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Comparative Evaluation of Surface Property Changes in Newly Developed Silicones Under Indoor and Outdoor Weathering

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Abstract: The study aimed to assess how weathering, both indoors and outside, affected the surface characteristics of newly developed silicone elastomers. 90 specimens were made and divided into 2 primary groups based on the surface roughness and hardness tests. Three environmental protocols were used to condition the specimens: baseline, six months of indoor and outdoor weathering. To guarantee consistency and accuracy in measurements, both surface roughness and hardness samples were manufactured in compliance with ISO 48-4:2018. The impacts of weathering conditions and material groups were assessed using one-way and two-way analysis of variance (ANOVA), with significance taken into consideration at $P < 0.05$. Both at baseline and following six months of indoor and outdoor weathering, the hardness test results revealed statistically significant differences ($P < 0.001$). At baseline, indoor, and outdoor weathering, surface roughness results showed non-significant changes across the groups ($P > 0.05$). It was concluded that the surface hardness considerably improved after six months of indoor and outdoor weathering, with Z004 showing the highest values. The 80H/20L formulation showed significantly more surface roughness after weathering, although it might still be sufficient for maxillofacial applications.

Keywords: hardness; roughness; silicone elastomers; weathering

1. Introduction

The most popular substitute materials are silicone elastomers due to their facile application, biocompatibility, aesthetic results, and pigmentation (Montgomery et al., 2010; Beumer et al., 2011; Zayed et al., 2014). Clinical observations indicate that silicone prostheses deteriorate rapidly in service, leading to discoloration and loss of mechanical integrity that necessitate frequent replacement (Hatamleh et al., 2011; Wang et al., 2014; Çevik et al., 2016). In general, air pollution, exposure to ultraviolet (UV) radiation from sunshine, and variations in humidity brought on by the application and removal of adhesives and cosmetics can all result in mechanical and physical damage (Al Dharrab et al., 2013; Babu et al., 2018; Fadhil Bunyan et al., 2022). Furthermore, patient behaviors may lead to prosthesis discoloration, staining, and substrate delamination (Hatamleh et al., 2016).

Surface roughness is often regarded as a reliable indicator of a material's mechanical performance, since surface irregularities can act as initiation sites for degradation, corrosion, or fracture (Al Kaabi et al., 2025a). The effectiveness and durability of silicone elastomers used in maxillofacial rehabilitation are thought to be reliably indicated by surface hardness. It represents the material's resistance to environmental deterioration, wear, and deformation—all of which are essential for preserving prosthesis integrity throughout clinical use (Bhushan, 2017). The degree of crosslinking and filler interaction within the polymer matrix, which both affect elasticity and tear strength, directly affects hardness (Raju & S, 2021; Atallah et al., 2023).

Platinum-catalyzed silicone elastomers (HTV) that undergo crosslinking in the presence of a platinum catalyst include silicone Z004 and M511. No published studies on the effect of indoor and outdoor weathering on the physical properties of Z004 and M511. In this study, long- and short-chain polymers, fumed silica, zirconium dioxide and SiO_2 generated from rice husks were

used to create a novel silicone material. This investigation aimed to evaluate the influence of indoor weathering on the roughness and hardness of newly developed silicone elastomers.

2. Methods

2.1 Materials

Cosmesil Z004 and M511 high-temperature vulcanized (HTV) silicone elastomers were obtained from Principality Medical Ltd. (Newport, UK) and used as controls. Polydimethylsiloxane (PDMS) bases (V46 and V21) were purchased from Iota Silicone Oil (Anhui) Co., Ltd. (Bengbu, Anhui, China), while the cross-linker (HMS-301) was sourced from Meryer Chemical Technology Co., Ltd. (Shanghai, China). The Rice Husk Nanosilica was synthesized in the Biomaterials Laboratory, School of Dental Sciences, USM. The platinum catalyst was purchased from Anhui Zinca Silicone Technologies CO., Ltd., Feng Huang International, China. The Hexamethyldisilazane (HMDS) was obtained from Sigma-Aldrich, Selangor Darul Ehsan, Malaysia. The fumed silica was got from Hubei Huifu Nanomaterial Co., Ltd, China. The plasticizer (Octamethylcyclotetrasiloxane) was purchased from Iota Silicone Oil (Anhui) Co., Ltd, Bengbu, Anhui, China. The zirconium dioxide (ZrO_2) nano powder was bought from Sigma-Aldrich (M) Sdn. Bhd., Malaysia.

2.2 Mold making

An AutoCAD software (Autodesk Inc., USA) and a CNC machine (Tengzhou Jianda, China) were used to create the plastic testing patterns. To create matching wax patterns, these plastic patterns for surface hardness and roughness testing were replicated in silicone. The silicone samples were then made using stone molds using the traditional flasking method in accordance with International Organization for Standardization (ISO) requirements (Figure 1)

(Figure 1. Stone mold and silicone specimens (a) Stone mold (b) Silicone specimens).

2.3 Preparation of Z004 specimens

The silicone material (Z004) was supplied as a two-component system consisting of a base and a catalyst. The components were hand-mixed for one minute on mixing pads, after which the mixture was placed in a vacuum mixer for five minutes to ensure the removal of entrapped air. The homogenized material was then poured into the stone mold and positioned under a hydraulic press to achieve uniform adaptation. The flask was subsequently clamped, and the material was cured in a dry oven at 100 °C for two hours. Specimens exhibiting air bubbles were discarded. After a 24-hour post-curing period, the specimens were considered fully stabilized and were prepared for testing (Jindal et al., 2016).

2.4 Preparation of M511 specimens

The fabrication procedure for M511 specimens followed the same protocol used for Z004, with the exception that M511 samples were cured in a dry oven at 100 °C for one hour. After curing, the specimens were allowed to stabilize prior to testing (Jindal et al., 2016).

2.5 Preparation of 80H/20L specimens

The process of Novel 80H 20L silicone specimens involved the following steps: -

2.5.1 Synthesis of SiO_2 from Rice Husk (RH)

The process of synthesizing SiO2 nanoparticles were synthesized from rice husk (RH) based on protocols of Zulkifli et al. (2013), Noushad et al. (2014), and Noushad et al. (2016). Rice husks were initially submerged in tap water for a whole day in order to remove dust, sand, soluble compounds, and other impurities. The husks were rinsed seven times with deionized water before being dried in an oven at 260°C for a full day. After being treated with 85 mL of

hydrochloric acid per 40 g of husk, they were placed in a water bath at 75 °C for an hour. The acid-treated husks were filtered after the leaching process, rinsed seven times with deionized water, and dried for sixty minutes at 260°C in a forced-air oven to balance the pH. After that, an alkaline treatment was applied using a sodium hydroxide solution (600 mL per 40 g of husk), heated to 90 °C for an hour, and then allowed to cool. Next, 200 mL of extracted silica and 40 mL of propylene were mixed in a mechanical mixer operating at 760 rpm. After that, acetic acid was added progressively until the mixture had a pH of 7. Following centrifugation, the extracted silica was moved to a porcelain cup and calcined in an electric furnace for two hours at 500°C. Synthesized nanoparticles were pre-dried at 150 °C for 2 h. A pre-mixed solution of 0.5 mL HMDS in 5 mL toluene was mixed with a suspension of 2 g silica in toluene, which was agitated at 500 rpm for one hour. According to Ibrahim, Zikry, and Sharaf (2010), the mixture was refluxed at 110 °C for three hours, cooled, and then sequentially washed with toluene and acetone to remove any unreacted modifier before being dried at 150 °C for two hours.

2.5.2 Formulations of PDMS Base Polymers

The novel silicone elastomers were prepared by blending high- and low-molecular-weight polymer bases (80H/20L) were weighed and blended with 20% fumed silica, 20% hydrophobic silica, 0.2% rice husk–derived nanosilica, and 0.2% zirconium dioxide (ZrO_2) using a mechanical stirrer for two hours to ensure homogeneous dispersion of the fillers. Subsequently, 1% plasticizer was incorporated into the mixture and stirred for an additional five minutes. The blend was then supplemented with 5% crosslinker, followed by 2.5% platinum catalyst, and mixed under vacuum for 30 seconds to eliminate entrapped air. The resulting mixture was carefully poured into pre-fabricated stone molds and clamped, positioned under a hydraulic press, and cured at 100 °C for one hour. After curing, the samples were removed and examined for surface integrity. Specimens exhibiting air bubbles or visible defects were discarded, while

defect-free samples were stored at room temperature for 24 hours before testing (Jindal et al., 2016).

2.6 Indoor weathering for six months

Indoor weathering was performed by storing the samples at a room temperature of 23°C and a relative humidity of 50 ± 5% in pigment-free plastic bags. Then samples were placed in a lightproof plastic box for 6 months. At the end of this period, specimens were removed and tested for surface hardness and roughness (Çevik, 2018).

2.7 Outdoor weathering for six months

Silicone specimens were hung from racks and positioned on the rooftop of the Health Medical Technology College/Baghdad- Iraq for six months (from June/ 2025 to December/ 2025) (Figure 2). Then specimens were taken away, washed in distilled water for fifteen minutes in an ultrasonic cleaner kept for twenty-four hours at room temperature (23 ± 1◦C), and then prepared for testing (Hatamleh et al., 2016).

Figure 2. Specimens exposed to outdoor weathering

2.8 Records of climate information during the outdoor weathering period

Using data from the AccuWeather online weather channel, the daily weather for six months, from June 1st, 2025, to December 1st, 2025, was recorded at Bab AL-Mudham -Baghdad - Iraq. This study recorded the following meteorological parameters: wind speed, rainfall, humidity, UV index, sunlight, lowest temperature, maximum temperature, and average temperature.

2.9 Testing

2.9.1 Surface hardness

Silicone specimens measuring 25 × 25 × 6 mm were evaluated using a Shore A durometer (Digital Shore A Durometer, Thincol, China) following the ISO 48-4:2018 standard (Figure 3). For each specimen, three readings were obtained, and the mean value was documented both at baseline and after six months of indoor and outdoor weathering.

Figure 3. Silicone specimen under shore A hardness test

2.9.2 Surface roughness

The surface roughness (Ra) of the specimens was evaluated using a TR-200 surface roughness tester (China)(Figure 4), both at baseline and after six months of outdoor and indoor weathering.

Figure 4. Profilometer surface roughness tester

Statistical analysis

Statistical analyses were conducted using SPSS software (version 27.0; IBM, Armonk, NY, USA) to evaluate the effects of the experimental conditions on the material properties. Both one-way and two-way ANOVA were employed to determine significant differences among the groups; differences were considered statistically significant at $P < 0.05$.

3. Results and discussion

3.1 Records of climate information during the weathering period

Using data from the AccuWeather channel, the daily weather for 6 months, from June 1, 2025, to December 1, 2025, was recorded. Baghdad exhibited a clear seasonal progression from extreme summer heat to milder late-autumn conditions. Mean temperatures were highest

during July and August (45.3°C and 45.1°C, respectively), accompanied by elevated minimum temperatures exceeding 30°C, indicating persistent nocturnal heat. Wind speeds during the summer months ranged between 18.0 and 19.6 knots, while relative humidity remained low (13.3%–17.4%), consistent with the extremely dry environment. No rainfall was recorded from June through October, with consistent sunshine duration averaging 14 hours per day. In contrast, October and November showed a notable decline in temperatures (33.6°C and 26.7°C, respectively) and an increase in humidity (28.9%–35%). Rainfall first appeared in November (0.7 mm/day), marking the onset of the rainy season. Atmospheric pressure also exhibited a progressive rise from 966.6 mb in June to 1019 mb in November, supporting the seasonal shift from hot, low-pressure summer conditions to cooler, more stable autumn weather. The average monthly outdoor weathering conditions in Baghdad are summarized in Table 1.

Table 1. Average monthly outdoor weathering conditions in Baghdad.

Date	Mix T (°C)	Min T (°C)	Wind speeds (Knots)	Humidity (%)	Rainfall (mm)/ day (n)	Sunshine (Hours)	Pressure (mbar)
June	43.6	28.5	18.0	13.3	0	14	966.6
July	45.3	31.6	19.6	16.2	0	14	997.2
Aug	45.1	30.6	18.2	17.4	0	14	999.9
Sept	39.8	26.6	12.4	16.1	0	14	1003.8
Oct	33.6	18.9	14.1	28.9	0	12	1013.1
Nov	26.7	13.4	14.6	35	0.7/1	12	1019

3.2 Surface analysis

The physical properties of the three silicone elastomers were evaluated at baseline and after six months of indoor and outdoor weathering by measuring shore A hardness and surface roughness (Ra). All values of mean and standard deviation are presented in Table 2.

Table 2. Physical characteristics of experimental formulations and commercial silicone materials.

TIME	Group	Hardness (Shore A)	ANOVA	Roughness (μm) Mean (SD)	ANOVA P value
Baseline	Z004	39.26(±.654)	P< 0.001 (S)*	0.527(±.282)	0.227 (N.S) *
	M511	28.60(±.383)		0.285(±.098)	
	80H/20L	29.29(±.323)		0.556(±.328)	
Indoor weathering	Z004	41.86(±.416)	P< 0.001 (S)	0.648(±.253)	0.194 (N.S)
	M511	31.46(±.288)		0.464(±.229)	
	80H/20L	31.56(±.254)		0.730(±.178)	
Outdoor weathering	Z004	42.23(±.325)	P< 0.001 (S)	0.737(±.188)	0.139 (N.S)
	M511	31.76(±.303)		0.446(±.182)	
	80H/20L	32.74(±.211)		0.627(±.264)	

Furthermore, two-way ANOVA was performed to assess the effects of time (baseline vs. indoor weathering and baseline vs outdoor weathering) and material group (Z004, M511 and 80H/20L) on hardness and surface roughness (Table 3). At baseline, Z004 exhibited the highest hardness (39.266 ± 0.654), followed by 80H/20L (29.298 ± 0.323) and M511 (28.600 ± 0.383) as demonstrated in Table 2. After six months of indoor weathering, hardness increased for all materials, with Z004 reaching 41.860 ± 0.416, 80H/20L rising to 31.566 ± 0.254, and M511 increasing to 31.460 ± 0.288. Outdoor weathering further increased hardness values, with Z004 at 42.233 ± 0.325, 80H/20L at 32.743 ± 0.211, and M511 at 31.767 ± 0.303 (Table 2). The current study showed that hardness values increased significantly after being indoors and outdoors ($P < 0.001$) compared to the baseline. Regarding the effects of time (baseline and

indoor weathering), both time (F = 247.096, P < 0.001) and group (F = 2697.547, P < 0.001) had significant effects on the hardness, indicating that hardness increased over time and differed among materials (Table 3).

Table 3. Two-way ANOVA results.

	Variable	factor	df	F test	P value
Indoor weathering	Hardness	time	1	247.096	P<0.001(S)*
		group	2	2697.547	P<0.001 (S)
		Time&group	2	1.093	0.336(N.S)*
	Roughness	time	1	2.819	0.119 (N.S)
		group	2	4.143	0.043 (S)
		Time&group	2	0.038	0.963 (N.S)
Outdoor weathering	Hardness	time	1	601.606	P<0.001 (S)
		group	2	1917.234	P<0.001 (S)
		Time& group	2	1.113	0.354 (N.S)
	Roughness	time	1	2.603	0.133(N. S)
		group	2	4.187	0.822(N. S)
		Time&group	2	0.200	0.522(N. S)

The interaction between time and group was not significant (F = 1.093, P = 0.336), suggesting that the increase in hardness over time was consistent across all groups.

For outdoor weathering, the hardness was significantly influenced by both time (F = 601.606, P < 0.001) and group (F = 1917.234, P < 0.001), while the interaction between time and group was not significant (F = 1.113, P = 0.354), indicating that the increase in hardness over time occurred similarly across all groups (Table 3). Such variations are probably caused by variations in the cross-linking density and conditioning type that affect the structural stability of the PDMS chains (Mohite et al., 1994; Lai & Hodges, 1999; Al Kaabi et al., 2025b).

Regarding indoors, the hardness values increased, and this might be due to continuous vulcanization of the silicone elastomers due to the presence of nanoparticles. A mechanism that may begin with oxygen intake during dark storage and produce cross-linkers that cluster in the silicone matrix, resulting in a denser network and higher hardness for silicone materials, could be one explanation for the hardness increase (Hatamleh & MM, 2010; Guiotti et al., 2010). Another explanation for the higher hardness of silicones reinforced with nanoparticles could be that the nanoparticles increase the silicone matrix's network density and affect the length of the polymer chains, making the material stiffer. Additionally, the length of the polymer chains can be influenced by the density of cross-linkers, which could eventually cause the mechanical characteristics of silicone elastomers to deteriorate (Mouzakis et al., 2010). In summary, maxillofacial silicone elastomer's relative hardness should mimic the surrounding tissues and human skin. During clinical service, a facial prosthesis should be both resilient and sufficiently soft and flexible to resemble the face motions. For a facial silicone elastomer, Shore A values between 25 and 55 units are suitable (Polyzois & Lyons, 2014).

Surface roughness is often regarded as a reliable indicator of a material's mechanical performance, as surface flaws can serve as initiation points for corrosion or fractures. Lower surface roughness is often preferred for extraoral prosthesis because it makes them look smoother and more natural, which is crucial for patient acceptability. Smoother surfaces are also less likely to be colonized by microorganisms, which lowers the risk of illness and makes cleaning and maintenance easier. Surface roughness values showed only minor changes across time points. At baseline, Z004 had a roughness of 0.527 ± 0.282 μm, 80H/20L 0.556 ± 0.328 μm, and M511 0.285 ± 0.098 μm. After indoor weathering, roughness increased modestly to 0.648 ± 0.253 μm, 0.730 ± 0.178 μm, and 0.464 ± 0.229 μm, respectively, and after outdoor exposure, values were 0.737 ± 0.188 μm, 0.627 ± 0.264 μm, and 0.446 ± 0.182 μm, respectively

(Table 2). ANOVA showed that differences in surface roughness were not statistically significant ($P > 0.05$).

For indoor weathering, time did not have a significant effect ($F = 2.819$, $P = 0.119$), while group showed a significant effect ($F = 4.143$, $P = 0.043$), indicating differences in roughness among the materials. The interaction between time and group was not significant ($F = 0.038$, $P = 0.963$), suggesting that changes in roughness over time were similar across the groups.

For outdoor weathering, surface roughness was not significantly affected by time ($F = 2.603$, $P = 0.133$), group ($F = 4.187$, $P = 0.822$), or their interaction ($F = 0.200$, $P = 0.522$), suggesting that roughness remained stable during outdoor weathering regardless of material type. These results might be due to the formation of microcracks on the material surface, which might decrease resistance to weathering and exacerbate other degradation processes (Goiato et al., 2009). All materials tested became rougher following weathering. These results were consistent with Mousa (2020), who reported an insignificant increase in the surface roughness of Silicone M511 after being subjected to outdoor weathering for 6 months. Furthermore, these results were similar to a study conducted by Rahman et al. (2018), which found that there was an increase in the surface roughness of silicone samples following outdoor weathering for 4 months. This might be explained by the presence of the fillers added during the fabrication of the samples.

Regarding indoor weathering, the present study exhibited a non-significant increase in the surface roughness ($P = 0.119$). There were no published articles on the effect of time passage on the surface roughness of maxillofacial silicone to compare with.

Overall, Z004 outperformed other silicones in surface hardness, while M511 exceeded other silicones in surface roughness. The 80H/20L formulation showed somewhat more surface roughness than commercial silicones, although this increase is generally not detrimental and is

anticipated to offer adequate performance for extraoral prosthetic applications (Mousa, 2020). In addition to the above, adding ZrO2 and RH nanosilica would improve the surface properties of newly developed silicone elastomers. Depending on the particular facial deformity being repaired, the 80H/20L formulation stayed within the clinically acceptable range of 25–55 Shore A.

4. Conclusions

The findings of this study concluded that while environmental weathering consistently increases the hardness of maxillofacial silicone elastomers, surface roughness changes are primarily dictated by material composition. The superior stability of Z004 and the greater surface susceptibility of the 80H/20L blend underscore the importance of selecting formulations with enhanced resistance to weathering-induced degradation. These outcomes emphasize that both intrinsic material properties and environmental exposure conditions are critical determinants of long-term performance, guiding more informed material selection for durable maxillofacial prosthetic applications. These findings indicate that environmental exposure leads to significant material stiffening, whereas surface texture remains largely unaffected.

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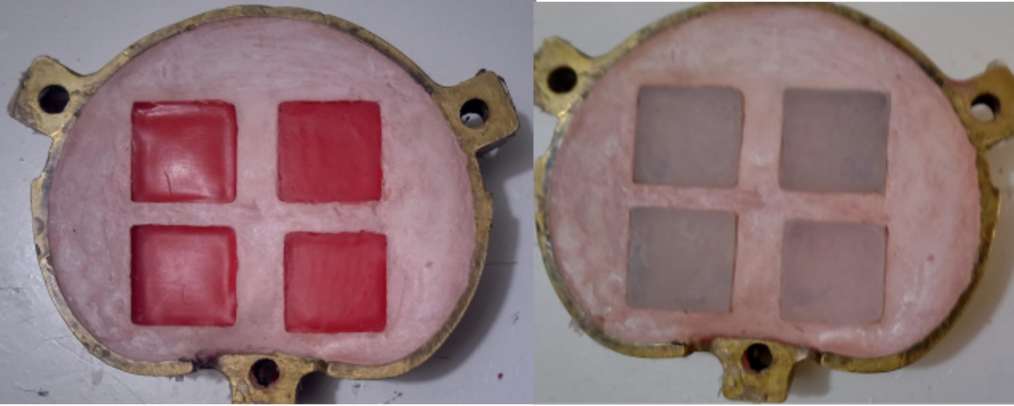
Figures

Figure 1. Stone mold and silicone specimens (a) Stone mold (b) Silicone specimens.

Figure 2. Specimens exposed to outdoor weathering

Figure 3. Silicone specimen under shore A hardness test

Figure 4. Profilometer surface roughness tester






Shore A Durometer
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