Silorane-based Dental Composite: Behavior and Abilities

Nicoleta ILIE and Reinhard HICKEL

Department of Restorative Dentistry, Dental School of the Ludwig-Maximilians-University, Goethestr. 70, 80336 Munich, Germany
Corresponding author, Nicoleta Ilie E-mail：nicoleta.ilie@dent.med.uni-muenchen.de

The purpose of this study was to examine the characteristics of an innovative composite material for dental restorations based on silorane − a monomer with a new chemical composition, and thereby compare the examined characteristics against those of well-known methacrylate-based composites.

Degree of conversion at 2-mm and 6-mm depths as well as hardness, modulus of elasticity, and creep resistance through the middle of 6-mm high samples were measured. It was observed that up to 20 minutes after curing, curing time − and not irradiance − played the determinant role for a high degree of cure. No differences were registered between the two categories of material in terms of hardness. However, modulus of elasticity of the silorane-based material was slightly lower and the creep resistance higher than a methacrylate composite (Tetric EvoCeram). In conclusion, siloranes exhibited good mechanical properties comparable to those of clinically successful methacrylate-based composite materials.

Key words : Silorane, Degree of cure, Hardness

INTRODUCTION

As shrinkage stress has been implicated as a causative factor for marginal discrepancies observed in composite restorations[1−3], considerable efforts have been invested to minimize shrinkage stress stemming from polymerization of composite materials. To reduce shrinkage, the main approaches adopted so far are to change the monomer structure or chemistry, respective to change the filler amount, shape or surface treatment. To date, versatile methods to modify the monomer matrix have been developed, starting with typical dimethacrylate monomers being replaced by methacrylates with reduced reactive group. Other approaches proposed for reducing polymerization shrinkage include the development of liquid crystal monomers or ring-opening systems so as to develop non- or minimally-shrinking dental composites that contain spiroorthocarbonates as additives to dimethacrylate or epoxy-based resins[4−8].

Some modern developments in dental composite research have focused on the use of ring-opening systems like oxirane-based resins cured under visible light conditions. Oxirane resins have shown many desirable properties such as improved depth of cure, lower polymerization shrinkage, higher strength, as well as equivalent hardness and acceptable glass transition temperature when compared with conventional bis-GMA-based dental resins[9−10]. It is now firmly established that residual monomers/additives released from commercial methacrylate-based composite materials after polymerization are found to be toxic. On this note, the *in vivo* cytotoxicity and mutagenicity of oxirane resins are also presumed[11]. As a result, research continued in the direction of ring-opening monomers, with intense effort and focus on reducing the effects of cytotoxicity and mutagenicity.

Recently, Weinmann *et al.*[12] described the synthesis of a new monomer system − named silorane − obtained from the reaction of oxirane and siloxane molecules. The novel resin claimed to have combined the two key advantages of the individual components: low polymerization shrinkage due to the ring-opening oxirane monomer and increased hydrophobicity due to the presence of the siloxane species. Further, Schweikl *et al.*[13] showed that the mutagenic potential of various siloranes tested in diverse test systems was much lower than those of related oxiranes, while Eick *et al.*[14] found out that siloranes were stable and insoluble in biological fluids simulated using aqueous solutions containing either epoxide hydrolase, porcine liver esterase, or dilute HCl. All this reported advantageous characteristics serve to enhance the potential of silorane monomers being used successfully in dental composite materials.

The purpose of this study was to examine the characteristics of a novel silorane-based composite material − in terms of degree of cure and mechanical properties − as a function of different curing conditions, and thereby compare them against those of well-known methacrylate-based composites when examined under equivalent curing conditions.

MATERIALS AND METHODS

The curing behavior of an experimental silorane-based composite (Hermes, 3M ESPE, Seefeld, Germany, Shade A3, Lot No. A-254; chemical composition: 3,4-epoxycyclohexylethylcyclo-polymethylsiloxane (5-15 wt%), bis-3,4-epoxycyclohexylethyl-phenylme-

thylsilane (5-15 wt%), silanized quartz (50-70 wt%), yttrium fluoride (10-20 wt%)) was evaluated by assessing the degree of cure and variation of hardness and modulus of elasticity with depth after polymerizing the material with 16 curing regimes comprising one halogen and three LED curing units (Table 1). Two of the tested curing units (Astralis 10 and Bluephase) were equipped with a light-concentrating (turbo) guide tip, whereas the other two were equipped with a standard light guide tip (MiniLED and Freelight 2).

To evaluate the degree of cure, two different sample geometries were considered (Fig. 1):

1) one increment in a mold 2 mm high and with a diameter of 4 mm, cured by applying the curing unit directly on the sample surface;

2) three consecutive increments, each 2 mm high, in a mold 6 mm high and with a diameter of 4 mm, cured by applying the curing unit after each increment at the top of the 6-mm high mold.

Measurements were made in real time with an FTIR spectrometer with an attenuated total reflectance (ATR) accessory (Nexus, Thermo Nicolet, Madison, USA). Therefore, unpolymerized composite

Table 1　Curing units and curing regimes, as well as degrees of conversion at depths of 2 mm and 6 mm as a function of curing regime. Superscript letters indicate statistically homogeneous subgroups (Tukey's HSD test, $\alpha = 0.05$). The Pulse program of the curing unit MiniLED emitted 10 pulses in 12 seconds, equivalent to a 10-second continuous exposure

| Type	Curing unit	Regime	Time (s)	DC (%)-2 mm		DC (%)-6 mm (layered in 3 increments)	
LED	Mini L.E.D (Satelec) Serial No.: 114-6064	Fast-cure	10	60.2^{cdef}	(2.7)	57.3^{abc}	(4.4)
			20	61.3^{fgh}	(2.1)	62.5^{fghij}	(2.2)
			40	66.8^{lm}	(3.0)	64.6^{ijklm}	(1.1)
		Pulse	12	56.8^{ab}	(4.5)	55.3^{a}	(5.5)
			24	64.3^{hijklm}	(2.7)	61.6^{fgh}	(2.5)
			48	66.4^{lm}	(2.7)	64.^{ghijklm}	(1.0)
		Step-cure	20	64.4^{hijklm}	(6.2)	57.0^{ab}	(1.5)
	Bluephase (Ivoclar Vivadent) Serial No.: 1547581	HIP	10	60.6^{ef}	(3.1)	57.6^{abcd}	(1.9)
			20	61.9^{fghi}	(2.7)	58.2^{bcde}	(3.2)
			40	64.9^{jklm}	(4.9)	60.5^{ef}	(3.2)
	Freelight 2 (3M-ESPE) Serial No.: 939820013826	Standard	10	62.4^{fghij}	(1.4)	57.5^{abcd}	(2.8)
			20	65.6^{klm}	(1.9)	63.7^{ghijkl}	(1.9)
			40	66.5^{lm}	(2.8)	64.7^{ijklm}	(2.9)
Halogen	Astralis10 (Ivoclar-Vivadent) Serial No.: 013336	HIP	10	60.5^{ef}	(4.5)	55.8^{ab}	(3.4)
			20	63.0^{fghijk}	(2.3)	58.2^{bcde}	(1.1)
			40	64.9^{jklm}	(4.2)	60.3^{def}	(1.1)
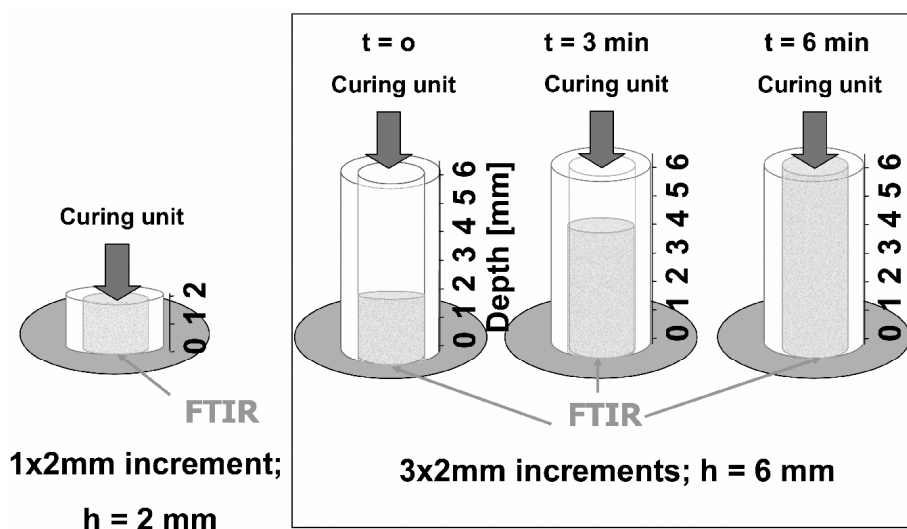
Fig. 1　Sample preparation and curing method for FTIR spectroscopy measurements.

paste was put directly in the mold on the diamond ATR as described above. FTIR spectra were recorded in real time for 20 minutes at the bottom of the samples irradiated according to the curing protocol presented in Table 1. Diameter of the measured surface was 800 μm; wavelength range of spectrum was 650-4000 cm^{-1}, and FTIR spectra were recorded with four scans at a resolution of 8 cm^{-1}. To determine the percentage of the remaining epoxy groups, degree of conversion (=DC) was measured by assessing the variation in peak height ratio of the absorbance intensity of C-O-C bond peak at 883 cm^{-1} and that of internal standard peak at 1257 cm^{-1} (CH bond) during polymerization, in relation to the uncured material.

To analyze the polymerization quality within the 6-mm high samples, hardness and modulus of elasticity profiles through the middle of the samples were measured. Therefore, samples were stored in 37℃ distilled water after curing for 24 hours, sectioned in the middle prior to testing with a slow-speed diamond saw (Isomet low-speed saw, Buehler, Germany) under water cooling, and polished with a diamond suspension (mean grain size: 1 μm). Measurements were made with an automatic microhardness indenter (Fischerscope H100C, Fischer, Sindelfingen, Germany) starting at 0.1 mm under the surface, with 100-μm intervals between the measuring points. Test procedure was carried out force-controlled, where the test load increased and decreased with constant speed between 0.4 mN and 500 mN. Load and penetration depth of the indenter were continuously measured during the load-unload hysteresis. Universal hardness is defined as the test force divided by the apparent area of indentation under applied test force. From a multiplicity of measurements stored in a database supplied by the manufacturer, a conversion factor between Universal hardness and Vickers hardness was calculated and input into the software. In this manner, measurement results were indicated in the more familiar Vickers hardness units.

Indentation modulus can be calculated from the slope of the tangent of indentation depth curve at maximum force. Hardness and modulus of elasticity variations with depth were calculated for each group as a curve-fitted line, based on data from five samples (300 measuring points).

Results were then compared using one-way ANOVA and Tukey's HSD post-hoc test (α=0.05) with SPSS software (SPSS, ver 11.0, SPSS Inc., Chicago, IL, USA).

Spectral distributions and irradiances of the tested curing units were determined by means of a calibrated fiber optic spectrally resolving radiometer equipped with an integrating sphere (S2000, Ocean Optics, USA) (Fig. 1). Total irradiance was obtained by integral calculus of irradiance as a function of wavelength over the entire wavelength range, and then divided by the effective area of the curing unit tip. Diameter of the tip was measured with a digital micrometer, whereby effective area was defined as the area of the tip without cladding. Due to dimension differences between curing unit tip and sample, irradiances from the curing unit passed through a round screen with an inner diameter of 4 mm (=dimension of cured samples) positioned at the center of the curing unit tip, and was additionally calculated[15]. Distance between curing unit tip and screen was varied in 1-mm steps starting at the screen surface up to 10 mm. Further, specific irradiance was defined as the irradiance at a wavelength range of 430-490 nm, which matched the absorption wavelength of the photoinitiator, camphorquinone.

RESULTS

Normalized spectral emissions of the four tested curing units are presented in Fig. 2a. Highest irradiance was measured for the halogen curing unit, Astralis 10 (1857 mW/cm^2), whereas LED curing units, MiniLED, Freelight 2, and Bluephase, with a narrow band spectral output, achieved irradiances of 1141 mW/cm^2, 1226 mW/cm^2, and 1435 mW/cm^2 respectively. Variations of irradiance, adapted to the geometry of the samples tested in this study (round samples with a diameter of 4 mm), are presented as a function of distance between curing unit tip and sample surface in Fig. 2b. For all curing units, irradiance decreased considerably with increased distance between sample surface and curing unit tip, so that less than 10% of total irradiance was available on the surface of 4-mm round samples at a distance of 1 cm — if curing units were equipped with a turbo tip. For curing units with a standard tip (Freelight 2 and MiniLED), less than 17% of total irradiance was available on the sample surfaces.

To evaluate the effectiveness of the tested curing units, Fig. 2b (right) presents specific irradiance — which was calculated as part of the spectral emission which matched the absorption wavelength of photoinitiator, camphorquinone. In terms of specific irradiance (wavelength range at 430-490 nm of the spectral emission of curing units), less difference could be observed between the halogen curing unit Astralis 10 and the LED curing units Bluephase and Freelight 2, whereas LED curing unit MiniLED provided considerably lower irradiances. However, at distances greater than 7 mm, the irradiances provided by MiniLED seemed to resemble those of the other curing units; as a result, fewer differences were noted among the tested curing units.

Highest decrease rate of irradiance with distance was observed for the halogen curing unit (Fig. 2c, right), whereas that of the LED curing unit, MiniLED, was less than a quarter of Astralis 10's during the first five millimeters. By comparing the
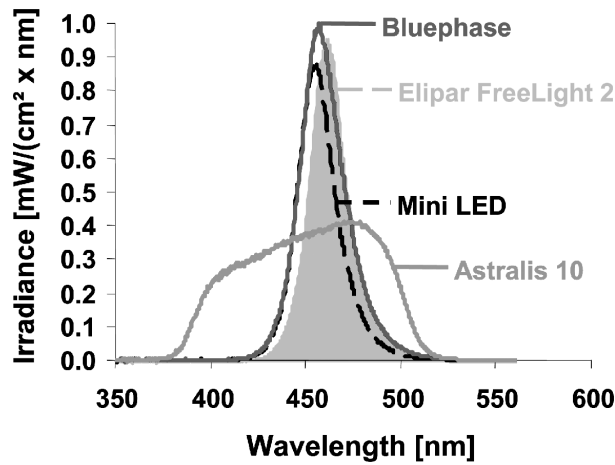
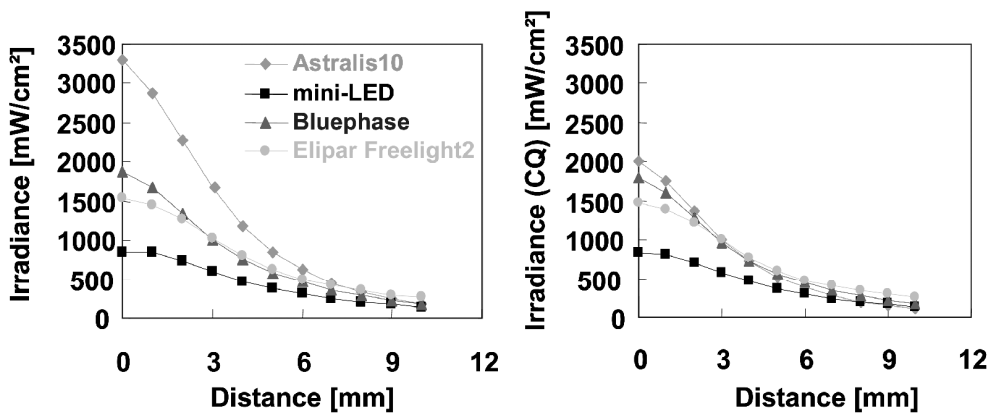Fig. 2a   Normalized spectral emissions from one halogen and three LED curing units.

Fig. 2b   Irradiance (left) and specific irradiance passed through a round screen with an inner diameter of 4 mm, as a function of distance. Specific irradiance was calculated as the irradiance at 430-490 nm wavelength range.
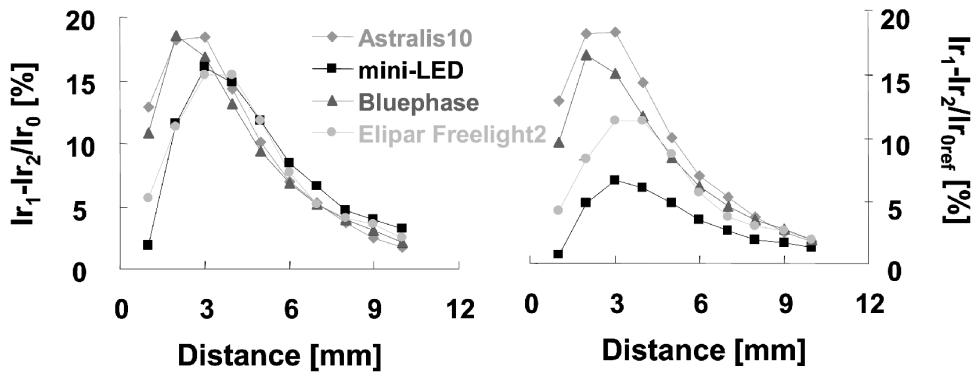
Fig. 2c   Irradiance decrease rate refers to the maximum irradiance of individual curing units (left), and then respectively to the maximum irradiance of a reference (right); Ir_{0ref}=maximum irradiance of Astralis 10.

irradiance decrease rate that referred to the maximum irradiance of individual curing units (Fig. 2c left), two different behavior patterns can be observed depending on the type of curing unit tip — standard or turbo.

Analysis results of the degree of cure are presented in Fig. 3 and Table 1. Homogenous subgroups can be identified by the same superscript. For the 10-second regime, post-hoc multiple pairwise comparisons with Tukey's HSD test showed no significant differences (p<0.05) among the curing units regarding the degree of cure at 2-mm depth — with exception of MiniLED Pulse regime. Similar relationships were also recorded for 40-second polymerization time.

At 6-mm depth, no significant differences in the degree of cure were observed for the 10-second polymerization time. However, with the 20-second and 40-second regimes, curing units with a turbo tip yielded significantly lower DC than the curing units with a standard tip. When considering the differences between the 2-mm and 6-mm depths within one curing regime, less differences were noted for the standard-tip curing units; on the other hand, statistically significant differences were noted for all other regimes of turbo-tip curing units. Fig. 4 shows an example of how the degree of conversion evolved with time with different photoinitiation times of the same curing unit. Fig. 5 then shows the differences between
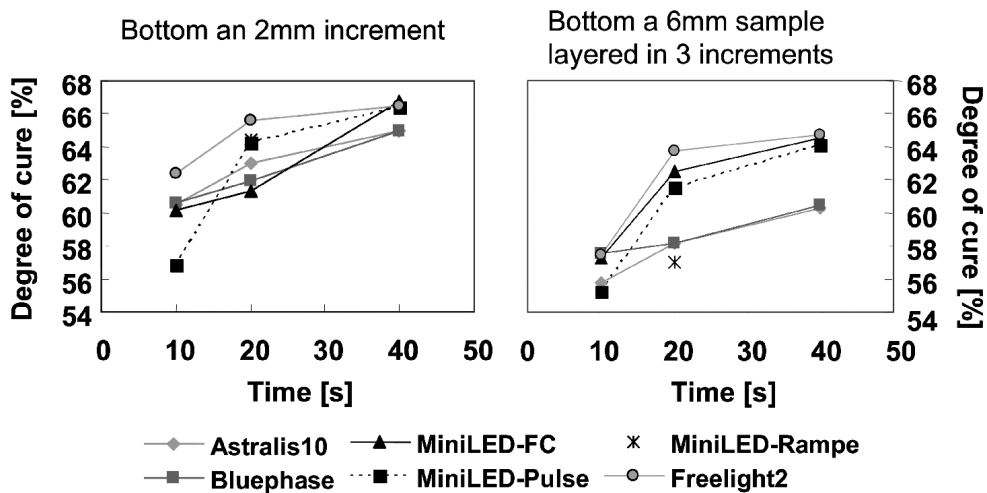

Fig. 3   Variation of degree of conversion after curing for 10 s, 20 s, and 40 s, measured at the bottom of 2-mm thick samples (left) and 6-mm samples layered in three increments (right).
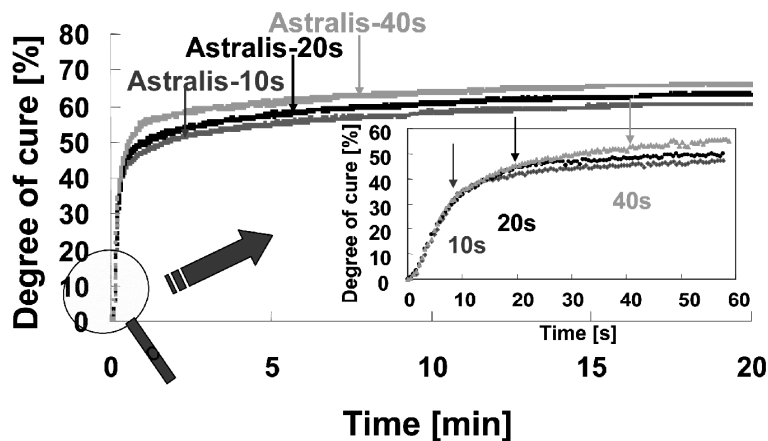

Fig. 4   Average real-time curves of the degree of conversion after curing with the halogen curing unit, Astralis 10, for 10 s, 20 s, and 40 s. Arrows indicate the end of photoinitiation after 10 s (grey), 20 s (black), and 40 s (red).

2 mm and 6 mm as a function of the curing time.

The mechanical properties — hardness and modulus of elasticity — are summarized in Table 2. These properties tended to decrease with depth. However, no significant differences were observed between 2-mm and 6-mm depths within one regime, nor between different curing regimes. Further, although a highly significant correlation was found at 2-mm depth between polymerization time and degree of cure (Pearson 0.51), no such correlation was found between polymerization time and mechanical properties, and that irradiance did not correlate with any measured property. At 6-mm depth, the influence of polymerization time on the degree of cure (Pearson
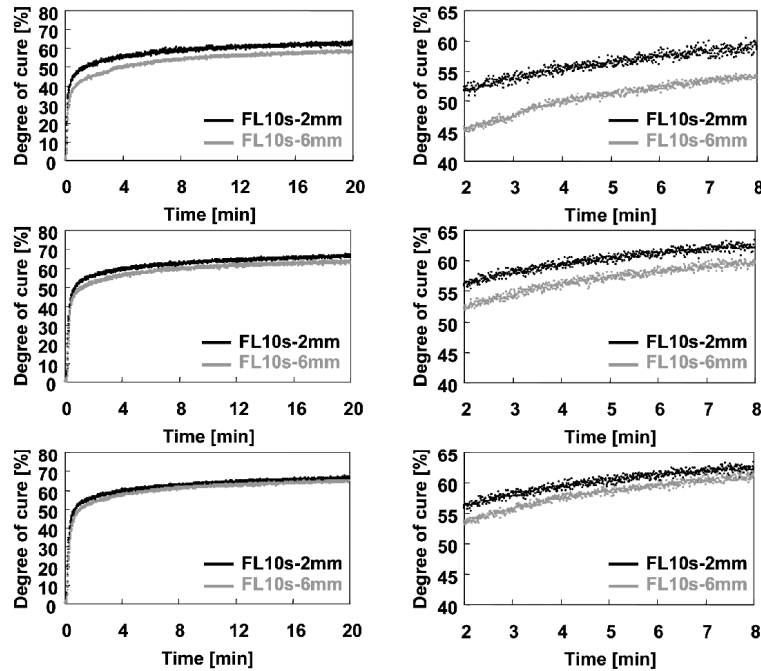

Fig. 5 Average real-time curves of the degree of conversion as a function of time after curing with the LED curing unit, Freelight 2, for 10 s, 20 s, and 40 s. Close-up views on the right focus on the effect of additional curing of the second increment (time＝3 min) and third increment (time＝6 min).

Table 2 Vickers hardness and modulus of elasticity at 2-mm and 6-mm depths as a function of curing method

| Curing unit	Regime	Time (s)	HV- 2 mm (N/mm^2)	HV- 6 mm (N/mm^2)	E- 2 mm (GPa)	E- 6 mm (GPa)
Mini L.E.D	Fast-cure	10	75.9 (4.1)	71.9 (4.6)	12.7 (0.1)	12.0 (0.4)
		20	73.7 (1.0)	72.6 (6.6)	12.4 (0.2)	11.8 (0.8)
		40	79.8 (4.6)	73.7 (6.2)	12.7 (0.6)	12.4 (0.6)
	Pulse	12	73.4 (2.2)	70.1 (8.2)	12.8 (0.2)	11.9 (0.4)
		24	75.2 (0.1)	71.4 (5.1)	12.6 (0.2)	12.5 (0.2)
		48	82.2 (5.2)	74.4 (6.3)	13.4 (0.3)	12.4 (0.4)
	Step-cure	20	76.0 (1.0)	74.2 (6.6)	12.5 (0.5)	12.8 (0.4)
Bluephase	HIP	10	76.8 (4.0)	68.6 (5.5)	12.7 (0.6)	11.2 (0.8)
		20	78.8 (2.1)	72.1 (4.4)	12.5 (0.9)	11.9 (0.9)
		40	78.5 (4.4)	75.7 (6.1)	12.8 (0.4)	12.3 (0.3)
Freelight 2	Standard	10	79.9 (3.4)	69.4 (6.7)	12.4 (0.7)	12.2 (0.9)
		20	82.5 (9.2)	76.6 (10)	12.8 (1.1)	12.7 (1.0)
		40	81.7 (5.7)	76.6 (10)	13.5 (0.1)	13.0 (1.2)
Astralis10	HIP	10	80.8 (7.7)	68.2 (5.7)	12.6 (0.6)	11.6 (1.5)
		20	81.5 (2.9)	72.3 (8.0)	12.4 (0.5)	11.7 (2.1)
		40	80.8 (5.0)	73.9 (4.0)	12.5 (0.4)	12.5 (0.3)
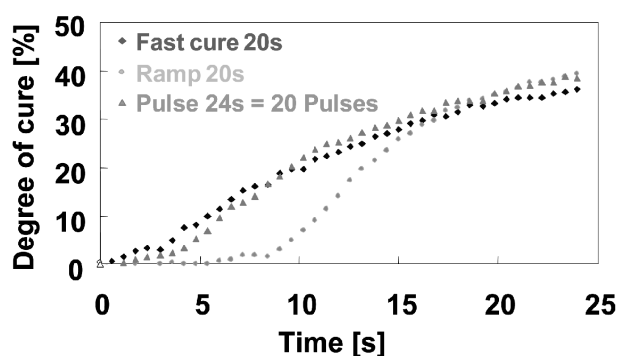
Fig. 6   Influence of soft-start polymerization on the degree of conversion.

0.6) and mechanical properties (Pearson 0.2) increased. Likewise, the correlation between light intensity versus DC and mechanical properties were also statistically significant, but low (Pearson 0.29 and 0.19 respectively).

Fig. 7 offers the possibility to compare a silorane composite with a representative commercial methacrylate-based composite (Tetric EvoCeram, Ivoclar Vivadent, Schaan, Lichtenstein, Lot No. F38346, Shade A3). Both materials were cured under the same conditions. Besides hardness and modulus of elasticity, the variation of creep with depth was also plotted out. Creep was defined in our study as the relative change of indentation depth by holding the maximum indentation force (500 mN) constant for five seconds. No differences were registered between the two categories of material in terms of hardness. However, modulus of elasticity of the silorane material was slightly lower and the creep resistance higher when compared with the methacrylate-based composite.

DISCUSSION

The present investigation determined the curing behavior and abilities of a composite material based on a new chemical composition for the matrix system. The new silorane monomer was developed with a primary target of overcoming some drawbacks pertaining to the polymerization of methacrylate-based composites, like radical oxygen inhibition, polymerization shrinkage, polymerization stress, and water sorption. As a result, the new silorane-based material has the ability to compensate shrinkage by opening the oxirane ring during polymerization — a photoinitiated cationic polymerization which is insensitive to oxygen, as well as increased hydrophobicity — due to the presence of siloxane species. The cationic polymerization initiation system consists of three components: camphorquinone, an iodonium salt, and an electron donor[12]. In the redox process, the electron donor decomposes the iodonium salt to an

acidic cation which then starts the ring-opening polymerization process[12]. Like the methacrylate-based composite, the silorane-based composite also contained camphorquinone so that current dental curing units can be used for polymerization.

Large variations in the spectral emission of curing units of the same manufacturer implies the necessity to check the spectral output of each device individually. The four curing units tested in this study not only differed in their spectral output, but also in the variation of irradiance with distance as well as the light guide tip. To determine the real influence of irradiance on the properties of the silorane composite, only the amount of irradiance which really reached the samples was considered. The surface area of the samples (12.6 mm^2) was only about one-third of the surface area of the curing units' tip. By applying the curing unit tip directly and centered on the sample surfaces, 52% of the total irradiance emitted by the halogen curing unit Astralis 10 and 41% of the irradiance emitted by the LED curing unit Bluephase reached the samples. As for the two LED curing units with a standard light guide, Freelight 2 and MiniLED, the irradiance that reached the samples were 35.7% and 21% respectively. The turbo light guide of Astralis 10 and Bluephase thus caused a concentration of irradiance at the center of the curing unit tip and also a more rapid decrease of irradiance with distance. In contrast, the standard light guide tip of MiniLED and Freelight 2 provided a more uniform light distribution over the surface tip and a slower decrease of irradiance in the first few millimeters.

These differences in irradiance did not significantly affect the tested properties at 2-mm depth, a finding that led to the speculation that the light intensity of the tested curing units attained a level at which the limits of the material were already reached. Only extensions in polymerization time could further enhance the degree of cure. As for the mechanical properties which were measured 24 hours after sample preparation, they remained unaffected by the curing time. However, the situation changed at 6-mm depth. Though curing time still played a significant role in reaching a high degree of cure, a lower polymerization occurred due to reduced irradiance with distance. As a result, the correlation coefficient between irradiance and degree of cure was very low (Pearson 0.29). Further, curing units with a turbo tip yielded a significantly lower degree of cure compared with curing units with a standard tip. When considering the differences in degree of cure at 2-mm and 6-mm depths within one curing regime, less differences were noted for the standard-tip curing units; on the other hand, statistically significant differences were noted for all other regimes of turbo-tip curing units. It has to be mentioned that the 6-mm samples were layered in three increments, so

that an additional curing of the second and third increments followed. As pointed out in Fig. 5, only the additional curing of the second increment really increased the degree of cure for short polymerization time (10 seconds), whereas curing of the last increment had no influence on the degree of cure at 6-mm depth. With increasing curing time, the effect of curing the second increment also decreased.

Fig. 6 shows three curing regimes of the LED curing unit, MiniLED: Fast cure 20 seconds, Ramp 20 seconds, and Pulse 20 Pulses (=24 seconds). They were employed to assess the effect of soft-start polymerization on the curing behavior of the silorane-based composite. Power provided for the continuous fast cure regime was 1141 mW/cm^2, whereas the Pulse regime delivered this power by an emission of successive one-second flashes with a rest period of 250 ms between the flashes. Accordingly then, the power densities of these two regimes were identical. In the case of Ramp program, the intensity slowly varied from 0 to 1141 mW/cm^2 in the first 10 seconds and then kept constant at the maximum intensity for an additional 10 seconds. Hence, power density was lower. Nonetheless, despite the slower initiation of cure in the Ramp program at 2-mm depth — which

also led to a slower rise of the degree of conversion in the first 10 seconds, the degree of conversion of the Ramp program approached that of other regimes as light intensity increased. As for the Pulse regime, its degree of conversion development corresponded with that of the Fast cure regime with a continuous light emittance. As such, no statistically significant differences were registered among these three regimes. At 6-mm depth, irradiance of the Ramp regime was too low in the first 10 seconds to act significantly on the polymerization process, such that the Ramp regime did not differ from the 10 second regime of the same curing unit in terms of degree of cure.

After an observation period of 20 minutes, it could be said that with the tested curing units the degree of conversion improved as polymerization duration increased (Pearson, correlation coefficient=0.52). However, no correlation was found between irradiance and degree of cure. Regarding the mechanical properties of the samples after 24-hour storage in water, no significant differences could be noted among the 16 tested curing regimes for both hardness and modulus of elasticity.
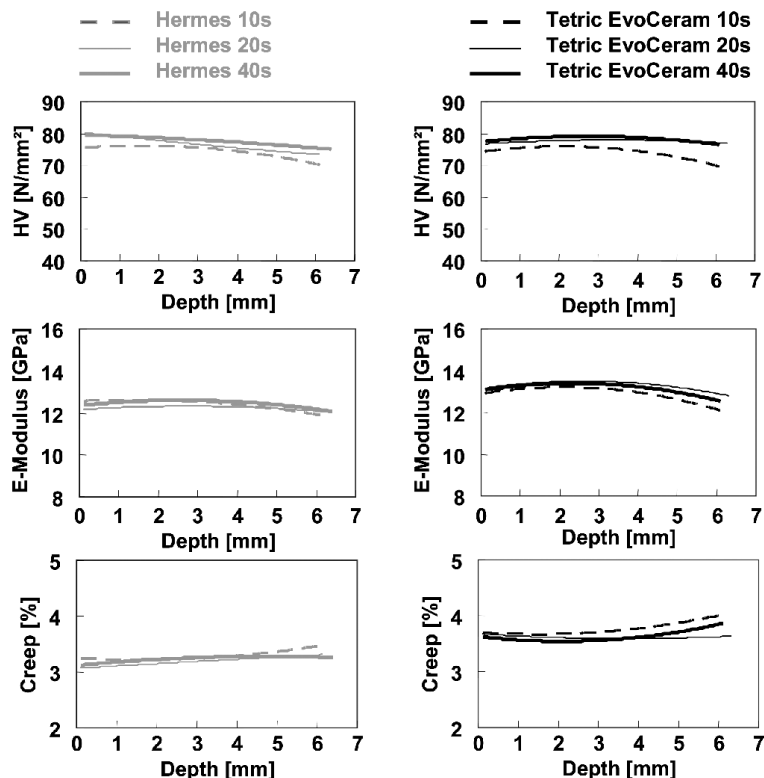
When compared to Tetric EvoCeram, Hermes

Fig. 7 Variation of the mechanical properties (Vickers hardness, modulus of elasticity, and creep) with depth for silorane-based composite, Hermes (left) in comparison to a widely used composite material, Tetric EvoCeram (right) after curing with LED curing unit, Bluephase, for 10 s, 20 s, and 40 s. The 6-mm samples are layered in three increments, each 2-mm thick.

showed no significant differences regarding Vickers hardness. However, modulus of elasticity of the silorane material was slightly lower and the creep resistance higher. Compared with a methacrylate-based nanocomposite, Filtek Supreme, the silorane composite exhibited a clearly lower Vickers hardness when both materials were examined under equivalent curing conditions[16]. However, it must be pointed out that a short polymerization time (10 seconds) was insufficient to cure the nanocomposite in deeper layers. Due to discontinuity between layers in the nanocomposite, hardness varied with depth — thus accounting for a decreased hardness of up to 30%. As for the silorane composite, no differences in degree of cure were noted at 2-mm and 6-mm depths, while Filtek Supreme showed a significantly lower DC at 6-mm depth with the tested curing units[16].

Further, the results of another study[17] offered the opportunity to compare the mechanical properties of the silorane material with other restorative materials polymerized under identical conditions (halogen curing unit Astralis 10, 10 seconds): hybrid composite Z100 (HV=150), hybrid composite Tetric (HV=100), submicron-filled hybrid composite Enamel Plus HFO (HV=100), fine hybrid composite Charisma (HV=90), hybrid composite InTen-S (HV=70), microfilled composite Durafill (HV=45), and micro-hybrid composite with spherical reinforcing fillers Palfique Estelite Low Flow (HV=35). Against these HV results, the silorane composite ranked in the middle amongst these widely used composite restorative materials.

Another important factors that affects the hydrolytic stability between organical matrix and inorganic filler is water sorption. Palin *et al.*[18] showed that the silorane composite exhibited significantly lower water sorption, solubility, and associated diffusion coefficient than the established methacrylate-based dental composites (Z100 and Filtek Z250). In other words, the decreased water sorption, solubility, and associated diffusion coefficient characteristics of silorane may potentially improve the hydrolytic stability of resin-based composite restorations.

CONCLUSIONS

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

• After an observation period of 20 minutes, it was found that the curing time — and not the irradiance — of the tested curing units played a determinant role in reaching a high degree of cure.

• At 6-mm depth, the standard light guide tip is a preferred choice than the turbo tip.

• The mechanical properties tended to decrease with depth, but there were no significant difference in mechanical properties between 2-mm and 6-mm depths within one regime, and likewise none among the different curing regimes.

• The mechanical properties of the silorane-based composite are comparable to clinically successful methacrylate-based composite materials.

REFERENCES

1) Irie M, Suzuki K, Watts DC. Marginal gap formation of light-activated restorative materials: effects of immediate setting shrinkage and bond strength. Dent Mater 2002; 18: 203-210.

2) Loguercio AD, Reis A, Schroeder M, Balducci I, Versluis A, Ballester RY. Polymerization shrinkage: Effects of boundary conditions and filling technique of resin composite restorations. J Dent 2004; 32: 459-470.

3) Sakaguchi RL, Peters MC, Nelson SR, Douglas WH, Poort HW. Effects of polymerization contraction in composite restorations. J Dent 1992; 20: 178-182.

4) Ferracane JL. Current trends in dental composites. Crit Rev Oral Biol Med 1995; 6: 302-318.

5) Braga RR, Ferracane JL. Alternatives in polymerization contraction stress management. Crit Rev Oral Biol Med 2004; 15: 176-184.

6) Rueggeberg FA. From vulcanite to vinyl, a history of resins in restorative dentistry. J Prosthet Dent 2002; 87: 364-379.

7) Eick JD, Robinson SJ, Byerley TJ, Chappelow CC. Adhesives and nonshrinking dental resins of the future. Quintessence Int 1993; 24: 632-640.

8) Eick JD, Byerley TJ, Chappell RP, Chen GR, Bowles CQ, Chappelow CC. Properties of expanding SOC/epoxy copolymers for dental use in dental composites. Dent Mater 1993; 9: 123-127.

9) Tilbrook DA, Clarke RL, Howle NE, Braden M. Photocurable epoxy-polyol matrices for use in dental composites I. Biomaterials 2000; 21: 1743-1753.

10) Eick JD, Kostoryz EL, Rozzi SM, Jacobs DW, Oxman JD, Chappelow CC, *et al. In vitro* biocompatibility of oxirane/polyol dental composites with promising physical properties. Dent Mater 2002; 18: 413-421.

11) Schweikl H, Schmalz G, Weinmann W. Mutagenic activity of structurally related oxiranes and siloranes in Salmonella typhimurium. Mutat Res 2002; 521: 19-27.

12) Weinmann W, Thalacker C, Guggenberger R. Siloranes in dental composites. Dent Mater 2005; 21: 68-74.

13) Schweikl H, Schmalz G, Weinmann W. The induction of gene mutations and micronuclei by oxiranes and siloranes in mammalian cells *in vitro*. J Dent Res 2004; 83: 17-21.

14) Eick JD, Smith RE, Pinzino CS, Kostoryz EL. Stability of silorane dental monomers in aqueous systems. J Dent 2006; 34: 405-410.

15) Hartung M, Wastian C. Effects of different light guides on the depth of cure. J Dent Res 2003; Spec

Iss/Abst 1499(v. 82): 199.

16) Ilie N, Kunzelmann KH, Visvanathan A, Hickel R. Curing behavior of a nanocomposite as a function of polymerization procedure. Dent Mater J 2005; 24: 469-477.

17) Ilie N, Kunzelmann KH, Hickel R. Evaluation of micro-tensile bond strengths of composite materials in comparison to their polymerization shrinkage. Dent Mater 2005; [Epub ahead of print].

18) Palin WM, Fleming GJ, Burke FJ, Marquis PM, Randall RC. The influence of short and medium-term water immersion on the hydrolytic stability of novel low-shrink dental composites. Dent Mater 2005; 21: 852-863.