Effect of Hydrothermal Aging on the Flexural Strength and Microhardness of Materials Used for Additive or Subtractive Manufacturing of Definitive Restorations

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Purpose: To evaluate the flexural strength (FS) and microhardness of various CAD/CAM restorative materials intended for definitive use. The effect of hydrothermal aging on the mechanical properties of these materials was also investigated. ***Materials and Methods:*** A total of 210 bar-shaped specimens (17 × 4 × 1.5 mm ± 0.02 mm) were fabricated via either subtractive manufacturing (SM) methods—reinforced composite resin (SM-CR), polymer-infiltrated ceramic network (SM-PICN), fine-structured feldspathic ceramic (SM-FC), nanographene-reinforced polymethyl methacrylate (PMMA; SM-GPMMA), PMMA-based resin (SM-PMMA)—or additive manufacturing (AM) methods with urethane acrylate–based resins (AM-UA1 and AM-UA2). Specimens were then divided into two subgroups (nonaged or hydrothermal aging; n = 15). A three-point flexural strength test was performed, and five specimens from the nonaged group were submitted to microhardness testing. Specimens were subjected to 10,000 thermal cycles, and the measurements were repeated. ***Results:*** Regardless of aging, SM-CR had the highest FS ($P < .001$), followed by SM-GPMMA ($P \leq .042$). In nonaged groups, AM-UA2 had a lower FS than all other materials except SM-FC ($P = 1.000$). In hydrothermal aging groups, AM specimens had lower FS values than other materials, except SM-PMMA. With regard to microhardness, there was no significant difference found between any of the tested materials ($P \geq .945$) in the nonaged and hydrothermal aging groups. ***Conclusions:*** The effect of hydrothermal aging on FS varied depending on the type of restorative material. Regardless of aging condition, SM-CR showed the highest FS values, whereas SM-FC had the highest microhardness. Hydrothermal aging had no significant influence on the microhardness of the tested materials. *Int J Prosthodont 2024;37(suppl):s133–s141. doi: 10.11607/ijp.8847*

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Table 1 Materials Used

Material	Type	Composition	Manufacturer
Brilliant Crios (SM-CR)	Reinforced composite resin	Resin matrix cross-linked methacrylate (Bis-EMA, Bis-GMA, TEGDMA), barium glass (70.7 wt%; < 1 μm), and amorphous silica (< 20 nm)	Coltene
Vita Enamic (SM-PICN)	Polymer-infiltrated ceramic network	Methacrylate polymer (UDMA, TEGDMA) (14 wt%; 25 vol%) and fine-structure feldspar ceramic network (86 wt%)	VITA Zahnfabrik
Mark II (SM-FC)	Fine-structured feldspathic ceramic	Feldspathic particles (average size = 4 μm; 20 wt%) and glassy matrix (80 wt%)	VITA Zahnfabrik
G-CAM (SM-GPMMA)	Nanographene-reinforced PMMA-based resin	PMMA doped with graphene	Graphenano Dental
M-PM Disc SM-PMMA)	PMMA-based resin	PMMA and cross-linked polymers, dyes, residual peroxide, and MMA	Merz Dental
Tera Harz TC-80DP C&B (AM-UA1)	Urethane acrylate–based resin	Urethane acrylate oligomer, bisphenol A ethoxylated dimethacrylate, 2-HEMA, diphenyl (2,4,6- trimethylbenzoyl) phosphine oxide, and additives	Graphy
C&B Permanent (AM-UA2)	Urethane acrylate–based resin	Diurethane dimethacrylate, 2-propenoic acid, 2-methyl-, (1-methylethylidene) bis (4,1-phenyleneoxy[1-methyl-2,1-ethanediyl]) ester, 2-HEMA, diphenyl (2,4,6- trimethylbenzoyl) phosphine oxide, and additives	ODS

Bis-EMA = ethoxylated bisphenol-A dimethacrylate; Bis-GMA = bisphenol-A diglycidylether methacrylate; TEGDMA = triethylene glycol dimethacrylate; UDMA = urethane dimethacrylate; MMA = methyl methacrylate; HEMA = hydroxyethyl methacrylate.

With advancements in CAD/CAM technologies, a range of monolithic restorative materials have been introduced to restore natural teeth and dental implants.[1,2] CAD/CAM monolithic restorative materials are either ceramic-based or resin composite–based, both with certain advantages and disadvantages.[3,4] Polymer-infiltrated ceramic networks, which combine the advantages of ceramics and composite resins, have also been developed as an alternative.[5–7] In terms of the fabrication of CAD/CAM reconstructions, subtractive manufacturing (SM), such as milling, is commonly used. Additive manufacturing (AM) in the form of various 3D-printing techniques is a more recently developed technology[8] that is increasing in popularity[9] because it allows for the creation of objects with complex geometries[10] and color gradients,[11] and even objects composed of multiple materials.[12] In addition, less waste is produced compared to SM.[13] One of the most often used AM techniques is digital light processing (DLP).[12] In recent years, urethane acrylate–based resins (Tera Harz TC-80DP [Graphy] and C&B Permanent [ODS]), glass filler–reinforced composite resins (Crowntec, Saremco Dental AG),[14] and hybrid composite resins (Varseo-Smile Crown Plus, Bego)[12,15] for AM and nanographene-reinforced prepolymerized polymethyl methacrylate (PMMA) resin (G-CAM, Graphenano Dental)[16] for SM intended for definitive restorations have been introduced.

Regardless of the manufacturing method used, restorative materials must have high biocompatibility, long-term stability in terms of their mechanical and optical properties, and adequate esthetics to be used for definitive restorations.[1,2] Depending on their mechanical properties, such as flexural strength (FS) and microhardness, CAD/CAM restorations can be used either provisionally or definitively.[17,18] FS refers to the maximal sustainable stress that a material can endure before failure and, therefore, defines the integrity of the material.[17] Microhardness describes the material's resistance to indentation or permanent surface penetration and defines its wear properties.[18] A harder surface is likely to exhibit greater wear resistance than a softer one.[18] The FS[19,20] and microhardness[4,21] of CAD/CAM restorations are determined by the material composition and the manufacturing procedure. Variations in the temperature of the oral environment can have an impact on the FS and microhardness of a resin-based restorative material. Dynamic loading and thermocycling conditions have also been reported to have a detrimental effect on the mechanical properties of provisional AM and SM resins.[22] Therefore, to predict the long-term mechanical success of novel CAD/CAM definitive restorative materials, it is essential to assess how the intraoral environment affects their mechanical properties.[22–24] Additional information on the effect of hydrothermal aging on the mechanical properties of AM and SM definitive composite/hybrid composite/nanographene-reinforced PMMA CAD/CAM restorative materials compared with commonly used SM feldspathic ceramic would enhance knowledge on their applicability.

The present study aimed to compare the FS and Vickers microhardness of various CAD/CAM restorative materials for definitive use, including urethane acrylate–based

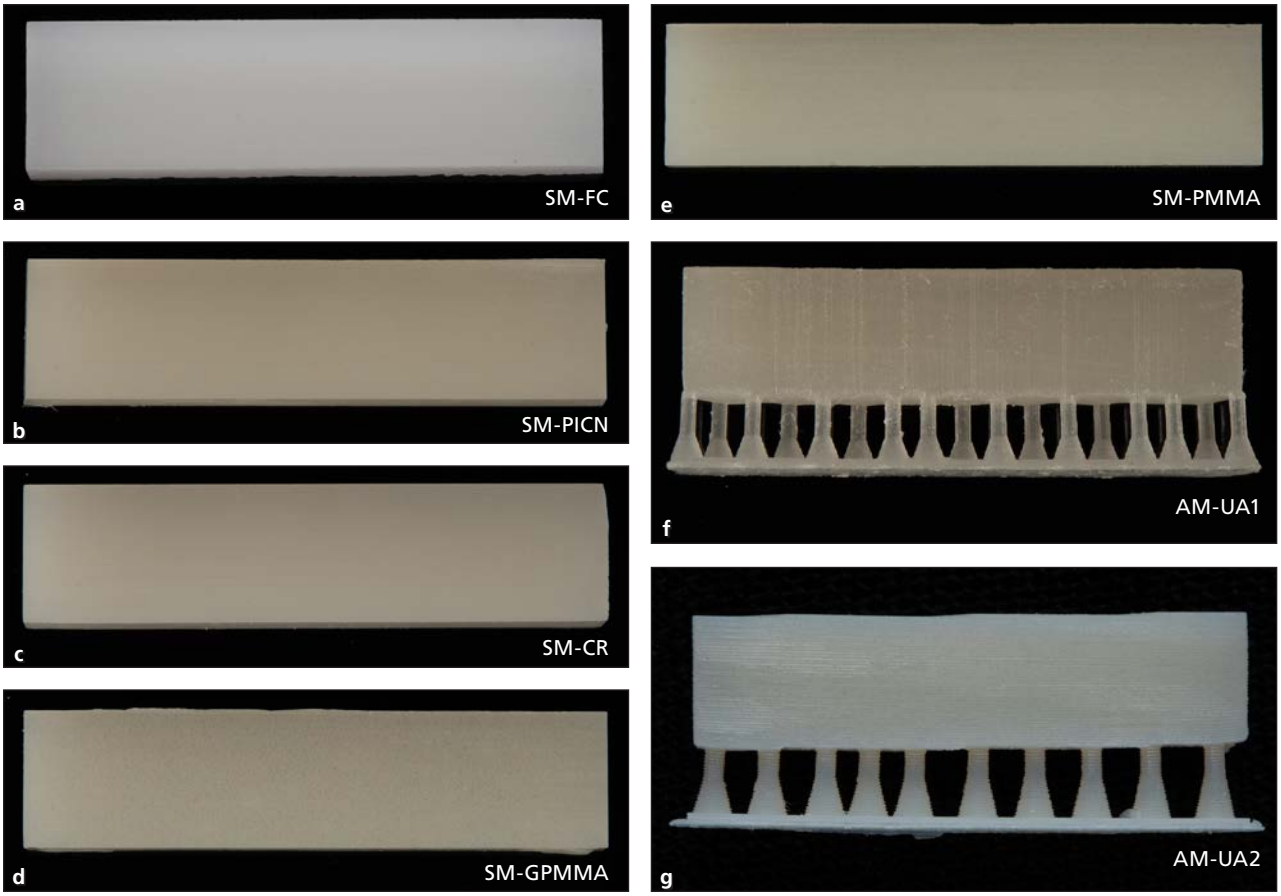

Fig 1 *(a to g)* Materials used in this study.

resins indicated for AM and feldspathic ceramic (positive control), reinforced composite resin, polymer-infiltrated ceramic network, and nanographene-reinforced PMMA indicated for SM. A PMMA-based resin indicated for SM was used as the negative control. In addition, the effect of hydrothermal aging on the mechanical properties of these materials was investigated. The null hypotheses of this in vitro study were that the FS (first) and microhardness (second) of tested restorative materials would not be affected by hydrothermal aging. In addition, the FS (third) and microhardness (fourth) would not be different among tested materials regardless of aging condition.

MATERIALS AND METHODS

Seven different restorative materials that can be used with CAD/CAM technology were tested in this study (Table 1 and Fig 1). A reinforced composite resin (Brilliant Crios [Coltene AG]; SM-CR), a polymer-infiltrated ceramic network (Vita Enamic [VITA Zahnfabrik]; SM-PICN), a fine-structured feldspathic ceramic (Mark II [VITA Zahnfabrik]; SM-FC), a nanographene-reinforced PMMA (G-CAM [Graphenano Dental]; SM-GPMMA), and a PMMA-based resin (M-PM-Disc [Merz Dental]; SM-PMMA) were used for the specimens fabricated by SM. Two urethane acrylate–based resins (Tera Harz TC-80DP [Graphy]; AM-UA1) and (C&B Permanent [ODS]; AM-UA2) were used for the specimens manufactured by AM. All fabrication procedures were conducted according to the manufacturers' recommendations.

A total of 210 bar-shaped specimens (17 × 4 × 1.5 mm ± 0.02 mm; n = 30) were prepared for the FS test in accordance with ISO standard 6872:2015.25. This study's sample size (n = 15) was determined based on a priori power analysis (95% CI, 95% power, and effect size = 0.623).[26]

For the fabrication of SM specimens (SM-CR, SM-PICN, SM-FC, SM-GPMMA, and SM-PMMA), a rectangular specimen (17 × 4 × 4 mm ± 0.02 mm) was designed with a software program (Meshmixer v3.5.474, Autodesk) and stored in STL format. It was milled according to the tested material and directions from the five-axis milling machine's manufacturer (PrograMill PM7, Ivoclar Vivadent). A high-finish milling strategy was selected for all tested materials. SM-CR, SM-PICN, and SM-FC were wet milled, and SM-GPMMA and SM-PMMA

were dry milled. After milling, the rectangular bars were further sliced using a precision cutter (Vari-Cut VC-50, LECO) under water to obtain a final thickness of 1.5 mm.

For fabrication of the AM specimens (AM-UA1 and AM-UA2), a bar-shaped specimen (17 × 4 × 1.5 mm ± 0.02 mm) was virtually designed with the same software and saved as an STL file. This STL file was imported into the build preparation software program (Composer v1.3.3, Asiga) of a DLP printer (MAX UV, Asiga; 385-nm wavelength and 62-µm pixel resolution) and positioned perpendicular to the platform. Supports were automatically generated on the bottom surfaces of the specimens, and this configuration was duplicated 15 times for standardization. Specimens were fabricated with a layer thickness of 50 µm. For the post-processing, specimens were removed from the build platform, cleaned in an ultrasonic bath of 96% ethanol (Ethanol absolut, Grogg Chemie) for 45 seconds, and further cleansed with an ethanol-soaked (96% ethanol) cloth to remove any unpolymerized resin on the surface. To ensure that no alcohol residue was left on the specimens, they were then completely dried with an air syringe and allowed to dry thoroughly for at least 10 minutes. Specimens were then post-polymerized with 2,000 flash exposures, repeated twice on the top and bottom surfaces of each specimen with a Xenon lamp-curing device (Otoflash G171, NK-Optik) under a nitrogen oxide gas atmosphere. The support structures were then removed with a cut-off wheel.

Each specimen was examined under a magnification loupe (EyeMag Pro ×3.5, Zeiss) for any defects and finished with wet silicon carbide abrasive paper (Norton Abrasives). The final dimensions of all specimens (17 × 4 × 1.5 ± 0.2 mm) were controlled using a micrometer (Digimatic IP65, Mitutoyo). No additional polishing was performed on any of the specimens before the FS test. Then the specimens were divided into two subgroups: nonaged and hydrothermal aging (n = 15 for each material). Specimens of the nonaged groups were stored in distilled water (37°C) for 24 hours, and specimens of the hydrothermal aging groups were subjected to 10,000 thermal cycles (Thermocycler, SD Mechatronik) from 5°C to 55°C with 10 seconds of transfer time (30-second dwell time) in distilled water.[26]

The FS of the specimens was measured using a three-point bending test with a universal testing machine (zwickiLine Z1.0 TN, Zwick). Prior to the three-point bending test, the dimensions of each sample were measured. Specimens were inserted on the sample holder apparatus, which had a support span of 12 mm. After inserting, the load was applied at a crosshead speed of 1 mm per minute at the middle of the specimens (in accordance with ISO 6872:2015).[25] The FS data (σ) were calculated in MPa using the following formula: $\sigma = 3Fd/2wh2$, where F is the load at fracture (N), d is the span (mm), w is the width of the specimen (mm), and h is the height of the specimen (mm).[26,27]

For the microhardness measurements, the specimens of nonaged groups were used. After the FS test, five specimens of each material were polished according to the manufacturer's directions. For SM-CR, a two-step polishing kit (Diatech Lab Finishing and Polishing Kit for Brilliant Crios [Coltene]; 7,000 rpm for 90 seconds with each polishing bur) was used with a polishing paste (Zircon Brite, Klasse 4 Dental). For SM-PICN, a two-step polishing kit (Vita Enamic Polishing Set Technical [VITA Zahnfabrik]; 7,000 rpm for the first bur and 5,000 rpm for the second bur for 90 seconds) was used with the same polishing paste. For SM-FC, a two-step polishing kit (Vita Ceramics Polishing Set Technical [VITA Zahnfabrik]; 7,000 rpm for 90 seconds with each polishing bur) was used with a diamond polishing paste (VITA Polish Cera, VITA Zahnfabrik). For SM-GPMMA and SM-PMMA, conventional polishing was performed as follows: A slurry of coarse pumice in water (Pumice Fine, Benco Dental) was used for 90 seconds at a speed of 1,500 rpm. An extra 90 seconds of fine polishing was conducted using a polishing paste (Fabulustre, Grobet USA). For AM-UA1 and AM-UA2, the manufacturer recommends the use of conventional laboratory polishing. Therefore, these specimens were polished similar to PMMA specimens with consideration for their urethane acrylate–based structures. Initial microhardness (weight/area of indentation; HV) was measured using a Vickers hardness tester (M-400 Hardness Tester, LECO). Each specimen was subjected to a load of 980.7 mN for 10 seconds[28] at five different sites that were at least 0.5 mm apart, and these values were then averaged. These specimens were then subjected to 10,000 thermal cycles, as previously described. Then, the microhardness measurements of each specimen were repeated after thermal cycling.

For FS and Vickers microhardness data, after Shapiro-Wilk Test and Levene's Test were performed, normality of residuals and homogeneity of variances in different groups could not be assumed. Therefore, Wilcoxon Rank-Signed Test was performed with Bonferroni correction, and the differences between the groups were further examined. All analyses were conducted using SPSS software (version 23, IBM) with a significance level of $\alpha = .05$.

RESULTS

Table 2 presents the mean FS values of the various materials, and Fig 2 shows the complementary boxplot graph. The effect of hydrothermal aging on the FS of the materials was nonsignificant in most cases ($P \geq .171$), except for SM-CR and AM-UA1 ($P = .001$), which showed a significant decrease in FS values. Regardless of aging conditions, SM-CR had the highest FS value ($P < .001$), followed by SM-GPMMA ($P \leq .042$). For nonaged groups,

Table 2 FS in the Nonaged and Hydrothermal Aging Groups

Material	Nonaged	Hydrothermal aging	*P**
SM-CR	211.35 ± 16.98[a]	172.37 ± 19.33[a]	.001
SM-PICN	115.98 ± 15.35[c]	103.38 ± 17.11[c]	1.00
SM-FC	95.69 ± 21.47[de]	103.46 ± 24.16[c]	1.00
SM-GPMMA	136.49 ± 12.24[b]	120.83 ± 16.79[b]	.371
SM-PMMA	112.91 ± 7.71[c]	96.03 ± 9.45[cd]	.171
AM-UA1	107.55 ± 15.69[cd]	79.55 ± 7.63[d]	.001
AM-UA2	90.82 ± 4.33[e]	84.81 ± 3.58[d]	1.00

Data are presented in MPa as mean ± SD. Different superscript lowercase letters indicate significant differences between materials in the same aging condition ($P < .05$).
*Nonaged-hydrothermal aging.

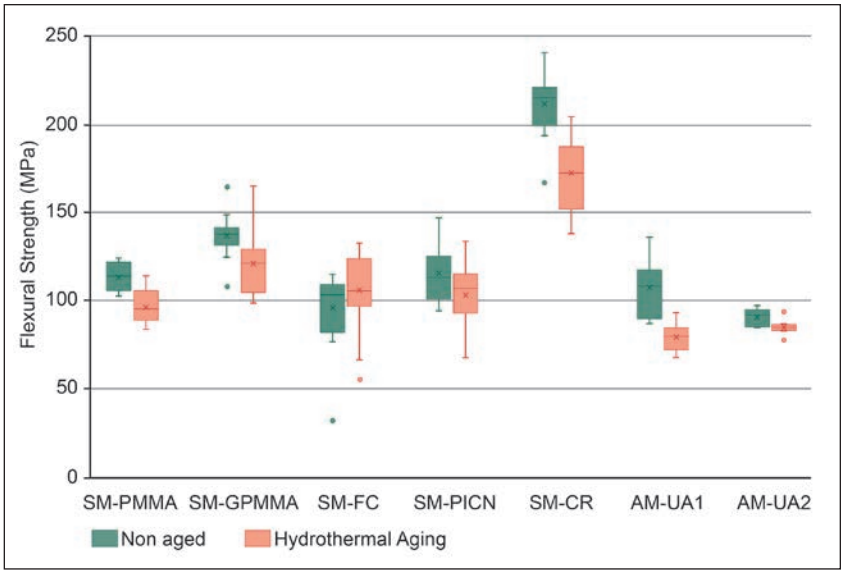

Fig 2 Boxplot graph of the FS values (MPa) in the nonaged and hydrothermal aging groups for each material.

SM-PICN, SM-PMMA, and AM-UA1 had similar FS ($P \geq .245$), whereas the FS of AM-UA1 was similar to that of SM-FC ($P = .595$). AM-UA2 had a lower FS than most other materials ($P \leq .032$), except for SM-FC ($P = 1.000$). For aged groups, SM-PICN, SM-PMMA, and SM-FC had similar FS ($P \geq .485$). AM-UA1 and AM-UA2 had a lower FS than other materials ($P < .001$), except for SM-PMMA. There was no significant difference between the FS of AM-UA1 and AM-UA2 ($P = .967$).

Table 3 presents the mean and SD values of Vickers microhardness, and Fig 3 shows the complementary boxplot graphs. The effect of hydrothermal aging on microhardness was nonsignificant for all materials ($P \geq .945$). Regardless of aging condition, SM-FC had the highest microhardness value ($P < .001$), followed by SM-PICN. For nonaged groups, microhardness of the materials in decreasing order was as follows: SM-FC > SM-PICN > SM-CR > SM-GPMMA ≈ SM-PMMA ≈ AM-UA2 ≈ AM-UA1. For aged groups, mean values for microhardness of the materials in decreasing order was as follows: SM-FC > SM-PICN > SM-CR ≈ SM-PMMA ≈ SM-GPMMA ≈ AM-UA1 ≈ AM-UA2.

DISCUSSION

Hydrothermal aging had a significant effect on the FS values, depending on the restorative material type. Therefore, the first null hypothesis was rejected. The second null hypothesis was accepted because hydrothermal aging had no significant effect on microhardness. The third and fourth null hypotheses were also rejected because the type of restorative material significantly affected the FS and microhardness in both nonaged and hydrothermal aging conditions.

Sufficient FS is required for the clinical success of definitive restorations so that they can withstand the forces of mastication and environmental changes in the oral cavity.[26,29] Hydrothermal aging is used to simulate temperature changes in the oral cavity for investigating the mechanical properties of restorative materials.[26,29]

Table 3 Vickers Microhardness in the Nonaged and Hydrothermal Aging Groups

Materials	Nonaged	Hydrothermal aging	*P**
SM-CR	85.39 ± 2.77[c]	82.22 ± 2.9[c]	.945
SM-PICN	252.65 ± 24[b]	275.25 ± 30.5[b]	.996
SM-FC	644.92 ± 44.54[a]	599.7 ± 115.7[a]	.95
SM-GPMMA	28.31 ± 1.14[d]	27.85 ± 2.1[c]	1.00
SM-PMMA	27.45 ± 5.58[d]	28.51 ± 0.5[c]	1.00
AM-UA1	19.45 ± 1.68[d]	27.7 ± 0.6[c]	.967
AM-UA2	23.08 ± 4.7[d]	20.5 ± 0.9[c]	.993

Data are presented in VH as mean ± SD. Different superscript lowercase letters indicate significant differences between materials in the same aging condition ($P < .05$).
*Nonaged-hydrothermal aging.

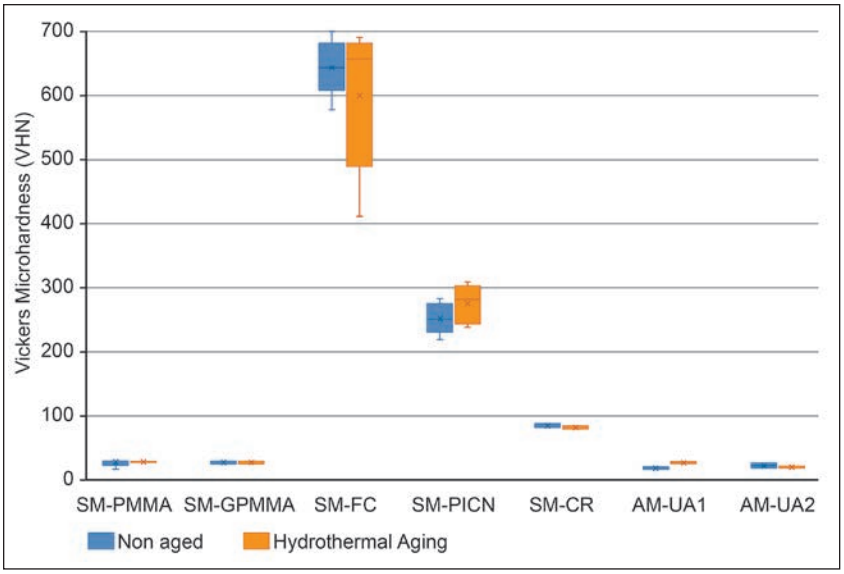

Fig 3 Boxplot graph of Vickers microhardness in the nonaged and hydrothermal aging groups for each material.

It has been reported that hydrothermal aging may induce water sorption, which degrades polymeric chains and reduces their mechanical properties due to the plasticizing action of water.[26,30] Regarding the effect of hydrothermal aging on the FS of different restorative materials, previous studies have reported contradictory results depending on the material type.[17,23,26,27,31] In the present study, most of the tested materials placed under hydrothermal aging showed a decrease in FS, except for SM-FC. However, a significant decrease in FS with hydrothermal aging was seen only in SM-CR and AM-UA1. According to ISO 6872:2015 standards,[25] the minimum FS required for adhesively cemented, single-unit anterior or posterior crowns is 100 MPa. This threshold value was reached by most of the SM groups but not by the AM materials when the materials were submitted to aging conditions. Among the tested restorative materials, SM-CR had the highest FS, followed by SM-GPMMA, regardless of aging conditions. Considering nonaged conditions, only AM-UA2 and SM-FC had an FS value less than 100 MPa, SM-PMMA, AM-UA1, and AM-UA2 had FS values less than 100 MPa in hydrothermal aging conditions. Most of the SM materials, however, had FS values greater than 100 MPa.

In AM specimens, the effect of temperature change may be deemed detrimental. It can be hypothesized that AM definitive restorative materials are less resistant to temperature changes than the other tested restorative materials. SM may have appeared to be less susceptible to hydrolytic degradation processes than AM materials due to its densely cross-linked and homogenous structure.[24] The different chemical compositions and filler contents of the tested restorative materials may explain this difference in FS.[24]

Grzebieluch et al[24] evaluated FS, flexural modulus, and microhardness of SM composite resin (Grandio Blocks [VOCO Dental], Brilliant Crios, and Vita Enamic)

and hybrid composite AM resin for definitive prostheses (VarseoSmile Crown Plus). However, the authors did not include aging conditions in the study and included a limited number of materials. This study[24] showed that SM-CR had greater FS than SM-PICN and AM composite resin, whereas SM-PICN and AM composite resin materials had similar FS in nonaged conditions. In the present study, nonaged SM-PICN specimens had similar FS values to one of the tested AM resins (AM-UA1), and both materials had greater FS than the other AM resin (AM-UA2). Considering that both AM resins were printed with the same printer and build orientation, the difference between the FS of nonaged AM specimens can be attributed to the difference in the chemical structure and their viscosity. In line with the present study, Nam et al[29] reported similar results with the same AM urethane acrylate–based resin (AM-UA1) and attributed the difference between the FS values of different AM permanent resins to the difference in their chemical structure. SM-FC is a feldspathic ceramic that can be considered a brittle material.[32] The FS values of SM-FC were similar to AM resins in nonaged conditions and less than the FS values for SM-PICN. Consistent with the present study results, Wendler et al[33] reported lower FS with the same feldspathic ceramic compared to that of polymer-infiltrated ceramic network.

SM-GPMMA is a nanographene-reinforced PMMA. Nanographene is a crystalline form of carbon that is incorporated into PMMA to improve the mechanical properties.[16] In line with the results of the present study, Ionescu et al[34] and Çakmak et al[35] reported that nanographene-reinforced prepolymerized PMMA had greater FS than milled prepolymerized PMMA. Considering the results of the present study and ISO thresholds,[25] it can be speculated that nanographene-reinforced PMMA may be a promising definitive restorative material alternative to feldspathic ceramics or a polymer-infiltrated ceramic network. Nevertheless, these results should be interpreted carefully, as future clinical studies are needed to verify these findings.

In terms of microhardness, SM-FC exhibited the greatest HV values, followed by SM-PICN and SM-CR, respectively. The smallest values were observed in the prepolymerized PMMA, nanographene-reinforced PMMA, and AM urethane acrylate–based resins groups, regardless of aging condition. Grzebieluch et al[24] reported similar hardness values for SM reinforced resin, polymer-infiltrated ceramic network, and AM definitive resins. Previous studies found a strong linear correlation between filler volume and surface hardness, which may explain the greater microhardness values of SM feldspathic ceramic, polymer-infiltrated ceramic network, and reinforced composite resin. Because a material's microhardness is related to its reaction to abrasive forces,[36] and materials with low microhardness may be more prone to wear,[24,37] it can be presumed that SM-FC, SM-PICN, and SM-CR may be less prone to wear. However, this must be confirmed by future studies. In the present study, there was no difference in microhardness values between prepolymerized PMMA, nanographene-reinforced PMMA, and AM urethane acrylate–based resins groups, regardless of aging. This was in line with other studies, which reported similar hardness with nanographene-reinforced PMMA and prepolymerized PMMA.[38,39] Whereas Nam et al[29] reported lower hardness results with one of the same AM resins used in the current study (AM-UA1), as well as different microhardness values among different AM permanent resins, this difference may be attributable to different loads applied when measuring microhardness. In the present study, hydrothermal aging had no significant effect on the microhardness values of any of the tested materials. Al-Haj Husain et al[31] compared the microhardness of various AM definitive and provisional resins and reported that whereas material type affected microhardness, aging conditions had no effect, which is consistent with the results of the present study.

In the present study, AM resins were fabricated using a vertical build orientation because, according to the literature, this orientation provides increased mechanical strength and facilitates the transmission of tensile forces that occur during mastication along the print layers.[19] Due to the possibility of the printing layers acting as a potential mechanical weakness of the material, different outcomes can be achieved with different build orientations. In the present study, 10,000 thermal cycles were applied to correspond to 1 year of clinical use, and distilled water was used as a medium.[26] However, different mediums and extended thermal cycling durations may yield different results. In addition, three-point bending was chosen as the test technique because it is commonly used and has been reported to be more reliable than the biaxial test.[17]

One of the limitations of this study was its in vitro design, which did not include saliva and masticatory forces. Additionally, only one type of 3D printer and a single curing unit were used. Future studies should investigate the effect of different build orientations, printer types, post-processing, and post-curing times on the mechanical properties of AM definitive resins. Furthermore, in the present study, other material properties, such as compressive strength, wear resistance, and adhesion strength, were not investigated, which could be considered a limitation. These properties should be investigated in future studies. Finally, polishing may affect the hardness of composite resins.[40] However, because the tested materials differed in composition and manufacturer recommendations were followed for optimal surface polishing, the polishing technique was not considered as an independent variable in the present

study. Hardness before polishing was not measured in the present study, so it is not possible to comment on the state of the hardness depending on polishing technique. The effect of various polishing techniques on the hardness of tested materials should be investigated in future studies. Future studies should also investigate the surface roughness, microbial adhesion, biocompatibility, and color stability of different definitive restorative materials using larger sample sizes and thermomechanical aging.

In ISO specifications, the minimum mean FS values for the various clinical indications are indicated, as well as the specifications required to perform the Weibull statistics for dental ceramic CAD/CAM materials. Esthetic ceramics, used for veneers and inlay and onlay restorations, are classified as Class 1 ceramics and should have a minimum mean FS of 50 MPa. Esthetic ceramics, used for adhesively cemented, single-unit, anterior or posterior prostheses, are classified as Class 2 ceramics and should have a minimum mean FS of 100 MPa.

CONCLUSIONS

Within the limitations of the present study, the following conclusions were drawn:

1. The impact of hydrothermal aging on FS varied depending on the type of restorative material used for both manufacturing techniques.
2. Within SM materials, hydrothermal aging decreased the FS of only reinforced composite resin. Before and after hydrothermal aging, reinforced composite resin exhibited the greatest FS, followed by nanographene-reinforced PMMA resin.
3. Hydrothermal aging significantly decreased the FS of one the tested AM urethane acrylate–based resins, indicating a potential degradation of this material under hydrothermal conditions.
4. Hydrothermal aging did not significantly alter the microhardness of any tested material. Within SM materials, before and after hydrothermal aging, feldspathic ceramic demonstrated the greatest microhardness values, followed by polymer-infiltrated ceramic network.

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