7], and for studying cellular motility [8], as a biological membrane mimic in microfluidics [9], in biohybrid devices [10, 11, 12], and for cardiomyocyte growth [13, 14].

The tunability of bulk elastic and surface properties awarded by PDMS (or often the common branded product Dow SYLGARD 184 [15]) has driven its popularity in the fields of mechanics and advanced materials. PDMS is often used during method development for measurements of the elastic, adhesion, and fracture properties of soft materials [16, 17, 18, 19, 20]. Because of its relative chemical stability, many researchers also rely on PDMS during the development of tough materials that can undergo large deformations before failure [21, 22, 23, 24, 25, 26, 27].

The same fabrication flexibility that makes PDMS applicable across a range of fields leads to a critical problem of mechanical reproducibility: the elastic moduli of PDMS reported in literature vary widely. Authors rarely use consistent preparation and cure conditions unless they are from the same research team. Teixeira et al. [28] note this in their 2021 review, where they consolidate 25 articles on a range of preparation techniques that have been reported for PDMS used to perform a range of goals from stiffness modification, to foaming, to incorporation or inhomogeneities such as nanoparticles, metals, or carbon nanotubes. When looking at stiffness alone as a property of interest, the soft (elastic modulus <1 MPa) nature of PDMS further lends itself to a wider subset of mechanical characterization methods than are available for stiffer engineered materials. While standardized dogbone tension, compression, and impact tests are the standard for metal samples, as a soft material, PDMS has been tested with not only tension (both ASME standard and non standard) and compression but also indentation, nanoindentation, needle induced cavitation rheology, volume controlled cavity expansion (VCCE), and simple shear.

“Round Robin” studies have been used to compare test methodologies and increase the “reliability and repeatability” of measurements in ceramics [29, 30], composites [31], adhesives [32], concrete [33], steel [34], and many other materials and industries. In their Versailles Advanced Materials and

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Standards report, Kubler et al. [29] articulate their motivation for conducting the study to determine if the Single-edge-V-Notched beam method for measuring fracture toughness is “user-friendly, reliable and... comparable to other recognised methods”. A similar effort in the context of PDMS elasticity characterization is, in the view of the authors, overdue. To this end, we embark on this study in an effort to understand the magnitude of the problem at hand. We present the scale of variability observed across literature and hope to motivate the community to converge on more consistent preparation, and testing methodologies to improve repeatability and reprehensibility for PDMS and across the field of soft material mechanics.

This letter is organized as follows: we begin by describing how studies were chosen for inclusion in this review (Sec. 2.1) and provide a brief description of the mechanical testing methods used across the included studies (Sec. 2.2). We then present the results of our analysis (Sec. 3) and include new data for moduli obtained via VCCE (detailed in Appendix B). Finally, we conclude with remarks and cautions on stiffnesses reported in literature for PDMS (Sec. 4).

2. Methods

2.1. Data gathering

Articles surveyed for this review were found through key word searches and references lists of included articles. Keywords included “elasticity” or “modulus” or “stiffness” and “PDMS” or “polydimethylsiloxane” or “SYLGARD 184”, as well as related derivatives and searches were performed across Google Scholar and Web of Science from January - August 2023. Studies included in the results presented here were those with defined a) mix ratios for curing agent and base, b) cure time, and c) cure temperature. We restrict this study to Dow’s SYLGARD 184. Hence, studies that used GE RTV PDMS silicones were excluded (such as [35] and some results reported in [36]). Note that one of the most commonly cited studies on PDMS moduli (See Fig. A1 in Section Appendix A), Lötters [4] has not been included as the authors used ABCR PS851 PDMS. All included studies are summarized in Table C.3 of Appendix C and includes new data collected by the authors as detailed in Appendix B. Studies with parameters listed as “variable” intentionally survey a large range of values and are therefore not listed in the table (though included where appropriate in corresponding figures).

Dow recommends a mixing ratio of 10 parts base to 1 part curing agent (crosslinker) on a weight to weight basis; we will abbreviate this as 10:1 or more generally $w_B:w_C$. Where the mix ratio was instead reported as a percent, we have converted to the *X parts base:1 part curing agent* format. All stiffnesses are reported here as shear modulus, μ . Where the authors initially report the stiffness as an elastic or Young’s Modulus, E , incompressibility is assumed with a Poisson’s ratio $\nu = 0.5$ [37] and $\mu = E/(2(1 + \nu)) = 3E$. For studies investigating viscoelastic material parameters or high strain rate response, the quasistatic modulus is reported in the summary charts and where only an instantaneous modulus is reported, we denote it as μ_0 .

For studies reporting a cure at room temperature, 25 °C was used in plotting and comparison tables.

2.2. Test methodologies

Authors have used a diverse range of test methods to establish the stiffness of PDMS depending on the curing agent ratio in question and goal of the study. The fundamental assumptions and geometries of the different methods are discussed below and depicted in Fig. 1.

Tension: Tension testing was undertaken using a commercial tension test machine in all cases except [7] which used a fixed applied weight, [38] that uses a dynamic testing with a modified split Hopkinson bar, and [8] that uses a custom stretching tool and load cell. Tracking the force F , and sample extension ΔL , from initial length L , the material stiffness is calculated as $\sigma = E\epsilon$ in the linear regime where $\sigma = F/A$ and $\epsilon = \Delta L/L$ are the stress and strain, respectively for a sample cross sectional area, A . Clamp displacement is used in [39, 40, 21, 36] for tracking average sample extension, while [38] use particle tracking and digital image correlation, [41, 42, 8] use optical image capture and post process with a known calibration, and [7] use direct measurement. The ASTM Standard D412 for a “Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension” [43] includes a set of defined sample geometries, ramp rates, and test conditions and was used by [40, 44, 39, 45] who all focus on only a 10:1 base to curing agent ratio.

Compression: Unconfined compression using $\sigma = E\epsilon$ in the linear regime as with tension testing was employed by [46] to compare against nanoindentation, as well as by [47] in their comparison of moduli across curing agent ratios.

Nanoindentation: With an indenter tip possessing a projected contact area A , and geometry described by β , the modulus of a material near a free surface can be determined from the slope of the pressure-displacement curve $S = dP/dh$ of an indentation. Calculating the reduced modulus E_r based on the indenter geometry, then combining with the indenter modulus E_i and Poisson’s ratio ν_i returns the sample modulus, E . Commercially available hardware was used by most authors, however [45] were the only authors to use the standard analysis method included with their tool, while all other authors reported specifics of their analysis: [19] used the Oliver Pharr method (not accounting for adhesion) to determine E_r^{OP} . To avoid the overestimate of modulus that is typical in polymers when using Oliver Pharr, Cheng et al.[48] instead used a Hertzian contact model, whereby

$$E_H = \sqrt{\frac{S^3(1 - \nu^2)^2}{6R_i P_{max}}} \quad (1)$$

for a spherical indenter with radius of curvature R_i and ν is assumed to be 0.5 for PDMS. Multiple authors acknowledge the significance of adhesion in nanoindentation measurements and employ the Johnson, Kendall, Roberts (JKR) model instead of [46, 49, 20], or in addition to [50, 51], Hertzian contact. However authors disagreed whether the Hertzian contact model returned a higher moduli than the JKR model [46] or a lower moduli [20].

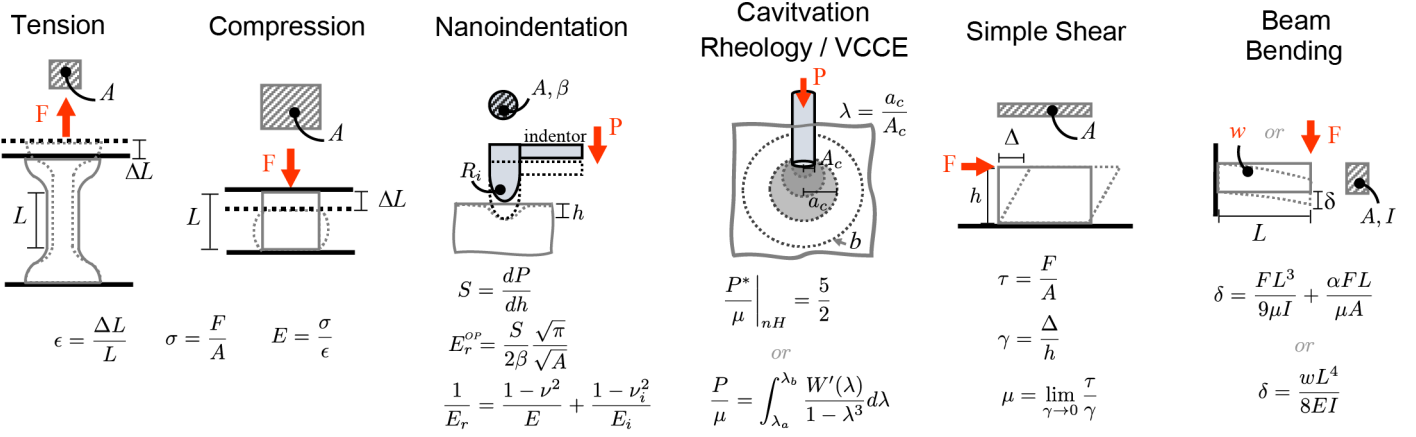


Figure 1: Common types of testing used to determine shear or elastic modulus, μ and E for PDMS. Variable definitions are included in the text.

Volume Controlled Cavity Expansion (VCCE): Controlled injection of an incompressible working fluid at the tip of an injection needle is used in this method to expand a spherical cavity in the sample [52, 17]. The resisting pressure in the cavity, P , is simultaneously measured to obtain a nonlinear pressure-volume relationship, or equivalently $P = P(a_c)$, where a_c is the effective cavity radius. Comparison with theoretical prediction of elastic, spherically symmetric, cavity expansion in incompressible hyperelastic materials, namely

$$P(a) = \int_{a_c/A_c}^1 \frac{W'(\lambda)}{1 - \lambda^3} d\lambda, \quad (2)$$

then allows to determine material parameters. Where λ is the circumferential stretch which varies from a_c/A_c at the cavity wall to 1 in the remote field, $W(\lambda)$ is the corresponding elastic potential energy, and A_c is the initial defect size, which needs to be determined. This method can also be applied to probe viscoelastic properties [53].

Li et al.[54] use similar assumptions in a cylindrical geometry, finding a very good match between analytical and experimental results.

Cavitation Rheology (CR): Alternately, a second type of cavity expansion, cavitation rheology, aims to identify the peak value of the resisting pressure, P^* , and assumes that it is well represented by the theoretical cavitation limit which is then used to determine the material parameters. In contrast to VCCE, this approach does not require control of the injected volume (it typically uses gas as an injection medium). Milner [55, 56] and Yang [57] assume a neo-Hookean material model¹, which implies $P^* = (5/2)\mu_{nH}$.

Simple Shear: Both [58] and [59] assume linear (small strain) deformations in simple shear. An applied shear force, F , induces a displacement, Δ , and corresponding shear strain $\gamma = \Delta/h$. The shear modulus is then estimated as $\mu = \tau/\gamma$, where the shear stress is $\tau = F/A$ and h and A are sample height and area shown in Fig. 1.

Beam Bending: This method relies on connected a displacement of a beam with know geometry to an applied load. Armani [37] measured tip deflection, δ , of a length L cantilever beam that was displaced under its own weight (w per unit length) and calculated modulus using $\delta = \frac{wL^4}{8EI}$ with I describing the second moment of area. By contrast, Du[60] considered a point load at the tip of a low aspect ratio beam and added a Timoshenko term $\alpha \frac{FL2(1+\nu)}{EA}$ with the shear coefficient α .

Membrane Deflection: A unique measurement method [61], uses optical profilometry to measure the membrane deflection of a nanometer thickness layer of spin coated PDMS on a silicone wafer. By pressurizing a circular portion of the membrane with radius r and thickness t , the authors were able to connect deflection, δ , and material modulus as

$$\frac{P}{\delta} = \frac{C_1 t}{r^2} \sigma_0 + \frac{C_2 f(\nu) t}{r^4} \frac{E}{1 - \nu} \delta^2$$

using geometric coefficients C_1, C_2 and $f(\nu)$ and residual stress σ_0 , and again assuming $\nu = 0.5$.

2.3. Correlation analysis

Compiled data is visualized to observe trends and the monotonicity of relationships is quantified using Spearman rank correlation coefficients, ρ [62]. The Spearman correlation is executed via MATLAB and is applied between preparation conditions (cure temperature, time) and within subgroups of individual test methods in order to isolate possible origins of stiffness discrepancies. While ρ provides indication of how *monotonic* the relation between two inputs is ($0.3 \leq |\rho| < 0.6$: Fair, $0.6 \leq |\rho| < 0.8$: Moderate, $0.8 \leq |\rho| < 1$: Very strong, $|\rho| = 1$: Perfect[63]), it does indicate the *magnitude* or linearity of an effect.

3. Results

3.1. Wide modulus variability and dominance of 10:1 ratio

Despite reportedly identical mix ratios, the measured shear moduli can vary by three orders of magnitude between different studies as shown in Fig. 2. We observe that this is due to

¹This result can be obtained directly from (2) at the limit $\lambda \rightarrow \infty$, with a neo-Hookean form of $W(\lambda)$, as shown in [52].

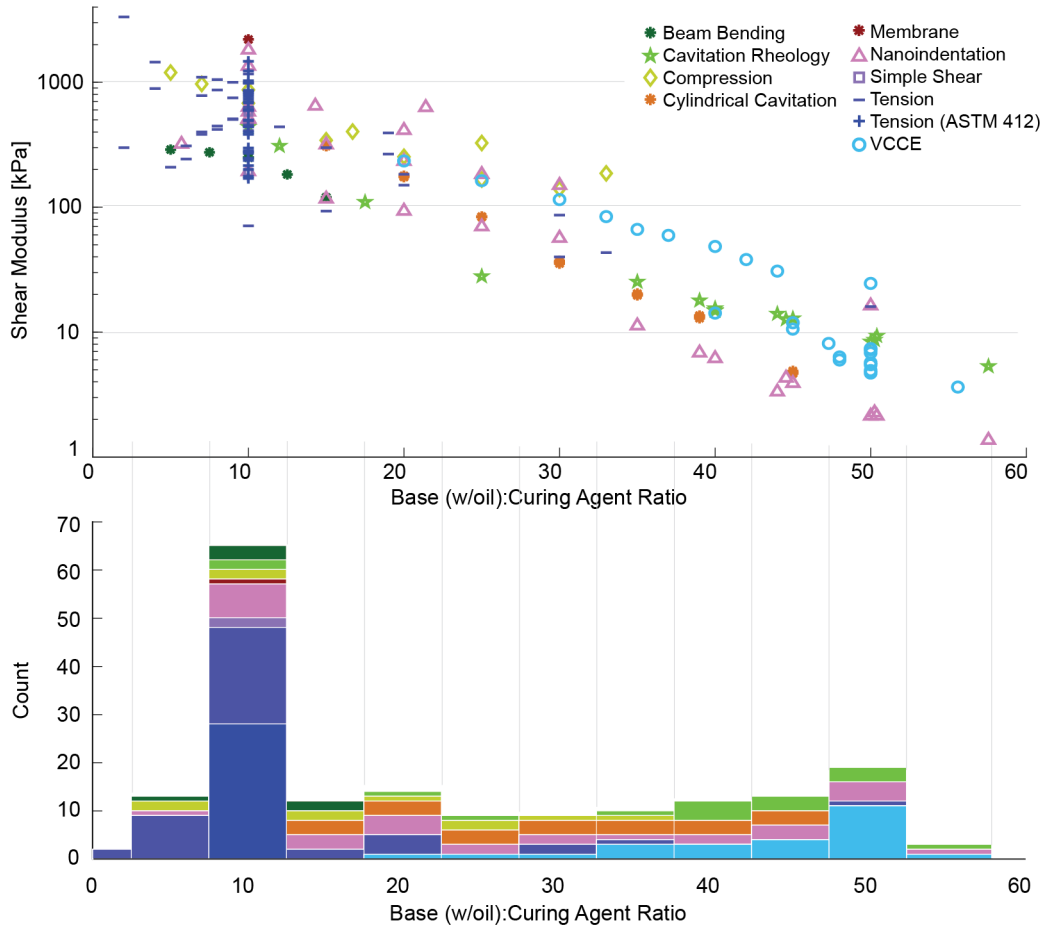


Figure 2: Stiffness data from all included studies relative to material composition show wide variability in reported moduli. Sorting by test methodology reveals trends in how test methods correspond to mix ratios. The stacked histogram shows that the TDS recommended mix ratio of 10:1 $w_{base}:w_{linker}$ has the most reported data for moduli in literature. The abundance of data at 10:1 makes trend interpretation for combined data challenging when studies reporting only a value are averaged in with studies exploring stiffness by mix ratio. Tension testing is common for stiffer samples however cavity expansion dominates in softer mix ratios while Nanoindentation and compression have been used across a range of compositions.

three main factors: 1) different test methods producing ranging results, 2) variation in specified cure schedule, and 3) the inclusion of non reactive oils in the base mixture that are sometimes included to manipulate the viscoelasticity of the cured silicone. The histogram in Fig. 2 shows a count of how many experimental results exist by test method across a range of crosslinking densities and highlights how different test methods tend to be used for different stiffness of materials. While combining all the data is useful to inspire caution when using literature reported “stiffness” for SYLGARD 184, diving further into the data is necessary to try and identify the sources of the variability and the key parameters driving the reported ranges. Note that in the Technical Data Sheet (TDS), Dow reports a tensile modulus of 6.7 MPa for a 10:1 mix ratio[15]. Though not included in Fig. 2 given that no test method or cure conditions are available, this is significantly above all results compiled here.

Table 1 presents the Spearman correlation between shear modulus and key process parameters: curing agent ratio, cure temperature, and cure time. Correlations are calculated for all tests and cure ratios combined, then separately for select testing methods with data from multiple authors (and conditions). The

second section of the table is split into only tests performed at the 10:1 ratio (that recommended on the product TDS [15]), and those excluding this ratio. All comparisons between stiffness and curing agent ratio indicate very strong correlations with an exceptionally low p-value, as expected, except for those tests performed using tension testing, which returns only fair to moderate correlation.

3.2. Hotter cures result in stiffer material

An increase in cure temperature is more directly correlated to a monotonic increase measured stiffness (fair correlations considering the full data set) than is an increase cure time (weak - fair correlations). Fig. 3 shows that cure temperatures evaluated are not uniformly distributed amongst the base:curing agent ratios, with larger ratios being more often cured at room temperature and never over 150 °C compared to the stiffer, low ratio, samples. This likely compounds the effect of higher mix ratio samples appearing softer due to both lower temperature and less curing agent.

Table 1 also shows the counterintuitive result that longer cure times correlate with softer samples, however this is likely due to

Test type	$N_{articles}$	N_{tests}	Curing agent ratio		Cure temperature		Cure time	
			ρ	p	ρ	p	ρ	p
All tests	36	178	-0.88	0.00	0.32	0.00	-0.29	0.00
Cavitation Rheology	3	16	-0.98	0.00				
Compression	2	11	-0.94	0.00	0.52	0.10	-0.52	0.10
Nanoindentation	9	30	-0.90	0.00	0.72	0.00	-0.37	0.05
Tension	12	66	-0.44	0.00	0.43	0.00	-0.16	0.20
VCCE	4	25	-0.92	0.00	-0.85	0.00	0.85	0.00
All tests 10:1	27	53			0.30	0.03	-0.37	0.01
Nanoindentation	7	7			0.35	0.45	-0.45	0.31
Tension	12	38			0.26	0.12	-0.46	0.00
All tests excluding 10:1	24	122	-0.92	0.00	0.24	0.01	-0.13	0.14
Compression	2	9	-0.90	0.00	0.61	0.11	-0.61	0.11
Nanoindentation	6	23	-0.91	0.00	0.61	0.00	-0.05	0.82
Tension	6	28	-0.63	0.00	0.62	0.00	0.33	0.09

Table 1: Correlations of stiffness with preparation conditions (ρ) and p-value of each. Very strong negative correlations between curing agent ratio and modulus across all test methods and groups of samples appears as expected. The later two sections of the table isolate samples prepared at the 10:1 w/w in order to remove the disproportionate number of tests recorded at this ratio from biasing the results. Blanks in the table indicate cases where conditions are the same for all trials within the row.

the significantly longer times used with room temperature curing. With the strength of the correlation between temperature and stiffness, this can be explained by the tendency of lower temperature curing to produce softer samples overshadowing the effect of time on cure. In an effort to reduce the variability imparted by different test methods, Table 1 is subdivided by test types and further to isolate 10:1 ratio samples. Across compression, nanoindentation and tension testing, the correlation between cure temperature and stiffness increases to moderate - strong when test methods are considered independently, and is even stronger when 10:1 ratio samples are excluded (confirming that the number of tests performed *only* at this ratio may be biasing the overall trends in results).

There is, however, a limit at which higher temperatures will no longer produce stiffer samples and instead will degrade the polymer. Liu et al. [39] set out to study the effect of heating on PDMS mechanical properties and also observe that stiffness increase between 100 and 150 °C, but decreases for 200 °C and 300 °C samples.²

3.3. False equivalencies arise due to test method

In an effort to isolate the cure schedule from the test method, Fig. 4 compares stiffness for samples cured 120 minutes at 85-100 °C across multiple authors. Fitting this data with an exponential function results in $\mu = 1003e^{-0.073w_{B+oil}}$ with an R^2 of 0.74 (a linear fit on the same region had an R^2 of 0.65). Particularly for the higher curing agent ratio samples, the measured stiffness varies by hundreds of kilopascals between testing methods. Tension testing inconsistently reports moduli both higher and lower than nanoindentation, and is not used for softer samples. While the general softening trend with higher

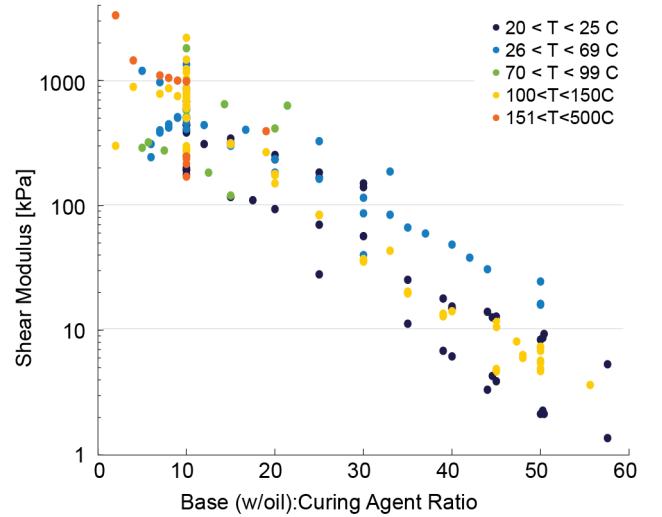


Figure 3: Cure temperatures are not equally likely across all $w_{B+oil}:w_C$ ratios. Room temperature cures are more common for larger ratio samples and cure temperatures over 150 °C are rarely seen for mix ratios over 10:1.

base ratios can provide a rough qualitative understanding of polymer composition's influence on stiffness, there is minimal overlap in test methods that are used between soft samples and stiff samples, leaving open the question that the trends are due to the test methodology.

Restricting the $w_B:w_C$ ratio to a more narrow range and examining three cavity-expansion based methods, encourages caution about biases that may be more pervasive in the dataset. Fig. 5 compares the μ_0 of Yang et al. [57] measured through CR and assuming a neo-Hookean material model, to results obtained via VCCE for comparable mix ratios (oil containing samples are excluded). The VCCE results from Raayai-Ardakani et al. [17, 52] are also μ_0 , while those of Chock-

²The data displayed here from [39] have been down selected to only the 100 °C and 200 °C data, though 150 °C and 300 °C cure temperatures were also evaluated in the original work.

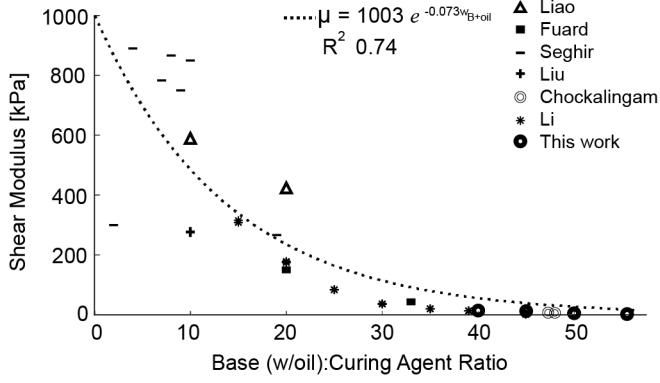


Figure 4: Test method imparts variability even when a similar cure schedule is used: 120 minutes at between 85 and 100°C. Test type indicated by marker shape matching those used in Figure 2.

alingam et al. [53] and this work are μ .

As expected, $\mu < \mu_0$ when measured with VCCE with instantaneous moduli more than double the quasistatic moduli for comparable $w_B:w_C$ ratio. However, it can be seen on Figure 5 that μ_0 does not correlate 1:1 between CR and VCCE. The observed deviation between Raayai-Ardakani and Yang et al. can therefore be attributed to the 6 day room temperature cure of Yang et al. producing softer samples than the 3 days at 40 °C cure schedule used by Raayai-Ardakani. By contrast, the unexpected 1:1 correlation between μ_0 by CR [57] and μ by VCCE [53] (blue line on Figure 5) is likely attributed to the discrepancy between the room temperature cure schedule used by Yang et al. and the 100 °C 2 hr schedule used by Chocaklingam et al. and this work.

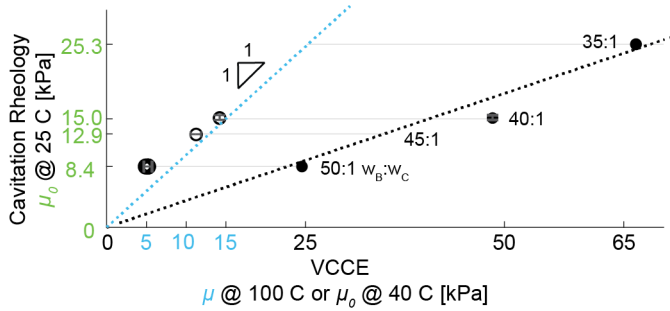


Figure 5: VCCE results of [17, 52] for μ_0 (filled marker), as well as μ from [53] and this work (open circle, blue axis labels) compared to CR results for μ_0 by Yang et al. [57] for comparable mix ratios ($w_B:w_C$ as noted on plot).

3.4. Nonreactive oils act as part of the w_B in stiffness trends

Oil-based thinners have been proposed as a method to decouple the viscoelastic and elastic responses of PDMS without effecting the stiffness. An unspecified ‘thinner’ was used in [36] while [44, 53, 57], and new data presented in this work, use silicone oil added to the base. Fig. 6 again shows results obtained by Yang et al. alongside those of Chockalingam et al. and this work, demonstrating that the correlation of shear modulus to mix compositions is stronger when the added oil is included in

the w_B than when it is not ($|\rho| = 0.96$ vs $|\rho| = 0.47$ in [57] and $|\rho| = 0.85$ vs $|\rho| = 0.74$ combining [53] and this work). Across both sets of data, increasing $w_{B+oil} : w_C$ reduces the observed shear modulus (μ or μ_0) by a similar amount (0.768 vs 0.766 kPa per added w_{B+oil} with a linear fit to the data in this region). While all authors report changes to the viscoelastic time constants when including nonreactive oils, the *trend* in softening with increasing w_{B+oil} for soft PDMS is shown to be consistent a) regardless as to whether the ratio is altered with base or oil, and b) in both instantaneous and quasistatic modulus.

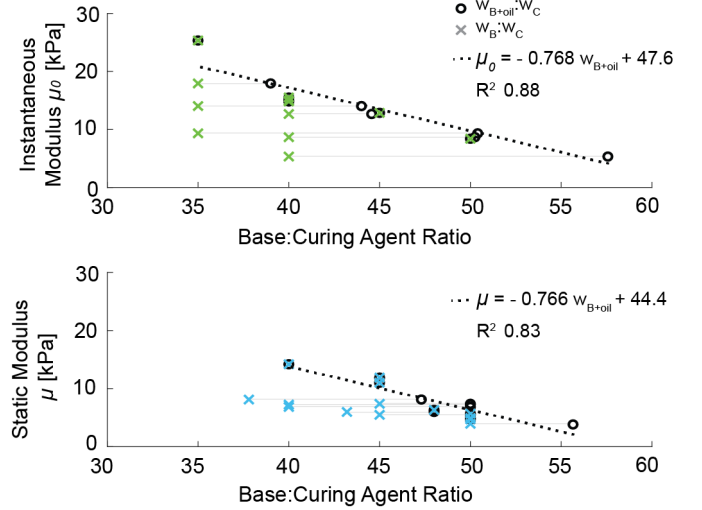


Figure 6: If $w_B:w_C$ is considered without taking oil into account (crosses), the correlation of ratio with stiffness is not as strong as when $w_{B+oil}:w_C$ is considered (circles) and the R^2 of a linear fit drops from 0.88 to 0.21 for CR and 0.83 to 0.31 for VCCE. The top figure shows μ_0 from Yang et al. [57] against an abscissa calculated both with and without oil included in w_B ; the bottom plot show μ results from Chockalingam et al., [53] and this work.

4. Conclusions

It is clear that current literature is far from providing reproducible scientific results when it comes to measuring the mechanical properties of SYLGARD 184. If this is our goal as a community, a number of steps must be taken to better observe the properties that so many authors to date have claimed to measure. At present, cure schedules ranged widely between researchers with very little overlap if the authors were not currently or historically from the same research group. Of the utmost importance, is unifying how PDMS is cured and reporting full details of these conditions, as well as timing between cure and test. We would propose three temperatures for PDMS where control of mechanical properties is desired: a 25°C room temperature, a “moderate” 60°C at or below the glass transition temperature of plastics commonly used in additive manufacturing, and a “hot” 100°C for rapid curing.

While the TDS recommends four possible cure schedules [15] between room temperature and 150 °C, numerous authors note changes in mechanical properties after “fully curing” material with the recommended conditions. Further attention on

storage time and condition is warranted as pointed out by a number of the studies including [53] and [48] who showed nearly a doubling in stiffness with 18 vs 3 days of storage at room temperature after an initial cure.

Tension tests on PDMS reported the widest variation of stiffness, with nanoindentation also providing widely variable results. Though these are both common testing techniques, we recommend caution in the use of both methods. At low mixing ratios PDMS is brittle [42] and tension testing is highly sensitive to surface imperfections on the sample, while at higher $w_B:w_C$ ratios, the soft modulus means measurement set up is prohibitively challenging and results are influenced by the clamping conditions. The variability of nanoindentation is likely due to the uncertain nature of the adhesion between the sample and indenter tip, which was the focus of many of the authors referenced here. Using a method that relies on consistent surface adhesion, in a material where surface treatments are applied to widely varying degrees, will continue to produce imprecise results.

Each researcher has unique needs for their research, and not each mechanical testing method is possible for a given sample. However, by noting the current discrepancies in literature and advocating additional attention is focused on consistency and comparisons to the full body of literature going forward (not selected works that happen to align with ones results), we anticipate better agreement in measured mechanical properties is easily attainable if the community decides it is important.

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Appendix A. Connectedness of existing literature

Litmaps software was used to create a connectedness diagram of all the studies used in this review shown in Figure A1. [4] is seen to be particularly commonly cited with work on PDMS.

 Litmaps

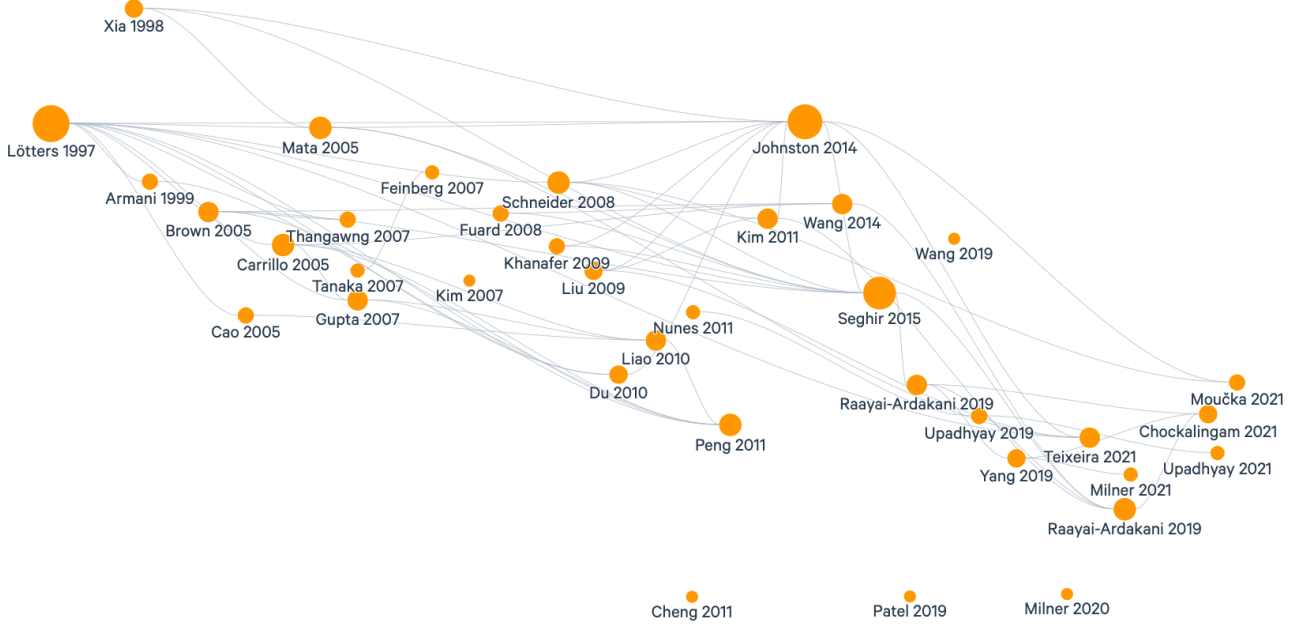


Figure A1: Included studies show citation links between articles. Markers are sized based on relevance within the network and sorted chronologically from left to right, and vertically on a log scale by total citations in any field per the Litmaps Database [64]

Appendix B. Additional data

Previously unpublished data included in this paper was collected with the method described by Chockalingam et al. [53] via cyclic loading between $a = 0.06$ mm and 0.08 mm with 400 seconds of relaxation to determine μ . All samples are SYLGARD 184 mixed via a THINKY planetary mixer and cured at 100°C for 2 hours. Sample identifiers indicate the composition used as $S[w_{B+oil}] - [(w_{oil}/w_{B+oil})100]$ e.g. S40-10 is a 40:1 base to curing agent ratio with 10% non-reactive PDMS oil ($\mu\text{MicroLubrol}$, 350cSt). Reported shear modulus in Table B.2 is the mean $\bar{\mu}$ of results collected for each rate of $\dot{a} = 0.01, 0.02, 0.04, 0.08, 0.16$, and 0.32 [mm/s] with a standard deviation calculated from all six rates for all trials, N , within a sample.

Sample ID	$w_{B+}:w_{oil}:w_C$	N_{trials}	$\bar{\mu} \pm \sigma$ [kPa]	$\bar{A} \pm \sigma$ [mm]
S55-10	50+5.6:1	2	3.65 ± 0.11	0.326 ± 0.01
S50-00a	50+0 :1	4	5.71 ± 0.16	0.319 ± 0.01
S50-00b	50+0 :1	3	4.71 ± 0.51	0.321 ± 0.01
S50-00c	50+0 :1	2	5.47 ± 0.29	0.342 ± 0.007
S50-10	45+5 :1	3	7.38 ± 0.37	0.366 ± 0.02
S50-20	40+10:1	3	7.24 ± 0.34	0.395 ± 0.006
S45-00a	45+0 :1	1	11.9 ± 0.24	0.448 ± 0.02
S45-00b	45+0 :1	4	10.6 ± 0.81	0.414 ± 0.03
S40-00	40+0 :1	4	14.4 ± 1.8	0.460 ± 0.02

Table B.2: Additional data presented in this work with associated composition and fit parameters for shear modulus and initial defect size.

Appendix C. Included studies

Author	Test Type	Cure Temp [C]	Cure Time [hr:min]	Mix Ratio [base+oil: curing agent]
Chockalingam 2021 [53]	VCCE	100	2:00	variable, Si Oil
Raayai-Ardakani 2019 [17]	VCCE	40	72:00	variable
Raayai-Ardakani 2019 [52]	VCCE	40	72:00	variable
This work	VCCE	100	2:00	variable, Si Oil
Milner 2021 [55]	Cavitation Rheology	25	144:00	
Milner 2021 Thesis [56]	Cavitation Rheology	25	144:00	variable
Yang 2019 [57]	Cavitation Rheology	25	144:00	variable, Si Oil
Nunes 2011 [59]	Simple Shear	25	144:00	10:1
Upadhyay 2019 [58]	Simple Shear	60	3:00	10:1
Brown 2005 [7]	Tension	60	20:00	10-50:1
Fuard 2008 [8]	Tension	100	1:30, 2:00	variable
Johnston 2014 [40]	Tension†	25-200	variable	10:1
Khanafer 2008 [65]	Tension	65	12:00	6-10:1
Kim 2011 [66]	Tension			5-15:1
Liu 2009 [39]	Tension†	100 or 200	variable	10:1
Mills 2008 [41]	Tension‡	150	12:00	10:1
Moučka 2021 [44]	Tension†	25-150	variable	10:1, Si Oil
Schneider 2008 [36]	Tension	150	0:15	10:1
Seghir 2015 [42]	Tension	10 or 160	2:00, 144:00	variable
Upadhyay 2021 [38]	Tension	60	3:00	10:1
Wang 2019 [21]	Tension	65	4:00	10-30:1
Wang 2014 [47]	Compression	65	12:00	5-33:1
Carrillo 2005 [46]	Compression & Nanoindentation	25	336:00	10-30:1
Cao 2005 [49]	Nanoindentation	70	24:00	10:1
Cheng 2011 [48]	Nanoindentation	65	1:30	10:1
Gupta 2007 [50]	Nanoindentation	25	0:20,2:40	variable
Liao 2010 [51]	Nanoindentation	85	2:00	variable
Mata 2005 [45]	Nanoindentation	95	0:30	5.7-21:1
Patel 2019 [19]	Nanoindentation	70	5:00	10:1
Peng 2011 [20]	Nanoindentation	60	20:00	50:1
Armani 1999 [37]	Beam Bending	90	0:15	5-15:1
Du 2010 [60]	Beam Bending	65	1:30	10:1
Li 2024	Cylindrical Cavitation	100	2:00	variable
Thangawng 2007 [61]	Membrane	110	0:15	10:1

Table C.3: Included studies. Tension tests performed per the ASTM D412 standard are indicated with † while tests per ASTM D 5045-99 are indicated with ‡.

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