Keywords: dual-cure composites, polymerization shrinkage, marginal adaptation, bulk-fill, delayed light activation

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Marginal Adaptation of Dual-Cure Composites Using Various Polymerization Modes

Abstract
This in vitro study evaluated the polymerization shrinkage and marginal adaptation of dual-cure resin cements compared with conventional and flowable composite systems. The effects of immediate and delayed light activation were analyzed under standardized deep cavity conditions. Using 3D-printed cavity models, polymerization-induced detachment was quantified via digital and scanning electron microscopy. Delayed light activation of EnaCem HF significantly improved adaptation to cavity floors, comparable to Surefil SDR Flow, whereas immediate activation led to increased shrinkage and gap formation. These findings suggest that controlled delayed activation of dual-cure composites may reduce polymerization stress and enhance clinical performance in deep restorations.

Introduction

Polymerization shrinkage of composite resins and its consequences have been extensively investigated over several decades. [1] Although complete elimination of this phenomenon is not possible, its adverse effects can be minimized through an appropriate combination of cavity design, material selection, and clinical technique. The magnitude of polymerization shrinkage depends on the cavity configuration factor (C-factor) and the volume of the remaining hard tissues.

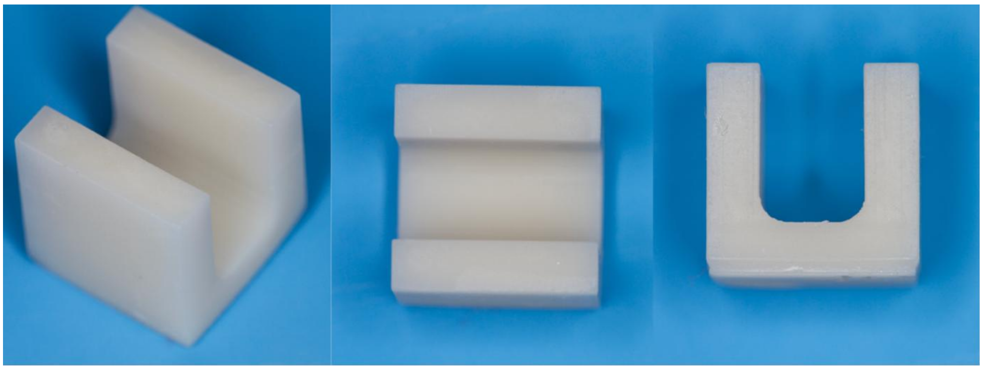
With increasing cavity depth, several clinical challenges arise: reduced light penetration, altered dentin structure, and limited adaptation of the composite to cavity walls. Incremental placement techniques have been developed to reduce internal stresses, but they are time-consuming and error-prone in deep cavities.

Bulk-fill composites enabled more efficient filling of large cavities. Most are light-cured with a maximum reliable increment thickness of 4 mm [2] , but the use of dual-cure materials with delayed light activation offers additional flexibility. [3,4] This approach has been used in our clinical practice since 2007,is particularly beneficial for core buildups and post-endodontic restorations.

The aim of this study was to compare the polymerization behavior and marginal adaptation of various restorative materials and polymerization protocols under extreme conditions of 6-mm-deep Class II cavities. The null hypothesis was that no significant differences would be observed between the tested materials and curing modes.

Materials and Methods

A total of forty-five standardized Class II cavity models were fabricated using 3D printing technology (Straumann CARES P30, Basel, Switzerland) from Sheraprint Model Plus UV resin. Although this material is less stiff than mineralized dentin, it was suitable for comparative evaluation.



Cavity dimensions were measured using a VHX-5000 digital microscope (Keyence, USA). The internal surfaces were sandblasted with 50-µm aluminum oxide and coated with a bonding layer (EnaSeal, Micerium, Italy). External surfaces were covered with Teflon tape to standardize the restoration procedure.

Tested materials:

- ECD: EnaCem HF (Micerium, Italy), delayed light polymerization (6 min chemical + 40 s light + 60 s glycerin-cured)
- ECL: EnaCem HF, immediate light polymerization
- ENH: Enamel HRi UD (Micerium)
.
- SDR: Surefil SDR Flow (Dentsply Sirona, Germany)

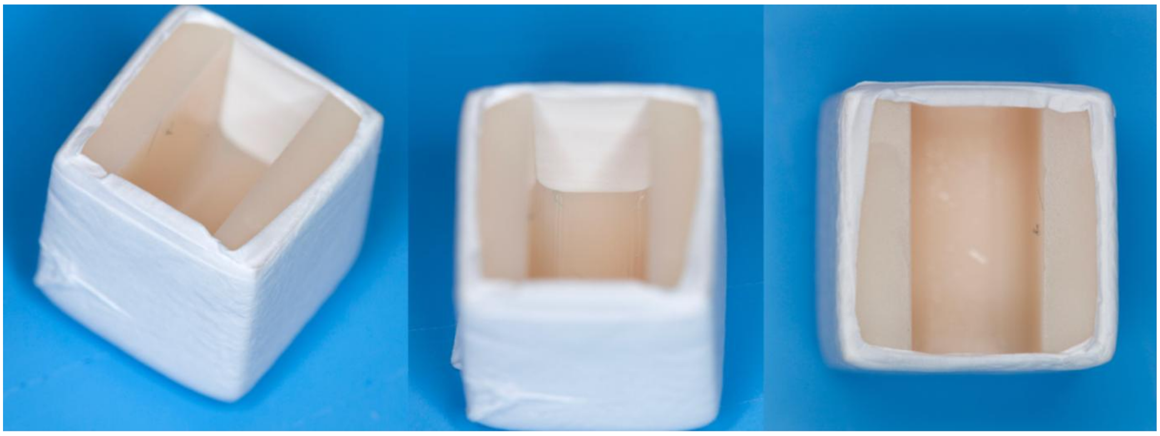
Polymerization was performed using an LED curing unit (Elipar, 3M, USA) at 1200 mW/cm². After curing, samples were stored in distilled water at 37 °C for 24 hours and examined using digital and scanning electron microscopy (VEGA3, Tescan, Brno, Czech Republic).

Measured parameters:

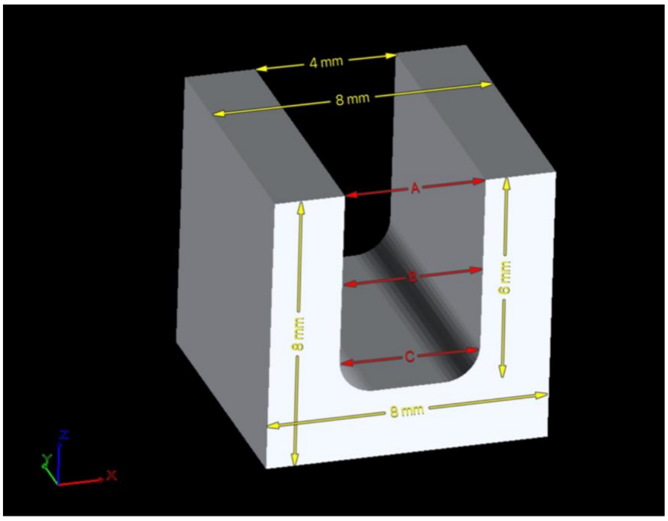
- Cavity width before filling (A, B, C)
- Gap width after polymerization (D)

Statistical analyses were performed using SPSS 23.0 (IBM, USA) with Kruskal–Wallis and Mann–Whitney U-tests (Bonferroni correction, $\alpha = 0.05$)

Manufacturer's Name	Characteristics	Coverage with an additional layer	Composition (according to the manufacturer's data)	Filler content (vol.%/wt.%)
Surefil SDR flow Densply, Konstanz, Germany	Light-curing composite ‘‘flowable bulk fill‘‘	Necessary	Modified UDMA, EBPADMA, TEG-DMA, BA-Al-F-Si glass, SR-Al-F-SI glass, Kafrchinon, accelerator, BHT, UV stabilizer	45/68
EnaCem HF Micerium, Avegno, Italy	Dual-cure cement	Necessary	UDMA, BDMA, Glass, dispersible SiO_2	72/77
Enamel HRi Micerium, Avegno, Italy	Light-curing fill composite	Not necessary	UDMA, Bis-GMA,BDMA, Glass, nano particles of ZrO_2	63/80
EnaSeal Micerium, Avegno, Italy	Light-curing low-viscosity resin / sealant	N/A	UDMA, BDMA	-/-



Printing Resin: Sheraprint Model Plus UV	
Viscosity at 23 °C	0.96 Pa s
Flexural Strength	75 MPa
Elastic Modulus	1,65 – 1,75 GPa
Hardness Shore HSD	71 -84

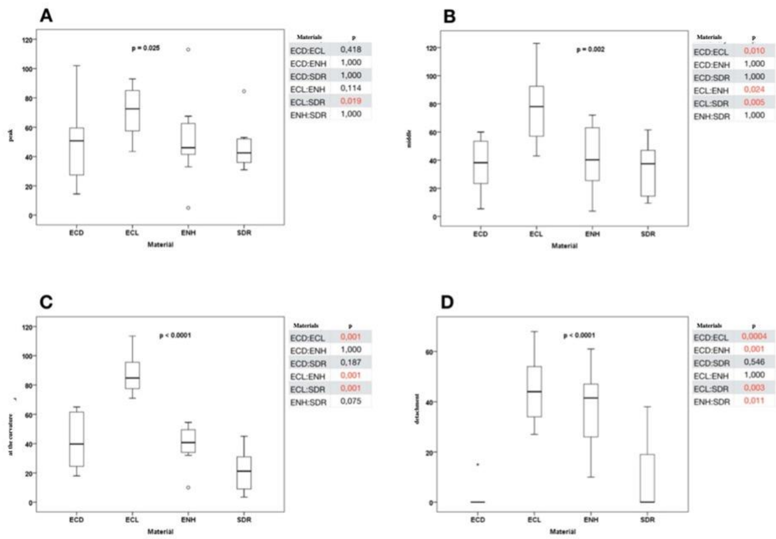


Results

Significant differences were observed between materials and curing protocols ($p < 0.05$). Surefil SDR Flow exhibited the lowest shrinkage values, while EnaCem HF with delayed light activation showed the best adaptation to cavity floors. Immediate polymerization of EnaCem HF resulted in the highest detachment levels.

Graphical analysis (box plots) confirmed these trends. The null hypothesis was therefore rejected.

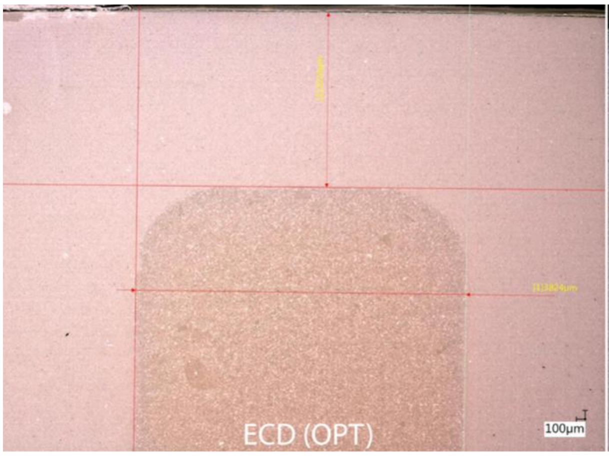
	ECD [µm] (n=10)					ECL [µm] (n=10)					ENH [µm] (n=10)					SDR [µm] (n=10)					p[a]
	Med.	Min	Max	Mean	SD	Med.	Min	Max	Mean	SD	Med.	Min	Max	Mean	SD	Med.	Min	Max	Mean	SD	
ΔA	50,8	14,5	102,0	51,5	28,2	72,5	43,5	93,0	71,2	16,1	46,0	5,0	113,0	51,1	27,8	42,5	31,0	84,5	46,1	15,5	0,025
ΔB	38,3	5,5	60,0	36,9	18,8	78,0	43,0	123,0	77,7	24,4	40,3	3,8	72,0	39,7	22,9	37,5	9,5	61,5	33,2	18,3	0,002
ΔC	39,8	18,0	65,0	41,7	17,3	84,8	71,0	113,5	87,1	13,1	40,8	10,0	54,5	39,5	12,8	21,3	3,5	45,0	22,6	14,5	<0,0001
D	0,0	0,0	15,0	1,5	4,7	44,0	27,0	68,0	44,4	12,5	41,5	10,0	61,0	37,9	15,0	0,0	0,0	38,0	10,6	14,7	<0,0001

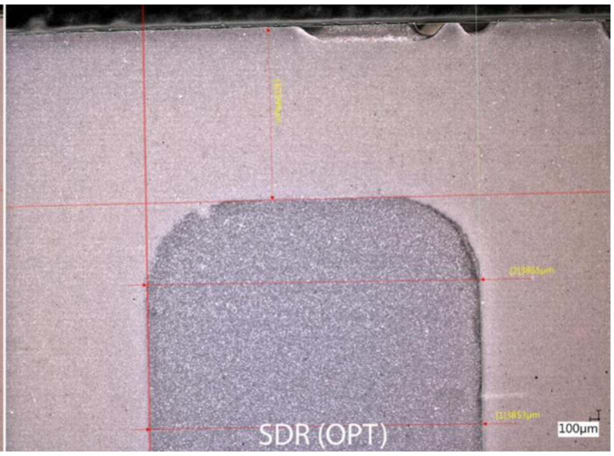


Discussion

There is limited literature on EnaCem HF. In this study, it was compared with Surefil SDR Flow, a well-established bulk-fill composite. The use of 3D-printed models provided standardized conditions while maintaining clinically relevant geometry for post-endodontic cavities. Adhesion to sandblasted surfaces was sufficient, with no adhesive failures recorded.

Consistent with previous studies [3], SDR demonstrated favorable shrinkage performance despite its lower filler content. EnaCem HF with delayed curing achieved comparable adaptation, while immediate curing induced greater shrinkage stress and detachment. The findings confirm the importance of controlled polymerization kinetics to minimize internal stress and improve marginal integrity. Future studies should evaluate the effects of ambient light during chemical curing and evaluate the long-term behavior of these materials under cyclic loading.





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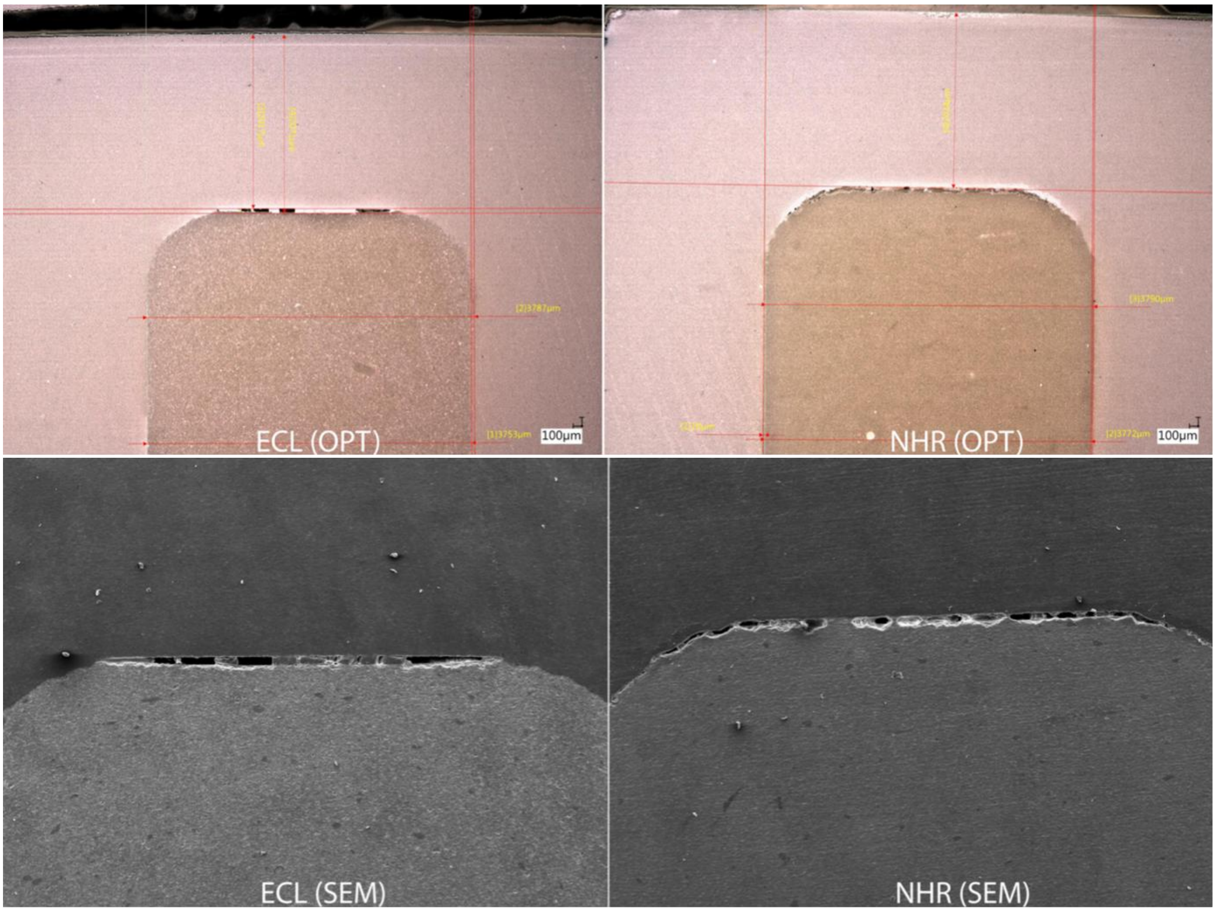

Conclusion

Within the limitations of this in vitro study:

- Surefil SDR Flow exhibited the lowest polymerization shrinkage.
- EnaCem HF with delayed light activation showed superior marginal adaptation.
- Immediate light activation of dual-cure composites significantly increased gap formation.

These findings suggest that delayed light activation protocols may reduce polymerization stress and improve restoration longevity.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: D. Č.; Methodology: R.A., D.Černý; Data Analysis: R.A.; Supervision: L. Černá, Writing – Original Draft: R.A.; Review & Editing: D.Černý,