J Dent Mater Tech 2024; 13 (3): 142-152
https://10.22038/jdmt.2024.79000.1612

J Dent Mater Tech

Original Article

Open Access

The impact of aging and storage conditions on the performance of universal adhesives: A systematic review

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Abstract

Objective: This systematic review evaluated how different storage times and conditions affect universal adhesives' bond strength and degree of conversion (DC).

Methods*:* A literature search was conducted in PubMed, Scopus, Web of Science, and Google Scholar databases for articles published from January 1st, 2000, until May 15th, 2022. The researchers comprehensively evaluated the articles using a multi-step process to identify articles relevant to the topic of interest. Quality assessment was performed through the ROBDEMAT tool. Due to the high heterogeneity in the preliminary data, performing a meta-analysis was not feasible.

Results: A total of 3169 records were obtained, and after removing duplicates, 2267 remained. Following title and abstract screening, 2253 studies were excluded based on the predetermined exclusion criteria. Of the 14 remaining studies, seven were further excluded due to the use of non-universal adhesives, experimental adhesives, or lack of aging protocols. Ultimately, seven studies were included in this systematic review. All studies focused on bond strength, with only one addressing DC. The Findings showed that aging or different storage conditions generally led to reduced bond strength and DC values in universal adhesives, although exceptions with stable or improved properties were noted.

Conclusions: Adhesives with higher pH and those containing methacrylamides, HEMA-free compositions, or hydrolytically stable monomers showed better durability than others. Strict adherence to storage instructions, lower storage temperatures, and immediate recapping of adhesive bottles after use is recommended to maintain adhesive properties. These findings provide insights for optimizing the long-term performance of universal adhesives in clinical settings.

Keywords: Bond strength, Dental adhesives, Dentin bonding agents, Dental bonding, Polymerization, Universal adhesives

Introduction

The ultimate goal of adhesive dentistry is to provide a quick and easy adhesive application with reliable bonding to enamel and dentin (1, 2). Adhesive agents are categorized into different generations based on the order in which they were developed by manufacturers. Each new generation aims to simplify the bonding process, provide faster application, and offer improved chemistry for more stable bonds (3).

In the early 1990s, three-step etch-and-rinse (E&R) bonding agents, also known as the fourth generation of adhesives, were created. The fifth generation is a simplified E&R adhesive system, and the application process involves acid etching of the tooth surface and the simultaneous application of a primer and an adhesive. Nevertheless, there are certain drawbacks to these adhesive systems, including the long chairside

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Accepted: 20 June 2024. Submitted: 29 March 2024.

period and complicated application procedure, which might cause issues with tooth isolation, particularly in posterior teeth. Due to these difficulties, studies have indicated the need for developing adhesive systems with a more straightforward application process and satisfactory bonding properties (4-6).

The "self-etching primers," or the sixth-generation bonding technology, were first introduced in the late 1990s and early 2000s and represent a significant advancement in adhesive dentistry. This generation of adhesives consists of two-step systems with one bottle for the adhesive and another for the acidic primer. Despite satisfactory results, these adhesives have drawbacks, including needing multiple stages and a time-consuming bonding procedure.

Seven-generation SE adhesives provide all the ingredients in a single bottle. Although they are simple to use, their clinical efficacy has been questioned in the literature (4).

In line with the seventh generation, the latest bonding agents are universal adhesives or multimode adhesives, which can be employed in E&R or SE modes or both modes in the selective enamel etching approach (7, 8). The term "universal" refers to the versatile application of these materials, enabling their use in both E&R and SE bonding modes. Additionally, they can bond to self-cure, light-cure, and dual-cure methacrylate-based materials, cement, or sealers and are compatible with various substrates, including dentin, enamel, and glass ionomers (9). They were developed based on the same "all-in-one" concept as the one-step self-etch adhesives (SEA) already on the market.

Universal adhesives offer adaptability with indirect restorative substrates such as metals, alumina, zirconia, and other ceramics. For example, they can bond to glass-rich ceramics via silane and glass-poor zirconia ceramics via 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) monomer (9-11). The inclusion of monomers like 10-MDP in universal adhesives is crucial as it enables adequate bonding to dentin and enamel in various etching modes while also contributing to improved bonding durability through the formation of acid-resistant MDP-calcium salts and stable binding interactions with collagen (12).

A variety of factors influence the effectiveness of adhesive systems. The bonding performance of the materials may be affected by material-related factors, storage time, and storage conditions. The expiration date determined by the manufacturers is typically around two years. This period is before the adhesive system exhibits unfavorable physicochemical properties that prevent its intended use. Studies have shown that bonding performance can be negatively influenced three months after the determined expiration date (7). Manufacturers advise utilizing adhesive systems before expiration and storing them at a relatively low temperature. However, the impact of storage conditions on universal adhesives has yet to be thoroughly investigated (13).

There is inconsistent evidence regarding how the shelf-life and storage circumstances of universal adhesives can alter their bonding efficiency and other features. Previous studies have compared the effectiveness of universal adhesives to other adhesive systems on various surfaces (1, 14) or assessed the characteristics of universal adhesives at different storage times after bonding to the specimens (15-17). However, to the best of the authors' knowledge, there is a lack of systematic research explicitly focusing on the storage conditions of universal adhesives before their involvement in the bonding process. This study aimed to conduct a systematic literature review to determine how universal adhesives' storage time and storage conditions impact their performance in terms of the bond strength to different substrates and the degree of conversion (DC).

Materials and methods

This systematic review followed the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analyses) guidelines (18). The research question addressed whether the storage time and storage conditions would affect universal adhesives' bond strength and degree of conversion (DC).

The eligibility criteria for the study were based on the PICOS (population, intervention, comparison, outcome, and study design) and defined as follows:

P: Studies assessing universal adhesives

I: Applying different storage times and conditions for universal adhesives before curing

C: Comparison of bonding performance of universal adhesives after different shelf-life simulations with new/as-received ones

O: Bond strength and DC of universal adhesives

S: In vitro studies

The exclusion criteria were studies involving non-universal adhesives, case reports, case series, review articles, and clinical trials. Additionally, studies on dental universal adhesives that did not include an aging or storage process were excluded.

Search strategy

A systematic search strategy was designed based on the keywords related to the topic of the study. The literature search was conducted from January 1st, 2000, to May 15th, 2022, in PubMed, Scopus, Web of Science, and Google Scholar databases. The systematic search strategy for each database is presented in Table 1. The search results were imported into Microsoft Excel (version 2016; Microsoft Corporation, Redmond, Washington, United States) to remove duplicates and manage the references.

Study selection and data extraction

The selection of eligible studies included two separate stages. Two independent researchers (MG and SM) initially screened the titles and abstracts of the retrieved studies. In the next stage, the same researchers comprehensively evaluated the remaining studies to identify the articles relevant to the study PICOS. Discussions and consensus with a third researcher (MGL) resolved all disagreements regarding the included studies.

Data extraction was performed using a standardized form within the Microsoft Office Excel 2021 software, consisting of all of the studies' detailed information: authors and publication date, storage time and conditions, the utilized analysis, the self-etch adhesive used, the type of substrate, and obtained results. DC and bond strength (micro-tensile bond strength, micro-shear bond strength, or shear bond strength) of universal adhesives were also extracted from the studies.

Quality Assessment

The methodology of the included studies was evaluated according to previous systematic reviews, and their risk of bias was estimated using the ROBDEMAT tool. ROBDEMAT is a risk-of-bias tool for pre-clinical research on dental materials. It evaluates the following parameters: description of sample randomization, sample size calculation, sample preparation by the same operator, material usage according to information supplied by the manufacturer, presence of a positive or negative control group, appropriate statistical analysis, and correct outcome measurement and reporting (19-21).

The ROBDEMAT tool comprises four domains of bias: bias related to planning and allocation (D1), specimen preparation (D2), outcome assessment (D3), and data treatment and outcome reporting (D4). If the authors provided the parameter, the article was marked with a "Yes" for that specific parameter. If the information was

Table 1. The databases and search strategy applied in this study

Database	Search strategy
PubMed	("universal adhesive" OR "multimode adhesive" OR "G bond plus" OR "all-bond universal" OR "one-step universal dental adhesive" OR "one-step plus universal" OR "G-Primio bond" OR "peak universal bond" OR "clearfil universal bond" OR "ibond self-etch" OR "futura bond u" OR "opti bond xtr" OR "opti bond universal" OR "prelude one" OR "prime and bond elect" OR "one coat 7 universal" OR "universal bond" OR "universal bonding agent" OR "multimode bond") AND ("product storage" OR "expiry date" OR "expiration date" OR "shelf life" OR "storage conditions" OR "storage time")
Scopus	(TITLE-ABS-KEY ("universal adhesive" OR "multimode adhesive" OR "G bond plus" OR "all-bond universal" OR "one-step universal dental adhesive" OR "one-step plus universal" OR "G-Primio bond" OR "peak universal bond" OR "clearfil universal bond" OR "ibond self-etch" OR "futura bond u" OR "opti bond xtr" OR "opti bond universal" OR "prelude one" OR "prime and bond elect" OR "one coat 7 universal" OR "universal bond" OR "universal bonding agent" OR "multimode bond") AND TITLE-ABS-KEY ("product storage" OR "expiry date" OR "expiration date" OR "shelf life" OR "storage conditions" OR "storage time"))
Web of science	TS = ("universal adhesive" OR "multimode adhesive" OR "G bond plus" OR "all-bond universal" OR "one-step universal dental adhesive" OR "one-step plus universal" OR "G-Primio bond" OR "peak universal bond" OR "clearfil universal bond" OR "ibond self-etch" OR "futura bond u" OR "opti bond xtr" OR "opti bond universal" OR "prelude one" OR "prime and bond elect" OR "one coat 7 universal" OR "universal bond" OR "universal bonding agent" OR "multimode bond") AND TS = ("product storage" OR "expiry date" OR "expiration date" OR "shelf life" OR "storage conditions" OR "storage time")
Google Scholar	"universal adhesive" + "multimode adhesive" + "G bond plus" + "all-bond universal" + "one-step universal dental adhesive" + "one-step plus universal" + "G-Primio bond" + "peak universal bond" + "clearfil universal bond" + "ibond self-etch" + "futura bond u" + "opti bond xtr" + "opti bond universal" + "prelude one" + "prime and bond elect" + "one coat 7 universal" + "universal bond" + "universal bonding agent" + "multi-mode bond" + "product storage" + "expiry date" + "expiration date" + "shelf life" + "storage conditions" + "storage time"

unavailable, the article was marked with a "No." Articles that received one to three "Yes" answers (five to seven No answers) were considered to have a high risk of bias, four or five as a medium risk, and six to eight as a low risk of bias (22).

Results

Study Selection

A total of 3169 records were initially obtained from all the mentioned databases, and after duplication removal, 2267 records remained. After an initial review of the records through their titles and abstracts, 2253 studies were excluded. Of the remaining 14 studies, 7 were excluded for the following reasons: One article used an experimental adhesive incompatible with different etching strategies and substrates (23). Another study contained an SE primer, and after applying the primer to dentin, the universal adhesive (Clearfil SE Bond) was used (24). Three studies did not use universal adhesives (25-27). In another study, the aging process was conducted after the bonding procedure (28), and another was a literature review (29). Seven studies met all selection criteria and were included in this systematic review (7, 13, 30-34). Figure 1 demonstrates the article selection strategy based on the PRISMA statement.

All studies that met the criteria had dentin substrates with a SE mode. Bond strength and DC values were assessed at various intervals: baseline, one month after aging, and after prolonged aging. The findings from the seven final studies are summarized in Tables 2- 4. Due to high heterogeneity in the preliminary data, performing a meta-analysis was not feasible.

Study Characteristics

Tables 2-4 present the data extracted from the selected studies. In most studies, aging resulted in decreased bond strength. OptiBond®, One Coat, and Single Bond Universal in the study conducted by Cuevas-Suárez et al. (31), iBond Universal in the study conducted by Mazzitelli et al. (7), Scotchbond Universal

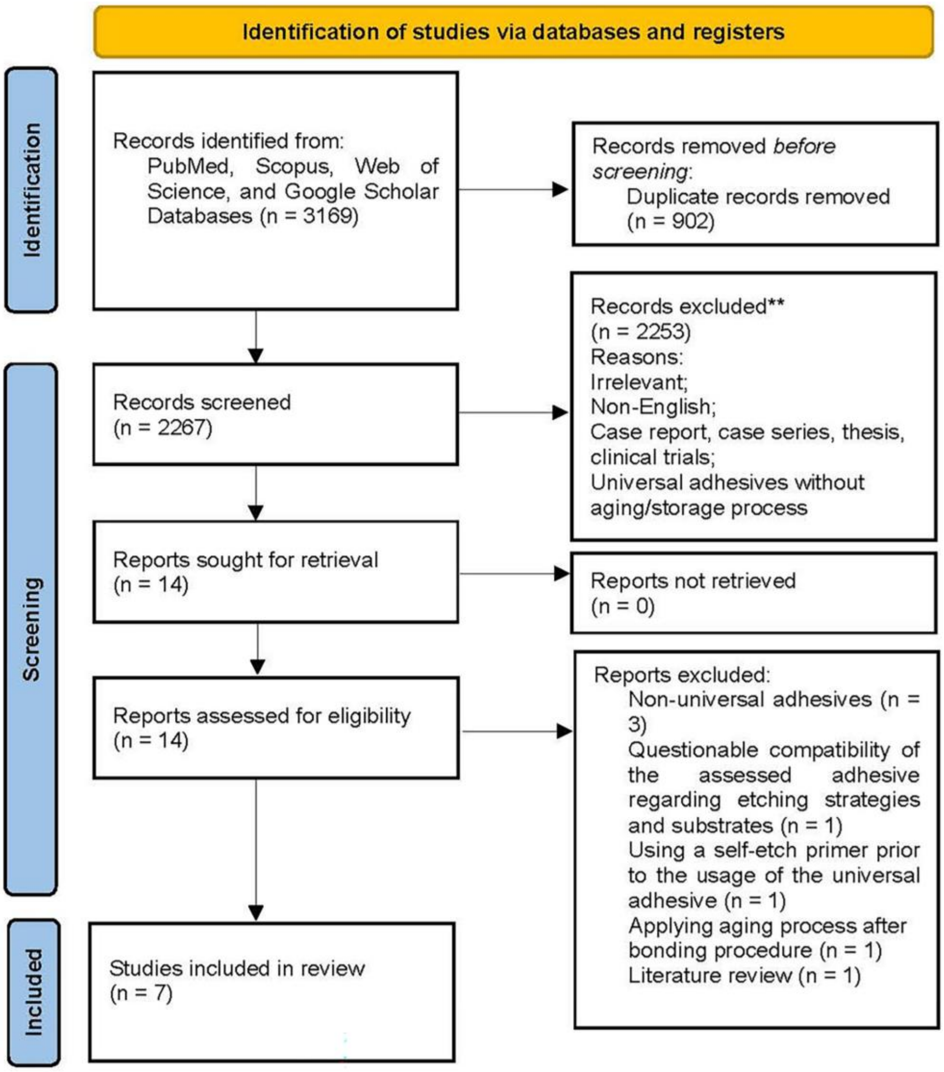

Figure 1. Flow diagram of the study process according to the PRISMA statement

Table 2. Characteristics of the included studies

Author, Year	Aging/Storage	Analysis	Self-etch adhesives	Substrate	Results
Mazzitelli et al. , 2020	Shelf-life (as-received vs expired)	µTBS, Nanoleakage, endogenous enzymatic activity	iBond Universal Adhesive (Heraeus Kulzer GmbH, Hanau, Germany)	Extracted sound human third molars (dentin)	The consequences of using the universal adhesive system after its expiration date were reduced bonding performance and increased endogenous enzymatic activity.
Cuevas-Suárez et al. , 2019	Materials storage in an acclimatization chamber for different periods	µTBS, Degree of conversion (by FTIR), Nanoleakage, SEM	Universal adhesives: Single Bond Universal (3M ESPE, St.Paul, MN, USA Tetric N-BondUniversal (Ivoclar Vivadent, Schaan, Liechtenstein) OneCoat 7 Universal (Coltene/Whaledent Inc., Cuyahoga Falls, OH, USA) OptiBond Universal (Kerr, Orange, CA, USA) Prime&Bond Elect (Dentsply Caulk, Milford, DE, USA) Two-step self-etch adhesives: Clearfil SE (Kuraray Noritake Dental Inc. AdheSE (Ivoclar Vivadent, Schaan, Liechtenstein)	Extracted bovine incisors (dentin)	the µTBS to dentin in Single Bond Universal, OneCoat Universal, OptiBond Universal, and Clearfil SE reduced considerably during the shelf-life evaluations. the µTBS to dentin in Tetric Bond Universal, Prime&Bond Elect, AdheSE, and Adper Singlebond 2 systems remained stable. DC reduced dramatically except for Prime&Bond, AdheSE, and OptiBond Universal.
Cardoso et al. , 2014	Shelf-life simulation (materials storage in an acclimate chamber at 40C and 50% relative humidity	µTBS, SEM	AdheSE (Ivoclar Vivadent, Barueri,SP, Brazil) Single Bond Universal (3 M ESPE, St.Paul, MN, USA) Clearfil SE Bond (Kuraray, Tokyo, Japan)	Extracted, sound human molars (dentin)	The shelf-life simulation had a detrimental effect on the bonding performance of all three adhesive systems under investigation. However, for Single Bond Universal, the bond strength was increased in some conditions.
Pongprueksa et al. , 2014	Weight-loss technique by leaving adhesive bottle open	µTBS, Degree of conversion (by FTIR)	Scotchbond Universal (3M ESPE, Seefeld, Germany)	Glass, Glass 37˚C, Human third molar (dentin - 4˚C), Human third molar (dentin - 37˚C), Human third molar (Dehydrated dentin), Dentin powder	100% solvent-containing adhesive (SBU100) had a higher DC than the 50% (SBU50) and 0% (SBU0) solvent-containing adhesives. Although SBU0 had a substantially higher µTBS than SBU50 and SBU100, its bonding strength to dentin was much lower.
Shibuya-Chiba et al. , 2010	Materials storage at 5˚C, 23˚C or 40˚C for 0, 1, 2, 3, 4, 5, and 6 months	SBS SEM	Absolute 2 (Dentsply Sankin KK, Tokyo, Japan) Adper Prompt L-Pop (3M ESPE, St Paul, MN, USA) Bond Force (Tokuyama Dental Corp, Tokyo, Japan) Clearfil tri-S Bond (CT, Kuraray Medical Inc, Tokyo, Japan) G-Bond (GB, GC Corp, Tokyo, Japan)	Extracted bovine mandibular incisors (dentin)	Significant decreases in bond strength were found for all the adhesives with more extended storage periods and higher temperatures.
Ma et al. , 2009	Materials storage at 8˚C, 20˚C or 40˚C for 1, 3, 7 and 14 weeks	SBS, C NMR for evaluation of the ratio of the hydrolyzed HEMA	Clearfil Tri-S Bond (Kuraray Medical Inc, Osaka, Japan) Clearfil Mega Bond Primer (Kuraray Medical Inc, Osaka, Japan)	Extracted bovine incisors (dentin)	Storage temperature and time significantly affect the alteration rate and stage of Clearfil Tri-S Bond (TSB) and Clearfil Mega Bond Primer (MBP). However, TSB and MBP exhibit expectant bond strength and durability when stored below 20˚C.
Sadr et al. , 2007	Materials storage at 4˚C, 23˚C or 27˚C for 1, 4, 16 and 60 weeks	µSBS Nanoindentation hardness of the polymerized bonding pH	Clearfil SE Bond (Kuraray Medical, Osaka, Japan) Clearfil Tri-S Bond (Kuraray Medical, Osaka, Japan)	Human upper premolars (enamel and dentin)	The bond strength of self-etching agents was severely impacted by storage time and temperature due to time-dependent hydrolysis and other alterations anticipated to occur in the water-containing self-etching agents at high temperatures.

Micro-tensile bond strength (µTBS), Micro-shear bond strength (µSBS), Shear bond strength (SBS), FTIR (Fourier Transform Infrared Spectroscopy), SEM (Scanning Electron Microscopy), C NMR (Carbon-13 nuclear magnetic resonance), DC (Degree of conversion)

Bond in the studies by Ma et al.(32), Sard et al.(34), and Shibuya-Chiba et al. (13) experienced a significant decrease in bond strength. However, Tetric® Bond and P&B Elect® in the study of Cuevas-Suárez et al. (31) did not experience a significant decline in bond strength values and remained relatively stable. Surprisingly, Cardoso et al. (30) and Cuevas-Suárez et al. (31) reported that Single Bond Universal showed increased bond strength values after being subjected to shelf-life simulation (Table 3).

Only one of the studies (31) evaluated the DC of universal adhesives. Except for P&B Elect® and OptiBond®, the DC of other universal adhesives significantly decreased after the shelf-life simulation using an acclimatization chamber (Table 4). The composition of different evaluated adhesives is described in Table 5.

Quality assessment

This systematic review included seven papers on bond strength data and one on DC. Four of the seven studies demonstrated a medium risk of bias, and three showed a low risk. The results of the quality assessment of the included studies are described in Table 6.

Discussion

The purpose of this systematic review was to critically evaluate the impact of storage time and conditions on the bonding performance and degree of conversion (DC) of universal adhesives. A total of seven studies were

Table 3. Dentin bond strength of universal adhesives in self-etch mode over time, following various aging and storage procedures.

Author, Year	universal adhesives	Aging/Storage	Analysis	Bond strength values (MPa)					
				baseline	SD	One month or middle temperature	SD	Higher aging	SD
Mazzitelli et al. , 2020	iBond Universal Adhesive (Heraeus Kulzer GmbH, Hanau, Germany)	as-received and three months after expiration in a ventilated room and the temperature of below 19 ˚C	µTBS	40.8	10.4			13.4	6.8
Cuevas-Suárez et al. , 2019	Single Bond Universal (3M ESPE, St.Paul, MN, USA)	as-received and after 4 and 9 weeks of storage in a climate chamber (half-life, end of shelf-life) at 40 °C and 50% relative humidity	µTBS	36.48	9.61	35.01	5.3	25.9	5.82
	Tetric® Bond (Ivoclar Vivadent, Schaan, Liechtenstein)			30.35	8.58	28.78	7.23	26.67	6.25
	One Coat (Coltène/Whaledent Inc., Cuyahoga Falls, OH, USA)			16.62	3.18	14.35	6.12	7.73	4.72
	OptiBond® (Kerr, Orange, CA, USA)			31.39	3.81	19.86	7.23	18.59	4.4
	P&B Elect® (Dentsply Caulk, Milford, DE, USA)			14.36	5.46	17.06	1.85	12.97	7.89
Cardoso et al. , 2014	Single Bond Universal (3M ESPE)	storage in a climate chamber at 40˚C and 50% relative humidity for different periods (4, 8, and 12 weeks)	µTBS	49.1	5.5			83	11.5
Pongprueksa et al. , 2014	Scotchbond Universal (SBU, 3M ESPE, Seefeld, Germany)	Weight-loss technique by leaving adhesive bottle open at 20 °C for more than 14 days	µTBS	42.1	3.3				
Shibuya-Chiba et al. , 2010	Clearfil tri-S Bond (CT, Kuraray Medical Inc, Tokyo, Japan)	Baseline and storage at 40˚C for 1 and 6 months	SBS	19.7	2	12.6	2.5	7.7	1.9
Ma et al. , 2009	Clearfil Tri-S Bond (TSB, Kuraray Medical Inc, Osaka, Japan)	Baseline and storage at 40˚C for 14 weeks	SBS	16.4	2.6			13.6	2.1
Sadr et al. , 2007	Clearfil Tri-S Bond (Kuraray Medical, Osaka, Japan)	Baseline and storage at 37˚C for 4 and 60 weeks	µSBS	36.3	5.5	33.9	4.8	17.3	4.6

Table 4. Degree of conversion of the universal adhesives

Author, Year	universal adhesives	Aging/Storage	Degree of Conversion					
			Baseline	SD	One month or middle temperature	SD	Higher aging	SD
Cuevas-Suárez et al. , 2019	Single Bond Universal	as-received and storage in a climate chamber (half-life, end of shelf-life)	88.29	0.08	83.92	0.34	64.04	1.21
	Tetric® Bond		87.10	1.70	74.29	1.43	76.45	3.05
	One Coat		92.41	0.16	73.83	2.57	65.41	1.39
	OptiBond®		74.89	0.95	79.82	0.71	82.36	1.56
	P&B Elect®		88.39	1.4	81.88	6.37	88.63	3.35

included in the review. The findings of this systematic review showed that aging or different storage conditions generally led to reduced bond strength and DC values. However, exceptions with stable or improved properties were also noted. Therefore, universal adhesives may experience decreased bond strength and DC over time due to storage conditions.

All the universal adhesive systems selected in this study were versatile enough to be used in E&R and SE modes; the differences in their compositions might be the reason for their different performances in bond strength values. These differences may also be attributed to the various aging methods used in the studies, such as storage in an acclimatization chamber, solvent evaporation, and exposure to a relative humidity of 50%.

In the present study, the dentin bond strengths of some single-step SEAs reduced when their storage temperatures were raised to 40°C and their storage times were extended (13, 30-32). This decrease in dentine bond strength values can be attributed to the etching effect of SEAs, which tends to weaken the bond strength over time. This process is accelerated by greater temperatures (9, 13). Interestingly, even after shelf-life simulation at a high temperature in an acclimatization chamber, Tetric N-Bond Universal (TBU) and Prime&Bond Elect (P&B) universal adhesives retained their bond strength values. This can be explained by the fact that the P&B universal adhesive contains a dipentaerythritol penta-acrylate phosphate monomer (PENTA), which is thought to be more resistant to hydrolytic breakdown than 10-MDP because it includes five vinyl groups in its chemical structure. Consequently, in the event of hydrolysis, if a vinyl group is detached from the main structure of the monomer, four vinyl groups are still accessible to retain the link to the phosphate group, allowing copolymerization with other monomers and simultaneously facilitating adhesion to the tooth structure (2,35).

Higher pH levels have been shown to improve the stability of adhesives (35). Using SE adhesives with a relatively higher pH may result in materials with good shelf-life stability because the hydrolysis of ester linkages decreases in less acidic environments (36). Given that the TBU universal adhesive has a relatively high pH of approximately 3, the methacrylated phosphoric acid ester in this material degrades more

Table 5. Composition of Universal adhesives

Universal adhesives	Composition
Single Bond Universal	HEMA, Bisphenol A Diglycidyl Ether Dimethacrylate, Decamethylene dimethacrylate, ethanol, Silane treated silica, water, 2-propenoic acid, 2-Methyl-, reaction products with 1,10-decanediol and phosphorous oxide, copolymer of acrylic and itaconic acid, dimethylamino ethyl methacrylate, CQ, dimethylaminobenzoate, 2,6-di-tert-butyl-P-cresol.
Tetric® N-Bond Universal	2-hydroxyethyl methacrylate, Bisphenol A Diglycidyl Ether Dimethacrylate, ethanol, 1,10-decandiol dimethacrylate, Methacrylated phosphoric acid ester, CQ, 2-dimethylaminoethyl methacrylate.
OneCoat 7 Universal	Ethanol, urethane dimethacrylate, 2-hydroxyethyl methacrylate.
OptiBond® Universal	Acetone, HEMA, glycerol dimethacrylate, ethanol, glycerol phosphate dimethacrylate.
P&B Elect®	Acetone, Urethane Dimethacrylate Resin, Dipentaerythritol pentaacrylate phosphate, Polymerizable dimethacrylate resin, Polymerizable trimethacrylate resin.
iBond Universal	MDP, 4-META, methacrylates, acetone, water.
Scotchbond Universal	10-MDP phosphate monomer, Vitrebond copolymer, HEMA, BISGMA, dimethacrylate resins filler, silane, initiators, ethanol, water
Clearfil Tri-S Bond	Water, MDP, bis-GMA, HEMA, hydrophobic DMA, CQ, ethyl alcohol, silanated colloidal silica

bis-GMA: bis-phenol A diglycidylmethacrylate; HEMA: 2-hydroxyethyl methacrylate; MDP: 10-methacryloyloxydecyl dihydrogen phosphate; DMA: dimethacrylate; CQ: camphorquinone; 4-META: 4-methacryloyloxyethyl trimellitic acid.

Table 6. Quality assessment and risk of bias according to ROBDEMAT tool

Study	Mazzitelli et al.	Cuevas-Suárez et al.	Cardoso et al.	Pongprueksa et al.	Shibuya-Chiba et al.	Ma et al.	Sadr et al.
Randomization of samples	No	Yes	No	No	No	No	Yes
Sample size calculation	No	No	No	No	No	No	No
Sample preparation by the same operator	No	No	Yes	No	No	No	Yes
Materials used according to information supplied by the manufacturer	Yes	Yes	Yes	Yes	Yes	No	Yes
Presence of a positive or negative control group	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Appropriate statistical analysis	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Correct outcome measurement	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reporting outcomes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Risk of bias	Medium	Low	Low	Medium	Medium	Medium	Low

slowly compared to other compounds. Cardoso et al. (30) found that the bond strength values in Single Bond Universal (SBU) increased after being subjected to a climate chamber at 40°C and 50% relative humidity. In contrast, the findings reported by Cuevas-Suárez et al. (31) showed a significant decrease in the bond strength values after evaluation in the half-life condition using the same aging protocols. According to Cardoso et al. (30), the increased bond strength after shelf-life simulation was related to the Vitrebond copolymer in the composition of SBU, which aids in increasing stability against moisture. The chemical interaction of Vitrebond with hydroxyapatite can relieve stress at the adhesive interface. In addition, including a polyalkenoic acid copolymer in Vitrebond is considered a possible explanation for the extended durability, low nanoleakage rate and enhanced bond strength of this adhesive (2).

There are multiple theories regarding the function of 2-hydroxyethyl methacrylate (HEMA) in SE adhesives. HEMA is still included in many commercial adhesives, as evidenced in Table 5. It acts as a co-solvent with other monomers to prevent phase separation between water and the monomer (9). For the acidic monomer to penetrate the hydrophilic dentin, single-step SE adhesives must contain water and water-soluble hydrophilic monomers, such as HEMA. It is important to note that water is a crucial component of adhesives because it produces the hydrogen ions necessary for efficient demineralization and dissolution of tooth substrate. The mineral component of the tooth substrate interacts with the hydrogen protons in acidic monomer solutions (13).

It has also been reported that the wettability of the dentin substrate is increased when 10-MDP is combined with HEMA, resulting in a more significant interaction between the adhesive and hydroxyapatite (30). However, Van Meerbeek et al. (37) showed that the presence of HEMA inhibited the 10-MDP monomer's ability to form nanolayering, which could result in increased nanoleakage. HEMA has several other drawbacks, including poor capacity for polymerization, minimal contribution to mechanical characteristics, considerable water absorption, and poor biocompatibility. Manufacturers try to lower the HEMA content significantly or even wholly replace HEMA with an alternative monomer, such as a methacrylamide monomer variation (9). To the best of our knowledge, Adhese, Prime&Bond Universal, and Clearfil Universal Bond Quick are examples of SEAs that contain methacrylamide in their formulations (14, 30). Methacrylamide monomers are more resistant to hydrolysis than esters, which helps preserve the chemical properties of adhesives over time. Cuevas-Suárez et al. (31) found that Adhese maintained stability regarding the degree of conversion and exhibited an increase in DC values when evaluated at the end of its shelf life. This could be due to the inclusion of methacrylamide monomers. In accordance with these findings, Tichy et al. (14) noted that while other adhesives lacking methacrylamide were significantly different, Prime&Bond Universal and Clearfil Universal Bond Quick were not statistically different from one another in terms of DC values after 24 hours or after thermocycling.

The first commercial universal adhesive was Scotchbond Universal Adhesive, which contains MDP.

Scotchbond Universal has received more in vitro and clinical research than any other universal adhesive (38). Pongprueksa et al. (33) reported a complete impairment of bond strength and DC in an ethanol-based adhesive, Scotchbond Universal when the ethanol solvent evaporation was more than 50%. Water is essential in universal adhesives, as it combines with alcohol or acetone and functional monomers to improve the self-etch bonding capability. The acetone evaporates due to repeated opening and use of the adhesive, increasing its viscosity and preventing it from penetrating the pores of tooth structures (33). By repeatedly opening the bottle, organic solvents and small amounts of low-molecular-weight monomers can quickly evaporate due to their volatility. Pongprueksa et al. (33) suggested that if the adhesive is used according to the manufacturer's instructions and the bottle is recapped after each use, the shelf life of the ethanol-based adhesive in a clinical setting is unlikely to be compromised by evaporation.

From a clinical perspective, it is crucial to adequately remove solvents from primers or mixed primer adhesive resin formulations, such as universal adhesives. Gentle air-blowing is recommended until the resin film becomes stable after application. However, a few HEMA-free, primarily acetone-based, one-step adhesives require a more vigorous air-drying. For instance, in G-Premio BOND, the insufficient evaporation of the solvent post-application leads to the separation of adhesive monomers from water. This can result in trapped droplets during polymerization, potentially compromising bonding performance. Strong air drying can mitigate this issue by reducing interfacial water, thereby enhancing long-term bonding efficiency (4). SEM (Scanning Electron Microscopy) findings have also shown that insufficient drying leads to the accumulation of round-shaped droplets inside the adhesive layer of G-Premio BOND. This was most likely a result of phase separation of its components (14).

It is important to note that universal adhesives may need additional time for the solvent to evaporate completely, ensuring the removal of any residual water from the interface. This evaporation process helps prevent hydrolytic deterioration of the hybrid layer and preserves the physical properties of the resin monomers. Extending the solvent evaporation time to 15 seconds with an air stream has been shown to achieve higher dentin bond strength and reduce nanoleakage (38).

The other functional monomer found in numerous universal adhesives is 10-MDP, which effectively forms ionic bonds with hydroxyapatite, creating stable monomer-calcium salt nanolayers. However, the ester in 10-MDP is vulnerable to hydrolytic degradation (39). Although 10-MDP is present in most universal adhesives, 10-MDP-based adhesives may still behave differently since the purity and concentration of 10-MDP have been demonstrated to impact bonding efficiency substantially. Manufacturers currently conceal information on monomer concentration and quality (9, 40).

Ester-based adhesive formulations with an acidic pH are particularly vulnerable to hydrolysis, which modifies the chemical composition of the universal adhesive. This process can lead to the formation of compounds like ethylene glycol, unbound methacrylic acid, and free phosphoric acid, altering the material's characteristics and reducing the bond strength (7, 31, 41). Additionally, frequent bottle openings can cause the evaporation of organic solvents and low-molecular-weight monomers, further impacting the adhesive's properties (33).

It is worth mentioning that previous investigations have shown that the stability and efficiency of camphorquinone (CQ) photoinitiators are poor in an acidic environment. The acid-base reaction between acidic monomers and the amine in CQ prevents it from acting as a co-initiator of polymerization. Additionally, the interaction of the acidic functional monomer and the amine may neutralize it, making it less capable of establishing stable bonds with the hydroxyapatite of the dentin substrate (42). This issue is addressed in some universal adhesive systems by using an alternate hydrophilic photo-initiator, such as TPO (2,4,6-Trimethylbenzoyl diphenylphosphine oxide), which is believed to overcome this problem as well as improve the DC and reduce the effect of phase separation (43).

Some limitations of the current review were the moderate level of scientific evidence in some studies and various adhesives and aging protocols employed in the included studies. Dental adhesive systems are usually evaluated in laboratory experiments based on their bond strength values. However, other elements can impact the bond strength in clinical settings, such as masticatory stresses, pH and temperature alterations, and the wet environment of the oral cavity, which could exacerbate the deterioration of the adhesive interface. It is still debatable whether bond strength tests are valid for predicting the performance of dental adhesives in the oral environment. Nevertheless, some studies have shown that clinical outcomes can, to some extent, be expected based on laboratory results such as bond strength tests (44, 45). Future research with standardized methods and materials is needed to reduce heterogeneity and enable a more robust quantitative synthesis of the effects of storage time and conditions on the bond strength of universal adhesives. Future studies should also optimize adhesive formulations to enhance their stability and performance under varied storage conditions. Further research should explore the underlying stability mechanisms in high-pH adhesives to aid future adhesive development. Additionally, clinical trials are needed to validate laboratory findings and to better predict the clinical performance of universal adhesives.

Conclusions

This study highlighted the susceptibility of universal adhesives to hydrolytic degradation when exposed to prolonged or improper storage conditions, particularly at higher temperatures. However, not all adhesives demonstrated a decline in performance; some with higher pH levels and those composed of HEMA-free blends or hydrolytically stable monomers like methacrylamides showed more stable characteristics over time. Adherence to recommended storage practices, such as maintaining low temperatures and promptly resealing the containers, can significantly mitigate these effects, ensuring universal adhesive durability and effective performance.

Conflict of interest

The authors declare no competing interests.

Authors' contributions

MG: Conceptualization, Methodology, Validation, Investigation, Writing – original draft. MGL: Conceptualization, Methodology, Investigation, Project administration, Writing – original draft, review & editing. SM: Methodology, Data Curation, Investigation, Writing – original draft. EHR: Methodology, Validation. HSM: Writing-original draft, and visualization. LT: Supervision, Writing – review & editing.

Ethical approval

Not applicable.

Funding

This study was self-funded.

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