

ORIGINAL ARTICLE

Assessing the Effect of Copper Oxide Nanoparticles on some Mechanical Properties of Maxillofacial Silicone

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Abstract

Purpose: Silicone elastomers are extensively used in the fabrication of maxillofacial prostheses, yet their characteristics are far from optimal. Key factors necessitating the frequent re-fabrication of these prostheses include their limited lifespan and the deterioration of both their color and mechanical properties. This study aims to evaluate the impact of Copper Oxide Nanoparticles (CuO NPs) on the mechanical properties of VST 50F maxillofacial silicone.

Materials and Methods: A total of 120 specimens were prepared, with 30 specimens for each test. Five mechanical tests—tear strength, tensile strength, percentage of elongation, Shore A hardness, and surface roughness—were conducted with two experimental groups and a control group for each test.

Results: Statistical analysis showed a significant increase in tear strength for both experimental groups ($P < 0.05$). Group B had a 12.5% increase (23.89 kN/m), while Group C had a 21.57% increase (25.81 kN/m) compared to the control (21.23 kN/m). Tensile strength improved as well, with Group B up by 13.9% (4.655 MPa) and Group C by 14.0% (4.660 MPa) compared to the control (4.08 MPa). Shore A hardness increased by 7.98% (33.34 IU) for Group B and 14.58% (35.37 IU) for Group C, with decreases in elongation—Group B down 3.36% (864.80) and Group C down 3.80% (860.86) vs. control (894.87). There was, however, a non-significant increase in surface roughness ($P > 0.05$): Group B up by 4.48% (0.303 μm) and Group C by 5.17% (0.305 μm) compared to control (0.290 μm).

Conclusion: The results of this study suggest that CuO NPs can improve silicone elastomers' shortcomings. However, further studies are required to fully comprehend these NPs' long-term effects and how they affect other silicone material physical properties.

Keywords: Copper Oxide; Maxillofacial Prostheses; VerSilTal ⁵⁰F Silicone Elastomers; Mechanical Properties; Nanoparticles.

1. Introduction

Maxillofacial defects, arising from congenital anomalies, developmental issues, trauma, or surgical interventions, profoundly impact physical appearance, functionality, and psychological well-being [1, 2]. Patients with these defects often grapple with severe psychological challenges, including depression, social anxiety, fear of negative evaluation, avoidance behaviors, and post-traumatic stress disorder. These conditions not only affect their identity but also hinder their ability to engage in social roles, perform fundamental tasks, and interact with their environment [2-4]. While surgical reconstruction is typically the primary therapeutic approach, it is not always feasible due to various constraints. This limitation underscores the critical importance of maxillofacial prosthetic reconstruction [5-7].

Polymeric materials, such as vinyl chloride polymers, co-polymers, acrylic types like polymethyl methacrylate, and silicone elastomers, are commonly used in creating these prostheses. Silicone elastomers, in particular, are highly valued in clinical settings for their exceptional heat and chemical resistance, durability, mechanical strength, elasticity, ease of handling, and aesthetic appeal [6, 8]. However, no single maxillofacial material, including silicone, meets all the requirements for an ideal prosthesis. Challenges such as mechanical degradation, color instability, limited longevity, and changes in properties necessitate regular maintenance and replacement of silicone prostheses within one to three months to ensure their durability and effectiveness. Enhancing the structural integrity of silicone maxillofacial materials is, therefore, crucial [9-11].

VST 50F maxillofacial silicone has essential mechanical properties like tear strength, tensile strength, hardness, and elongation, vital for performance and reliability. Key traits for maxillofacial prostheses include color stability, tear strength, tensile strength, elongation, and hardness [12, 13]. The mechanical properties of different maxillofacial elastomers vary due to their production formulas, including polymer chain length, types and amounts of fillers, degrees of crosslinking, and molecular weight [14, 15]. Advances in Computer-Aided Design and Computer-Aided Manufacturing (CAD-CAM) technology have revolutionized the

planning and fabrication of maxillofacial prostheses [12, 16]. Using three-Dimensional (3D) printing technologies, a maxillofacial prosthesis can be fabricated in indirect or direct ways [17, 18]. 3D printing offers potential solutions to limitations in traditional manufacturing methods, such as poor attachment, functionality, durability, aesthetics, and cost-effectiveness. Despite its potential, 3D printing is still in the early stages and faces challenges such as limited material availability, printability issues, and low mechanical strength. Additionally, the high cost of the necessary interfaces and software presents a barrier [19]. Despite these obstacles, digital workflows offer a promising therapeutic option due to their efficiency, convenience, and speed, although the quality of the prostheses still lags behind traditional methods in terms of appearance and fit [16, 20].

The integration of Nanoparticles (NPs) into elastomers to enhance their properties has gained significant attention following advancements in nanoscience and nanotechnology. Numerous studies have demonstrated the efficacy of NPs in improving the mechanical, physical, and antimicrobial properties of silicone elastomers [12, 21-23]. Copper Oxide (CuO) is a compound of copper and oxygen, appearing as a brownish-black powder. CuO NPs are stable, cost-effective, and exhibit photocatalytic properties, making them promising anti-infective agents due to their unique crystal morphologies and expansive surface areas [24-26]. Their potential biomedical applications include drug delivery and antioxidant, antibacterial, antifungal, antiviral, and anti-cancer activities. Additionally, CuO NPs have been investigated for use in COVID-19 face masks. These nanoparticles can be synthesized through various chemical, physical, and biological methods [27-29].

Also, CuO NPs have been extensively studied in biomaterial and nanomedicine applications due to their distinct physicochemical characteristics and availability in different oxidation states [27, 30]. Their substantial effect in the field of biomedicine is highlighted by these uses, which include, but are not limited to, antimicrobial, antioxidant, anticancer, antidiabetic, wound healing [30], biomedical imaging [31], and drug delivery [32]. Furthermore, CuO NPs are notable for their physicochemical stability and ability to mix and bind with other metals, ceramics, and polymers. This versatility has led to their

widespread use in dentistry, making them one of the most often employed metal NPs [33, 34]. Many previous studies have demonstrated that the incorporation of CuO NPs in titanium dental implants [35], polymers [36], glass ionomer-based materials [37], dental cement [38], polymethyl methacrylate resin [39], Titanium (Ti)-Cu alloy [40], orthodontic brackets [41], orthodontic adhesives [42], alginate impression materials [43], universal adhesive [44], orthodontic composite [45], and denture soft liner [46] leads to significant improvements in their physical, chemical, and antimicrobial properties.

However, there is a lack of data pertaining to their integration into maxillofacial silicone. The integration of CuO NPs into maxillofacial silicone holds great potential for various applications in maxillofacial prostheses. This lack of data hinders the development of optimized CuO NP-infused maxillofacial silicone materials, which could potentially enhance their functionality and effectiveness in silicone prostheses and other dental applications. Pure maxillofacial silicone does not adequately meet the needs of the physician and the patient. Enhancing maxillofacial silicone with CuO NPs can offer several benefits, including antimicrobial properties, odor reduction, and improved wound healing, addressing the material's current shortcomings. This study aims to evaluate the impact of CuO NPs on the mechanical properties of VST 50F maxillofacial silicone at various weight percentages, potentially leading to significant advancements in the field.

2. Materials and Methods

2.1. Pilot Study

CuO NPs (40 nm) (Sky Spring Nanomaterials, USA) and VST 50F maxillofacial silicone (Factor II Inc., USA) were employed in this study. An initial investigation was conducted to determine the optimal percentages for incorporating CuO NPs into the VST 50F silicone elastomer. CuO NPs were introduced into the VST 50F silicone elastomer at five different weight percentages (0.01 wt%, 0.02 wt%, 0.03 wt%, 0.04 wt%, and 0.05 wt%). A total of thirty-six specimens were meticulously prepared, with eighteen specimens allocated for the tear strength test and another eighteen specimens for the Shore A hardness

test. Each test group comprised six distinct groups: one control group and five experimental groups, each containing three specimens.

Based on the outcomes of the preliminary investigation, two percentages of CuO NPs additives (0.03 wt% and 0.04 wt%) were selected in addition to the control group. These percentages were chosen considering the influence of CuO NPs on tear strength, Shore A hardness, and color change of the specimens. The increase in the weight percentage of CuO NPs notably enhanced tear strength, coupled with a corresponding rise in Shore A hardness. However, incorporating a 0.05 wt% CuO NPs additive led to a Shore A hardness increase in silicone specimens beyond the acceptable normal range, resulting in darker specimens.

2.2. Main Study

2.2.1. Specimens Grouping

In the primary investigation, five comprehensive tests were undertaken: tear strength, tensile strength, percentage of elongation, Shore A hardness, and surface roughness. A total of one hundred twenty specimens were meticulously prepared, with thirty specimens dedicated to each test. Each set of specimens underwent division into three distinct groups: group A, the control group, and two experimental groups, namely group B (0.03 wt% CuO additive) and group C (0.04 wt% CuO additive).

2.3. Mold Fabrication

The test specimen molds were meticulously crafted using cutting-edge computer-aided software, specifically AutoCAD 2013 (Autodesk, USA). Subsequently, the template was meticulously constructed via precision laser engraving cutting technology, employing a CNC machine (JL-1612, Jinan Link Manufacture and Trading Co., Ltd., China). For tear strength (ISO 2015) [47] and tensile strength tests (ISO 2017) [48], three transparent acrylic sheets (PT. Margacipta Wirasentosa, Indonesia) of 2 ± 0.05 mm thickness each were employed, comprising the matrix, bottom, and cover. For Shore A hardness and surface roughness tests (ISO 2010) [49], sheets of 6 ± 0.05 mm thickness were utilized. The matrix sheet was securely affixed to the bottom using chloroform

(Weld-On, USA) as an adhesive, ensuring stability during the silicone pouring process. To further enhance stability and precision, G-clamps, nuts, and screws were strategically employed to secure the cover tightly in place [50].

2.4. Mixing

According to the manufacturer's recommendations, VST 50F silicone should be meticulously mixed at a precise 10:1 base-to-catalyst ratio. To maintain accuracy, a state-of-the-art 4-digit electronic scale (Denver Instrument, USA) was utilized to weigh the CuO NPs in a dedicated mixing bowl. The utmost care was taken to ensure the safety of personnel and prevent any potential contamination, particularly when handling NPs. Preventing the particles from becoming airborne during the weighing process was paramount, and this was achieved by conducting the task within a controlled environment, such as a fume hood.

Personal protective equipment, stringent handling practices, and appropriate weighing equipment were diligently employed to mitigate the risk of NP volatilization and ensure a secure working environment [51, 52]. Subsequently, a calculated amount of silicone base was carefully applied to prevent the dispersion of the volatile NPs (Figure 1(a and b)). The NPs were then meticulously combined with the silicone base to form the modified base, which underwent thorough mixing for a duration of 10 minutes in a precision vacuum mixer (Dentaurum Airvac, Germany) (Figure 1c). To prevent the suction of NPs, the vacuum was initially deactivated for the first three minutes. Following this, the vacuum was activated for seven minutes at a speed of 360 rpm and a vacuum pressure of (10-1) bar, effectively eliminating any entrapped air bubbles [53]. Before adding the catalyst, the mixture was allowed to cool for 2 minutes. The rotational action of the mixer generated heat, necessitating this delay. A vacuum mixer operating at 360 rpm can generate heat during mixing, which may occur as a result of friction, viscosity, shear forces, and mechanical energy that reduces the material's available working time [54]. Subsequently, the catalyst was meticulously mixed with the modified base for a duration of 5 minutes using the vacuum mixer, resulting in a homogeneous, bubble-free mixture (Figure 1d) [54].

The prepared material was then carefully poured into the mold under controlled conditions, maintaining a precise temperature of $23 \pm 2^\circ\text{C}$ and an approximate humidity level of $50 \pm 10\%$ [55]. The matrix cover was securely positioned over the poured material, with the margin gradually reduced at one end to facilitate proper flow. Excess material was allowed to flow out of the mold slowly and methodically. To ensure uniform pressure distribution, a one-kilogram weight was strategically placed in the center of the mold cover. The mold was then firmly secured with nuts and G-clamps until the specimens achieved sufficient hardness (Figure 1e).

In accordance with the manufacturer's guidelines, the mixture was left to set for a duration of 2-4 hours before the specimens were carefully removed, finished, and stored under controlled conditions for 16 hours at $23 \pm 2^\circ\text{C}$ and $50 \pm 10\%$ humidity (Figure 1f) [55].

2.5. Mechanical Testing Procedures

2.5.1. Tear Strength Test

The tear strength specimens employed in the study adhered strictly to type C tear specimen standards as certified by ISO 34-1 [47]. For testing purposes, a computer-controlled universal testing machine (Instron, China) was employed, ensuring precision and accuracy throughout the experimentation process. Illustrated in Figure 2a are the meticulously crafted angle test pieces along with their corresponding measurements, followed by a detailed depiction of the specimen's shape in Figure 2b. Each tear specimen was meticulously crafted to meet the stringent thickness requirement of $2 \pm 0.2\text{mm}$. To guarantee utmost accuracy, the thickness of each specimen was meticulously measured three times across its breadth utilizing a high-precision vernier caliper with an accuracy of 0.01mm. Subsequently, the average thickness was meticulously computed, ensuring consistency and reliability in the testing procedure. The tear strength, expressed in kN/m, was calculated using the following Equation 1 [47]:

$$T_s (\text{Tear strength}) = f/d \quad (1)$$

Where: f is the maximum force in kilo Newtons, d is the thickness of the specimen in meters.

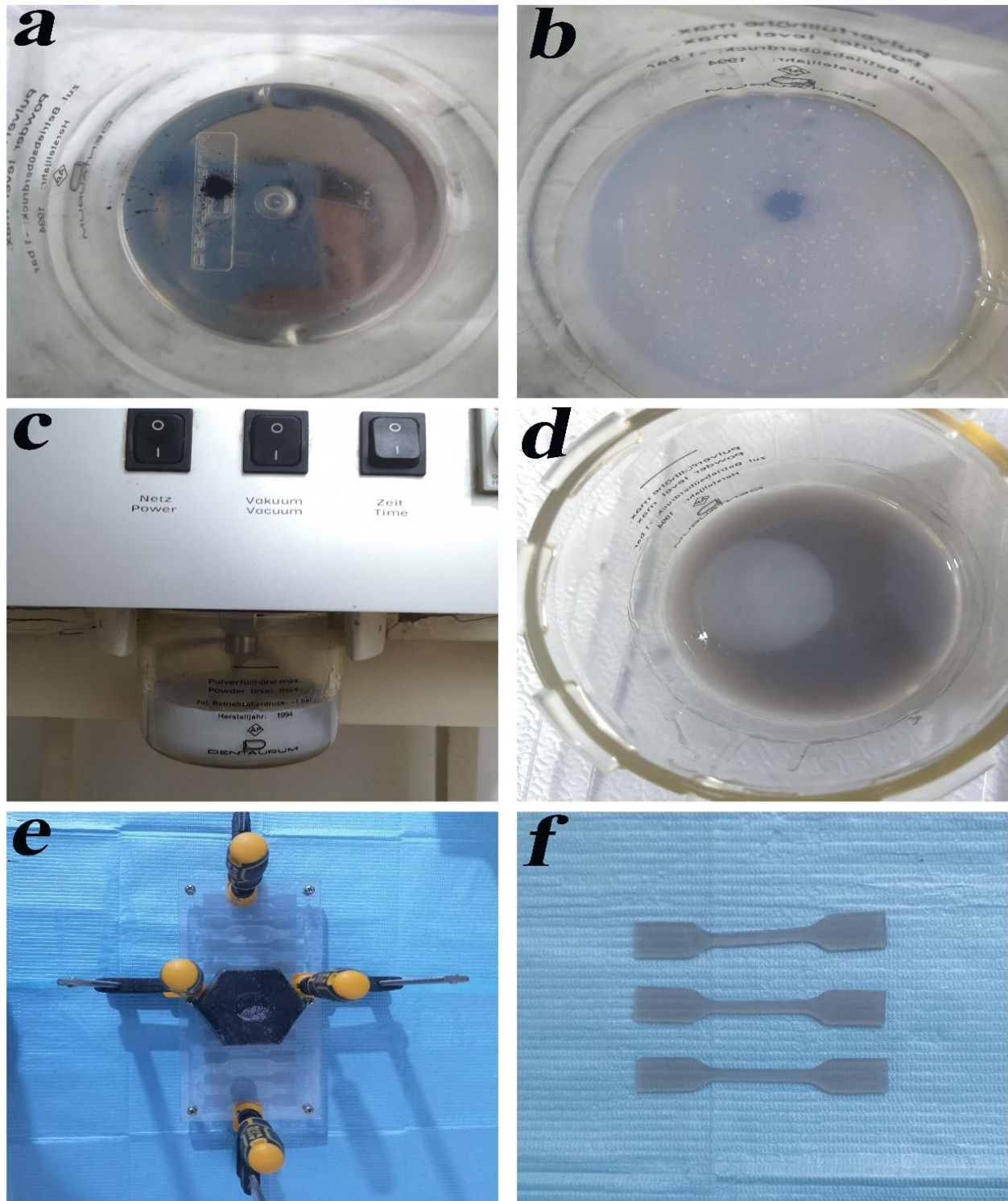


Figure 1. a: A measured weight of CuO NPs; b: Adding the silicone base; c: Mixing by the vacuum mixer; d: Adding the catalyst to the modified silicone base, then remixing with the vacuum mixer; e: Final shape of the mold after poring of silicone, then tightening it with nuts and G-clamps and weight application; f: Specimens of tensile strength and percentage of elongation after finishing

2.5.2. Tensile Strength Test

The specimens were prepared using the ISO 37 standard test approach [48] and were designed as dumbbells (referred to as Type 2, as illustrated in

Figure 3), using a universal testing machine (Instron, China). Throughout the testing process, the maximum force recorded at the point of specimen breakage and the initial cross-sectional area were meticulously

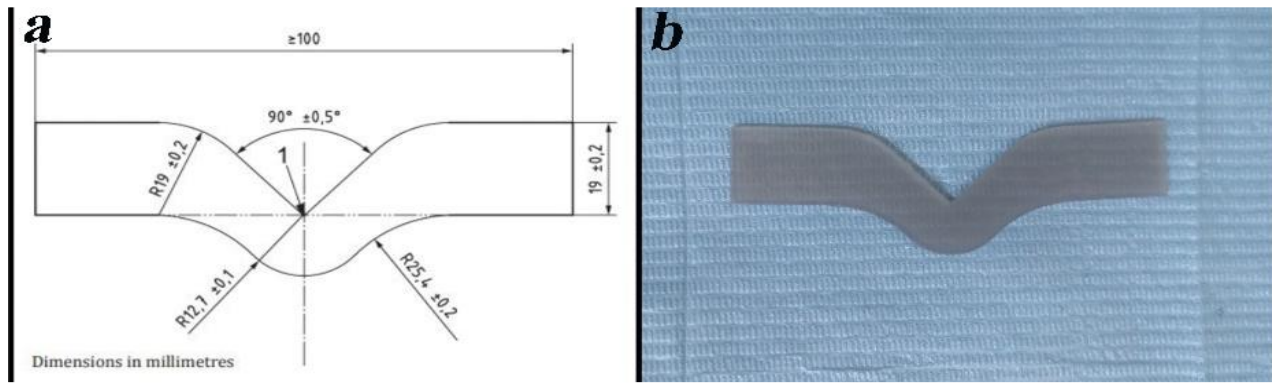


Figure 2. a: Design of tear strength test specimen (ISO 34-1) [46]; b: Tear strength specimen

utilized to calculate the ultimate tensile strength, employing the equation presented below. This approach ensured the precision and reliability of the tensile strength measurements, adhering to internationally recognized testing standards (Equation 2).

$$UTs \text{ (ultimate tensile strength)} = F_m / W_t \quad (2)$$

Where:

F_m : The highest force measured at break (N).

W_t : Specimen cross-sectional area (mm²).

2.5.3. Percentage of Elongation Test

The evaluation of elongation before fracture was conducted simultaneously with the assessment of tensile strength, adhering meticulously to the protocols delineated in ISO 37 [48]. The determination of the percentage of elongation at break was derived by calculating the disparity between the original length of the tensile specimen and its length at the point of fracture, employing the following Equation 3:

$$Eb \text{ (Elongation percentage at break)} = 100 \times (L_b - L^o) / L^o \quad (3)$$

Where: L^o , is the original length in mm, and L_b is an extension at the break in mm.

By employing this rigorous methodology, the percentage of elongation at break was accurately ascertained, ensuring precise characterization of the material's mechanical properties in accordance with established standards.

2.5.4. Shore A Hardness Test

The experiment was conducted following the guidelines outlined in ISO 7619-1 [49]. Square specimens of 25 x 25 x 6 mm³ were utilized for the test (Figure 4). A digital Shore A hardness device (TIME Group Inc, China) equipped with a blunt indenter, measuring 1.25 mm in diameter, was employed. The specimens' hardness was determined in five distinct locations, each spaced 6 mm apart from one another and from the specimen's border. The average measurement values were regarded as representative of the specimens' hardness.

2.5.5. Surface Roughness Test

The preparation of specimens strictly adhered to the exacting standards outlined in ISO 7619-1 [49], ensuring uniformity and consistency in their dimensions, mirroring those of the hardness specimens (Figure 4).

To meticulously assess surface roughness, a portable digital roughness tester (Profilometer) (TIME Group Inc., China) with a precision of 0.001 meters was meticulously employed. This advanced instrument, equipped with a sensitive diamond probe, enabled the detection of even the minutest surface irregularities. During testing, each specimen underwent meticulous examination, with three readings obtained from distinct locations on the surface. The design of the profiler ensured precise contact with the specimen at three points, facilitating the collection of comprehensive data. To ensure the accuracy of readings, specimens were positioned on a stable and rigid surface throughout the measurement process. The results were quantified using the Ra

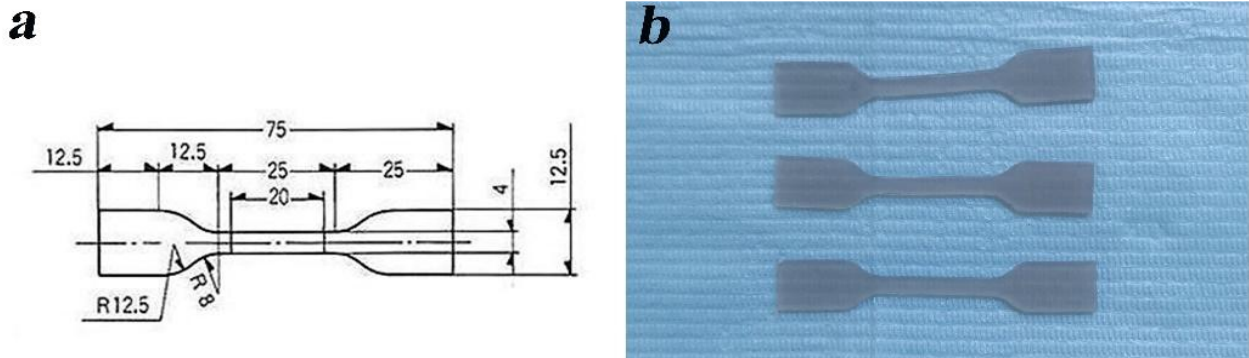


Figure 3. a: Dimension of tensile strength and percentage of elongation specimen [47]; **b:** Specimen shape

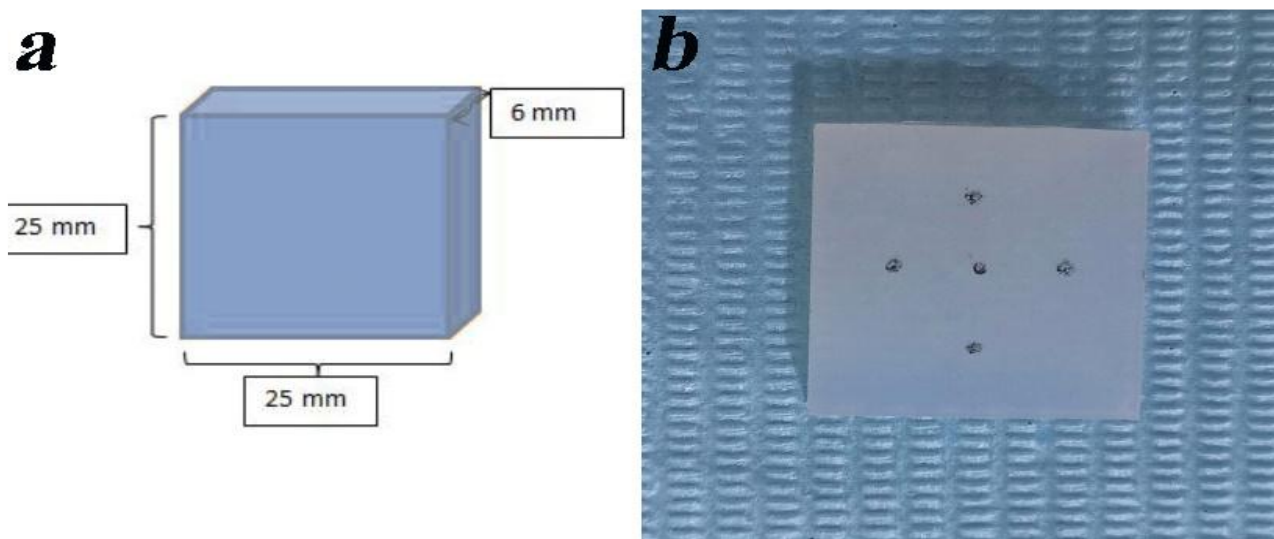


Figure 4. a: Dimension of hardness test specimen [48]; **b.** Specimen with a 5-point mark

parameter, denoting "roughness average," which represents the mean of multiple individual measurements of surface peaks and valleys. This parameter, expressed in micrometers (μm), provided a standardized metric for quantifying surface roughness [56]. The roughness value was meticulously calculated as the mean of the three readings, ensuring robust and reliable data acquisition.

2.6. Statistical Analysis

For the statistical analysis, we used SPSS (Statistical Package for Social Science, version 24) computer software. A probability " P " value of > 0.05 was considered non-significant statistically; ≤ 0.05 was considered significant. A normality test was done and all variables in this study were normally distributed among groups. Subsequently, Levene's test was employed to evaluate the homogeneity of

variances, aiding in the selection of the appropriate post hoc test for multiple comparisons. Comparative analyses were conducted between each experimental group (B and C) and the control group (A), employing robust statistical methods to ensure accuracy and validity of findings. Descriptive statistics were graphically presented using bar charts, showcasing mean values and standard deviations for clarity and comprehensibility. For multiple comparisons, the methodology employed one-way ANOVA, complemented by the post-hoc Tukey Honestly Significant Difference (HSD) test for homogeneous data and the Games-Howell test for non-homogeneous data. These analytical approaches were chosen meticulously to account for variations in data distribution and ensure a comprehensive assessment of the experimental outcomes.

3. Results and Discussion

The efficacy of prosthetic rehabilitation for facial deformities hinges crucially upon the mechanical and physical characteristics of the selected material. However, it is abundantly clear that no single material can universally meet the diverse needs of every patient. Material selection for prosthetic rehabilitation is deeply influenced by factors such as the nature of the defect and patient preferences, underscoring the complexity of the decision-making process [57, 58]. Regrettably, the materials traditionally employed often fall short of fulfilling all the requisite criteria for an optimal prosthesis, with issues such as limited service life and inadequate edge strength and color stability posing significant challenges [59].

Addressing these shortcomings necessitates innovative approaches, with the modification of maxillofacial silicone prostheses emerging as a promising avenue. Leveraging advancements in nanomaterials, nanofibers, and micromaterials, composite materials offer heightened potential for achieving superior outcomes. NPs, in particular, exhibit exceptional reactivity and surface energy, affording them the capability to augment silicone materials by integrating with the matrix, thereby fostering the development of a robust network structure within the foundation [12, 60]. Crucial to the success of a maxillofacial prosthesis are key physical and mechanical parameters, including tear strength, tensile strength, percentage of elongation, hardness, and color stability [12, 13]. However, the mechanical properties of various maxillofacial elastomers can vary significantly due to nuanced manufacturing factors, such as polymer chain length, filler types and quantities, crosslinking degree, and molecular weight [14, 15]. It is imperative to comprehensively understand and meticulously address these variables to optimize the performance and longevity of maxillofacial prostheses.

3.1. Field Emission Scanning Electron Microscope

The examination of CuO NPs within the matrix of Room Temperature Vulcanization (RTV) silicone elastomer (VST 50F) specimens was meticulously conducted using a Field Emission Scanning Electron

Microscope (FE-SEM) (Inspect F50, FEI, USA). To facilitate optimal electron interaction, a thin coating of metal or gold (1nm thickness) was uniformly applied to the silicone specimens using a sputter coater. This coating ensured enhanced visualization of the specimens under the FE-SEM, adhering to manufacturer specifications. The FE-SEM images depicted in Figure 5 reveal the intricate topography and morphology of CuO NPs within the VST 50F silicone matrix. Notably, the CuO NPs were observed to be uniformly dispersed throughout the matrix, with minor instances of aggregation (Figure 5(c-f)). This uniform distribution underscores the effective integration of CuO NPs within the silicone matrix, laying the foundation for further analysis and understanding of their impact on the material's properties.

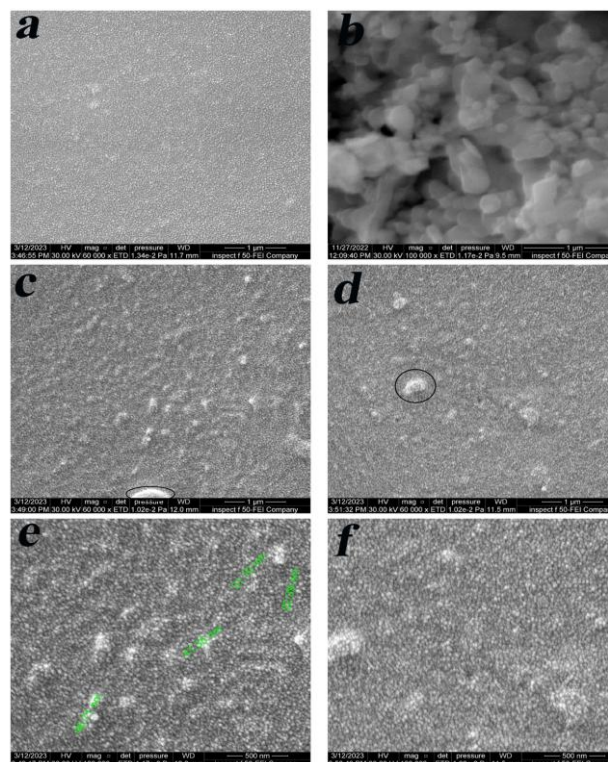


Figure 5. FE-SEM images of: **a:** VST-50F maxillofacial silicone control specimen at 1 μm magnification; **b:** CuO NPs at 1 μm magnification; **c:** Group B specimen at 1 μm magnification showing evenly distributed NPs, black circle pointing to filler agglomeration; **d:** Group C specimen at 1 μm magnification showing evenly distributed NPs, black circle pointing to filler agglomeration; **e:** Group B specimen at 500 nm magnification showing NPs and their size; **f:** Group C specimen at 500 nm magnification showing NPs distribution

3.2. Fourier Transform Infrared Spectroscopy

The investigation into potential chemical interactions between the silicone substance and CuO NPs was conducted with precision using Fourier Transform Infrared Spectroscopy (FT-IR) (Spectrum Two N, PerkinElmer, USA). Three meticulously prepared specimens, each representing groups A, B, and C, were subjected to FTIR analysis. These specimens were meticulously crafted to meet stringent specifications, following the manufacturer's guidelines, resulting in thin flushes with dimensions of 10x10x0.5 mm in length, breadth, and thickness.

Figure 6 (a-c) presents the comprehensive FT-IR data, revealing a critical observation: the incorporation of CuO NPs had no discernible impact on the spectra of VST 50F silicone. This absence of alteration indicates a lack of chemical interaction between the silicone matrix and CuO NPs, corroborating the findings of the analysis. Such precise and conclusive results underscore the thoroughness of the examination and provide valuable insights into the material's chemical stability and compatibility.

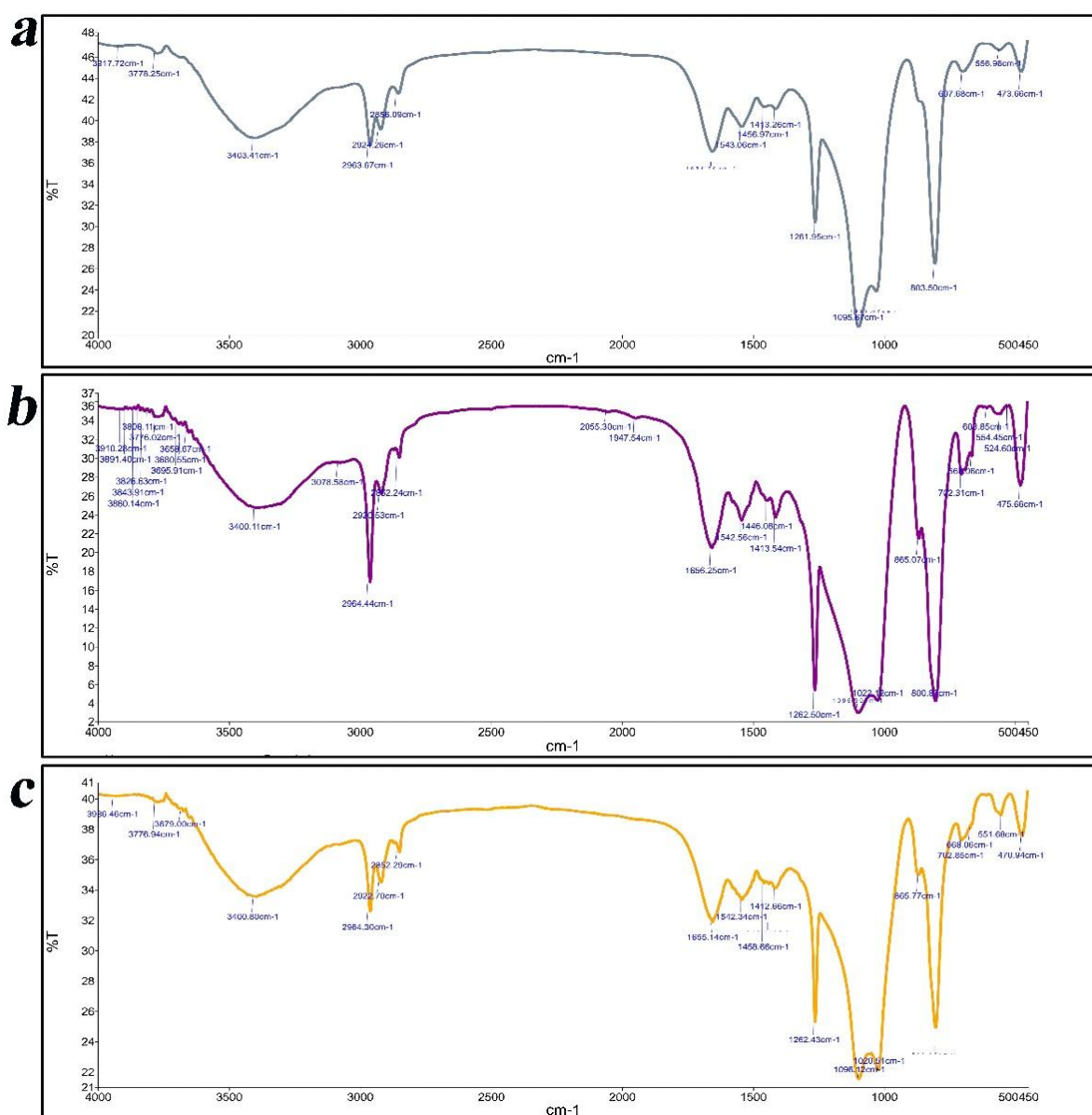


Figure 6. Fourier transforms infrared spectroscopy: **a:** control specimen (group A); **b:** group B specimen; **c:** group C specimen

3.3. Tear Strength Test

The mean tear strength exhibited notable enhancements in experimental groups B and C compared to the control group A. Particularly noteworthy was the substantial increase observed in the third group, registering a mean tear strength of 25.816 kN/m, followed closely by group B at 23.897 kN/m. In contrast, group A recorded a mean tear strength of 21.231 kN/m, as depicted in Figure 7a and summarized in Table 1. A comprehensive ANOVA confirmed a statistically significant difference among the groups at a *P*-value < 0.05, underscoring the efficacy of the modifications introduced (see Table 1). Further elucidation was provided through post-hoc analysis employing the Games-Howell test, which delineated significant differences among all test groups at a *P*-value < 0.05, affirming the discernible impact of the interventions implemented.

The tear strength test results reveal a significant enhancement in the tear resistance of VST50F maxillofacial silicone following the integration of CuO NPs at both 0.03wt% and 0.04wt% concentrations, in comparison to the Control Group (see Table 1). Group B exhibited a notable 12.5% improvement, while Group C displayed an impressive 21.57% increase relative to the Control Group. This attribute holds particular importance in areas of the maxillofacial prosthesis characterized by thinness, such as around the eyes and nasal regions, where the risk of tearing is heightened during removal, potentially leading to irreversible damage [61]. The

reinforcement of silicone elastomer density and tear resistance can be attributed to the formation of a 3D mesh facilitated by specific polymer chains and silicone's affinity for retaining NPs. With an increase in filler percentage, both the intermolecular forces within the polymer chain and its adherence to the filler surface are augmented, thereby explaining the observed rise in tear strength post-NP integration [62, 63]. Furthermore, rubber materials possess the capacity to disperse strain energy near the crack tip, wherein NPs contribute by transferring energy as the fracture expands. This fortifies the material's tear resistance, demanding greater force and load to provoke a complete rupture of the polymer matrix [64]. Numerous prior investigations corroborate these findings, illustrating the tear strength enhancement resulting from the inclusion of diverse NPs in silicone elastomers [64-67].

3.4. Tensile Strength Test

Both groups B and C exhibited higher mean values of tensile strength compared to the control group A, as illustrated in Figure 7b and summarized in Table 2. Group B demonstrated a noteworthy 13.9% improvement, while Group C displayed a slightly higher enhancement of 14.0% relative to the control group. Statistical analysis utilizing ANOVA for tensile strength among the groups unveiled a significant disparity at a *P*-value < 0.05, as detailed in Table 2. The homogeneity of variance was evaluated through Levene's test, indicating homogenous data

Table 1. Descriptive statistics, one-way ANOVA, and multiple comparisons using the Games-Howell test of tear strength in kilonewtons/meter results

Descriptive statistics						
Groups	N	Mean (kN/m)	S. D	Std. Error	Minimum	Maximum
Group A	10	21.231	0.53772	0.17004	20.28	21.80
Group B	10	23.897	0.80906	0.25585	22.89	25.15
Group C	10	25.816	0.33603	0.10626	25.42	26.33
ANOVA						
		Sum of Squares	df	Mean Square	F	P-value
Between Groups		106.041	2	53.021	150.536	0.000*
Within Groups		9.510	27	0.352		
Total		115.551	29			
Games-Howell						
(I) Groups	(J) Groups	Mean Difference (I-J)		Std. Error	P-value	
Group A	Group B	-2.66600		0.30720	0.000*	
	Group C	-4.58500		0.20051	0.000*	
Group B	Group C	-1.91900		0.27704	0.000*	

*= Significant at *P* < 0.05

with a P -value > 0.05 (non-significant). Further comparison of mean values among the groups was conducted using the Tukey HSD test. The outcomes revealed a significant difference between the experimental groups and the control group ($P < 0.05$), while no significant difference was observed between the experimental groups themselves ($P > 0.05$), as delineated in Table 2.

The observed enhancement in tensile strength of VST50F with the incorporation of CuO NPs is seen in Figure 7b and Table 2. This may be due to the intimate connection between the silicone matrix and NPs. Tensile forces cause polymer chains and NPs to slide over one another; the presence of nano-fillers prevents polymer chains from breaking [63]. The tensile strength of silicone elastomers after curing is greatly

affected by factors such as the method of cross-linking, cross-linking density, interactions between fillers and polymer chains, and the type of silicones and fillers [14, 68, 69]. As a result, varying results were found when different fillers were used in different types of silicone elastomers.

3.5. Percentage of Elongation Test

Compared to the control group A, both experimental groups B and C exhibited significantly reduced mean values of percentage elongation in the study, as illustrated in Figure 7c and detailed in Table 3. Specifically, control group A displayed the highest mean value (894.873), followed by Group B (864.807), and then Group C (860.862), as depicted in Figure 7c. The percentage of elongation decreased by

Table 2. Descriptive statistics, one-way ANOVA, and Tukey honestly significant difference multiple comparisons of tensile strength test in megapascal

Descriptives statistics						
	N	Mean (Mpa)	S. D	Std. Error	Minimum	Maximum
Groups A	10	4.087	0.18361	0.05806	3.86	4.37
Groups B	10	4.655	0.15729	0.04974	4.46	4.90
Groups C	10	4.660	0.19658	0.062165	4.41	4.93
ANOVA						
	Sum of Squares		Df	Mean Square	F	P-value
Between Groups	2.170		2	1.085	33.523	0.000*
Within Groups	0.874		27	0.032		
Total	3.044		29			
Tukey HSD						
(I) Groups	(J)Groups	Mean Difference (I-J)		Std. Error	P-value	
Groups A	Groups B	-.56800		0.08046	0.000*	
	Groups C	-.57300		0.08046	0.000*	
Groups B	Groups C	-.00500		0.08046	0.998**	

*=Significant at $P < 0.05$, **= Non-significant at $P > 0.05$

Table 3. Descriptive statistics, one-way ANOVA, and Tukey honestly significant difference multiple comparisons of percentage of elongation test

Descriptives statistics						
	N	Mean	S. D	Std. Error	Minimum	Maximum
Group A	10	894.873	6.99276	2.21130	885.00	905.00
Group B	10	864.807	7.20839	2.27949	853.00	878.00
Group C	10	860.862	8.46399	2.67655	850.76	877.00
ANOVA						
	Sum of Squares		Df	Mean Square	F	P- value
Between Groups	6920.918		2	3460.459	60.182	0.000*
Within Groups	1552.488		27	57.500		
Total	8473.407		29			
Tukey HSD						
(I) Groups	(J) Groups	Mean Difference (I-J)		Std. Error	P- value	
Group A	Group B	30.06600*		3.39115	0.000*	
	Group C	34.01100*		3.39115	0.000*	
Group B	Group C	3.94500		3.39115	0.485**	

*=Significant at $P < 0.05$, **= non-significant at $P > 0.05$

3.36% in Group B and 3.80% in Group C compared to the control group.

The ANOVA test revealed a noteworthy difference between the groups concerning the percentage of elongation, with a significance level of $P < 0.05$, as outlined in Table 3. The homogeneity of data, indicated by Levene's test, exhibited non-significant results with a P -value exceeding 0.05. The Tukey HSD test was employed for intergroup comparisons. The statistical analysis demonstrated a significant disparity ($P < 0.05$) between Group A and both groups B and C. Conversely, no significant difference was observed between Group B and Group C, with a P -value exceeding 0.05 (Table 3).

The reduction in elongation percentage observed in Groups C and B relative to Group A (Table 3) may be attributed to constraints in the flow and mobility of the polymer matrix. The presence of filler particles serves as focal points for tension concentration, thereby accelerating the rate of fracture. Additionally, a smaller disparity in aspect ratio between the filler and its constituents could contribute to the decrease in elongation percentage. This phenomenon is likely due to the close proximity of rubber molecules, which diminishes the elongation at fracture. Nevertheless, disparate outcomes were noted with the addition of various additives across different types of silicone elastomers [70-72].

3.6. Shore A Hardness Test

The experimental groups demonstrated a notable increase in hardness, as illustrated in Figure 7d and detailed in Table 4. Relative to the control group, Shore A hardness saw an elevation of 7.98% for Group B and 14.58% for Group C. ANOVA analysis applied to the Shore A hardness test indicated a significant difference among the groups at a P -value < 0.05 (Table 4). Levene's test confirmed the homogeneity of the data with a P -value > 0.05 (non-significant). For comparing mean values between groups, the Tukey HSD test was employed. The results revealed a significant difference (P -value < 0.05) among all test groups (Table 4).

The notable increase in hardness measurements following the addition of 0.03 wt% and 0.04 wt% of CuO NPs can be attributed to the uniform distribution of NPs within the polymer matrix and among the polymeric chains, as demonstrated in the FE-SEM images (Figure 5), thereby occupying the spaces between aggregates. This phenomenon possesses the capability to augment the material's ability to withstand indentation and penetration, thus leading to an elevation in its hardness. The increase in CuO NPs percentage is directly proportional to the rise in filler adsorption onto the surface of the polymer chain and the subsequent enhancement of intermolecular forces. However, the increase was within the normal range of silicone hardness [69].

The maxillofacial prosthesis should possess the same level of hardness as the anatomical structure it is

Table 4. Descriptive statistics, one-way ANOVA, and Tukey honestly significant difference multiple comparisons of Shore A hardness test

Descriptives statistics						
Groups	N	Mean	S. D	Std. Error	Minimum	Maximum
Group A	10	30.876	0.81190	0.25675	29.75	31.86
Group B	10	33.341	0.64456	0.20383	32.60	34.30
Group C	10	35.377	0.79744	0.25217	33.90	36.23
ANOVA						
		Sum of Squares	Df	Mean Square	F	P -value
Between Groups		101.602	2	50.801	89.096	0.000*
Within Groups		15.395	27	0.570		
Total		116.997	29			
Tukey HSD						
(I) Groups	(J) Groups	Mean Difference (I-J)		Std. Error	P -value	
Group A	Group B	-2.46500		0.33769	0.000*	
	Group C	-4.50100		0.33769	0.000*	
Group B	Group C	-2.03600		0.33769	0.000*	

*=Significant at $P < 0.05$

intended to replace. The hardness values of silicone elastomers might be affected by nanoparticles, aging, silicone types, or different filler types. Cevik [73] found that different nanoparticles affect the hardness of maxillofacial silicones differently. They observed that titanium dioxide nanoparticles increased hardness, while hydrophilic silica nanoparticles decreased hardness after dark storage. Importantly, all these values remained within clinically acceptable ranges [73].

3.7. Surface Roughness Test

Statistically, there was no significant increase in surface roughness ($P > 0.05$). Groups B and C exhibited mean surface roughness values higher than that of Group A (control), as depicted in Figure 7e and Table 5. Specifically, Group B displayed a 4.48% increase, while Group C showed a 5.17% increase compared to the control group. ANOVA test conducted on surface roughness among groups revealed a non-significant difference at $P\text{-value} > 0.05$ (Table 5). Levene's test was employed to assess the homogeneity of variance, and the results indicated homogenous data at a $P\text{-value} > 0.05$ (non-significant). To compare mean values between groups, the Tukey HSD test was utilized. The test revealed a non-significant difference ($P\text{-value} > 0.05$) among all test groups (Table 5).

Surface roughness is an intrinsic characteristic representing slight deviations from an ideally smooth

surface in materials [74]. In this study, a negligible increase in roughness values (non-significant) was observed following the addition of CuO NPs. This minor rise can be attributed to nanoparticle aggregation on the specimen surface during preparation, as corroborated by the FE-SEM images. Furthermore, the observed increase in surface roughness may be attributed to variances in the microstructural features between the silicone material and CuO NPs. However, the negligible increase in surface roughness was nearly imperceptible due to the minimal percentages of NPs utilized [72]. Diverse outcomes in surface roughness have been documented in studies employing different types of NP [68].

4. Conclusion

This study found that adding copper oxide nanoparticles (CuO NPs) to VST 50F maxillofacial silicone improved prosthetic properties without chemical interactions. FT-IR analysis showed no reaction, while FE-SEM imaging indicated even dispersion of NPs. The inclusion of CuO NPs significantly increased tear strength, tensile strength, and Shore A hardness, with the best performance at 0.04 wt%, surpassing the control and 0.03 wt% groups. Hardness levels remained clinically acceptable, and surface roughness was minimally affected. However, a reduction in elongation percentage was noted.

Table 5. Descriptive statistics, one-way ANOVA, and Tukey honestly significant difference multiple comparisons of surface roughness test

Descriptives statistics						
	N	Mean	S. D	Std. Error	Minimum	Maximum
Group A	10	0.290	0.04788	0.01514	0.21	0.36
Group B	10	0.303	0.04420	0.01398	0.24	0.36
Group C	10	0.305	0.03654	0.01156	0.23	0.36
ANOVA						
	Sum of Squares		df	Mean Square	F	P-value
Between Groups	0.001		2	0.001	0.373	0.692**
Within Groups	0.050		27	0.002		
Total	0.052		29			
Tukey HSD						
(I) Groups	(J) Groups	Mean Difference (I-J)		Std. Error	P-value	
Group A	Group B	-0.01350		0.01929	0.766**	
	Group C	-0.01520		0.01929	0.713**	
Group B	Group C	-0.00170		0.01929	0.996**	

**= Non-significant at $p > 0.05$.

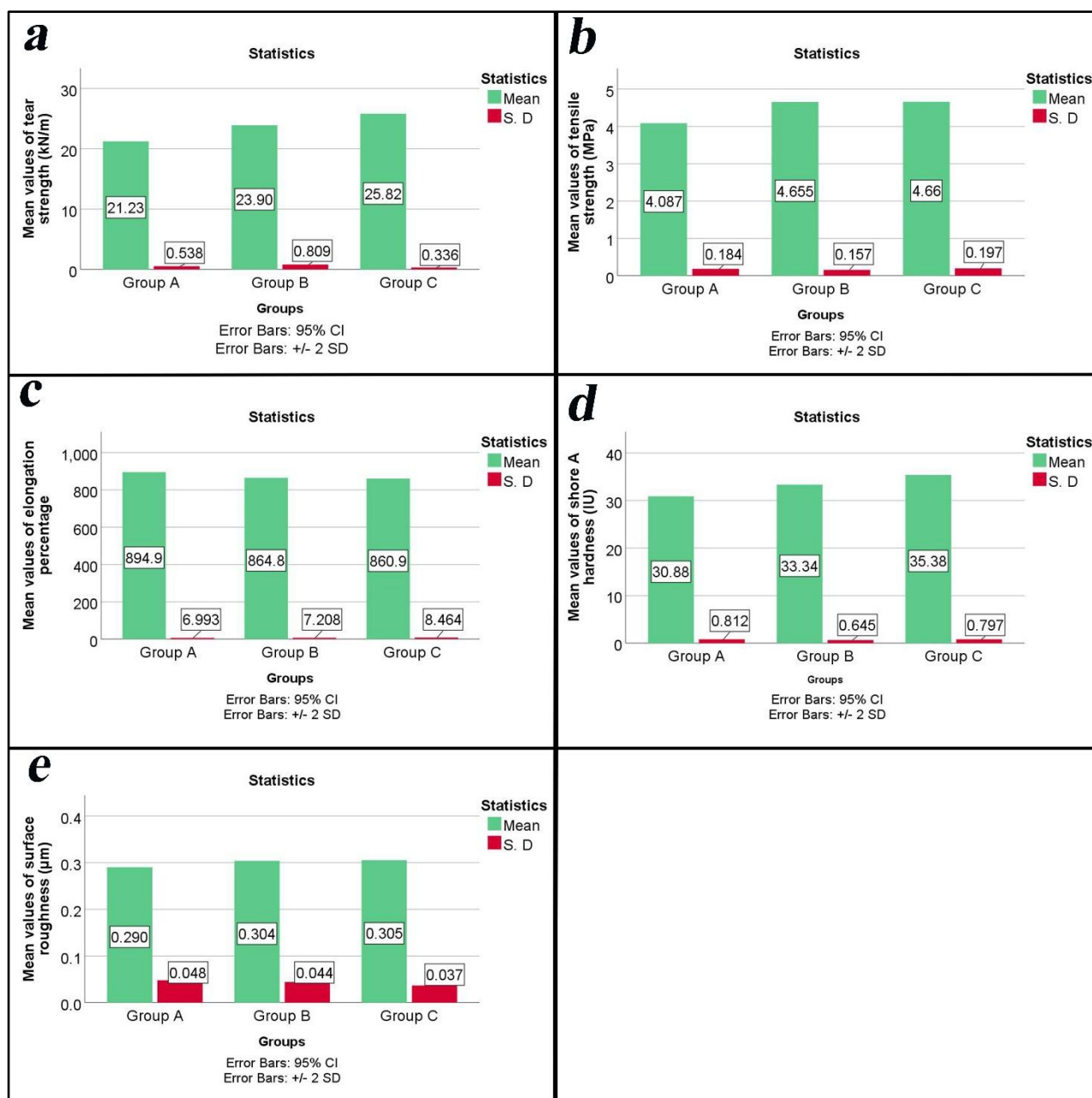


Figure 7. Bar chart presentation of mean values and standard deviation of **a.** Tear strength, **b.** Tensile strength, **c.** percentage of elongation, **d.** Shore A hardness, **e.** Surface roughness for all study groups

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