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Review

Self-Adhesive Flowable-Resin Composites: From Chemistry to Clinical Evidence—A Critical Review

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Abstract

Self-adhesive flowable-resin composites (SAFRCs) incorporate acidic functional monomers to bond to tooth structure without a separate adhesive. This critical narrative review relates the composition of eleven products identified in September 2026 to laboratory properties and clinical outcomes. A structured search of PubMed/MEDLINE, Scopus and Web of Science identified 69 reports for qualitative synthesis; study design and methodological limitations informed interpretation, without formal risk-of-bias assessment. Acidic monomer-mediated adhesion provides a general framework, but interactions with tooth tissue and interfacial stability vary by formulation. Laboratory studies generally report lower dentin bond strength than adhesive-based controls and improved enamel bonding after phosphoric-acid etching. Water uptake is often high, although results obtained under non-standard conditions cannot establish non-compliance with ISO 4049. Selected S-PRG-containing formulations show favourable mechanical, bonding or ion-release properties in vitro; 10-MDP-containing products do not consistently show higher bond strength. Ion release and surface antibacterial activity do not establish clinical remineralisation or caries prevention. Clinical findings are heterogeneous and product-specific, with most follow-up limited to 24 months and one trial extending to 5 years. They support cautious consideration of the tested products for small, retentive Class I restorations, without establishing equivalence to conventional protocols or efficacy across the material class. Laboratory evidence and product instructions inform selective enamel etching; its incremental clinical benefit remains untested in direct randomised comparisons.

Keywords: self-adhesive flowable-resin composite; functional monomer; 10-MDP; selective enamel etching; bond strength; water sorption; ion release; bioactivity; cytotoxicity; clinical performance

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1. Introduction

Resin-based composites (RBCs) are the most widely used direct restorative materials because of their aesthetics, versatility and reliable clinical performance [1–3]. However, their success is inseparable from the adhesive system, and multi-step etch-and-rinse or self-etch protocols add chair time and technique sensitivity [4,5]. The logical endpoint of adhesive simplification has been to incorporate adhesive chemistry into the restorative material itself [5].

Self-adhesive flowable-resin composites (SAFRCs) are light-cured flowable RBCs that contain acidic functional monomers—glycerol phosphate dimethacrylate (GPDM), 4-methacryloyloxyethyl trimellitic acid/anhydride (4-MET/4-META), 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) or proprietary phosphoric/phosphonic acid esters—intended to condition and bond to enamel and dentin without a separate adhesive [6–8]. Although often promoted as "one-step" materials, most are placed as a thin, actively brushed initial layer followed by conventional incremental layering, and most manufacturers now recommend or permit selective phosphoric-acid etching of enamel [8]. It must also be emphasised that SAFRCs are resin composites: they contain no polyalkenoic acid, do not undergo an acid–base setting reaction and therefore cannot reproduce the water tolerance or ion-exchange adhesion of glass-ionomer cements [5,9].

Terminology in this field is inconsistent. The term "self-adhesive composite" has been applied to materials with fundamentally different chemistries, including dual-cure hybrid restoratives based on polymerisable polyacids [9,10], ionic-resin restoratives marketed as "bioactive" [11] and giomers, while the abbreviation "SAC" is widely used for self-adhesive resin cements. In line with current usage [8], we use SAFRC exclusively for light-cured flowable-resin composites whose adhesion relies on acidic methacrylate monomers; materials of different chemical nature are not compared with them on a like-for-like basis.

A comprehensive mapping review of SAFRCs has recently been published [8], cataloguing eleven commercial products together with their laboratory and clinical literature. The present review is intended to complement rather than duplicate that work, and differs from it in four respects: (i) it applies explicit classification criteria (Section 3.2) to separate true SAFRCs from resin-modified glass-ionomer (RMGI)-type, compomer and ionic-resin materials that are frequently included in comparisons; (ii) consistent with the scope of this Special Issue on bioactive restorative composites, it critically appraises ion-releasing SAFRC formulations using an explicitly defined tissue-bonding concept of bioactivity, while recognising broader biological functions [12]; (iii) it links product-specific instructions for use (IFUs) and clinical evidence to a practical protocol centred on selective enamel etching (Section 9.3); and (iv) it incorporates studies published up to 2026 [13–16], summarised in multi-study evidence tables for each property. Earlier systematic reviews meta-analysed only bond strength [17] and short-term clinical performance in occlusal cavities [18]. The first two of these differences concern the interpretation rather than the collection of evidence, but they lead to conclusions that integrate classification, biological function and clinical applicability: comparisons across different chemical categories cannot isolate performance differences within SAFRCs; measured ion release must be distinguished from demonstrated biological function and clinical benefit; and indications must be tied to the products and protocols actually studied. Section 10 brings these conclusions together with the remaining evidence gaps. The contribution is therefore an integrated critical interpretation, rather than a claim that all of the underlying questions or findings are new.

Ion release and bioactivity are considered alongside adhesion and mechanical performance not because they determine whether a composite can function as a self-adhesive restoration, but because several SAFRCs contain ion-releasing fillers and are promoted

with remineralising or antibacterial claims, and because the acidic, hydrophilic matrix that enables self-adhesion also governs water uptake and ion exchange. Their evaluation therefore belongs to an assessment of the overall clinical value of these materials, provided that ion release is not mistaken for a proven therapeutic benefit.

Accordingly, the aim of this critical narrative review was to relate the composition of commercially available SAFRCs to their adhesive, physico-mechanical, biological and ion-releasing behaviour, and to translate this evidence into evidence-informed indications and a suggested clinical protocol. Four questions guided the review: (1) which commercial materials meet a chemical definition of an SAFRC; (2) how composition relates to adhesion and its durability; (3) what is known about the biological safety and the ion-release and bioactivity claims of these materials; and (4) to what extent laboratory properties are reflected in clinical outcomes and which indications they support.

2. Literature Search and Material Classification

A structured search was performed in PubMed/MEDLINE, Scopus and Web of Science Core Collection on 25 September 2026, covering 1 January 2009 to the search date, using database-specific search strings (Supplementary Table S1, which reports the full search strings, including Boolean operators, field tags and filters, for each database). The search combined the terms ("self-adhesive" OR "self-adhering" OR "self-bonding") AND ("flowable" OR "resin composite" OR "composite resin" OR "restorative material") with the trade names of all commercial SAFRCs (Vertise Flow, Dyad Flow, Fusio Liquid Dentin, Constic, Y-Flow SA, FIT SA, Oxford Flow SE, Profil Flow SE, Beautifil Kids SA, Fusion Flo SE, Nova Compo SF and SimpliShade Self-Adhesive Flow). The search retrieved 2162 records (PubMed 593, Scopus 853, Web of Science 716). After removal of 1104 duplicates by DOI, PMID and title, 1058 records were screened by title and abstract, and 789 were excluded, mainly because they concerned self-adhesive resin cements, adhesive systems, indirect restorations, giomers or bioactive materials used with an adhesive, or ACTIVA and Surefil One. The full texts of the 269 potentially eligible reports were assessed against three criteria: the study (i) tested at least one SAFRC, as defined below, in at least one group without a separate adhesive; (ii) reported a quantitative outcome related to composition, adhesion, physico-mechanical properties, water sorption, biological response, ion release or clinical performance; and (iii) described the materials, specimen preparation, test or clinical conditions and statistical analysis in sufficient detail to allow interpretation. Sixty reports were selected for the narrative synthesis. The remaining 209 reports were excluded because they used the SAFRC only with a separate adhesive or only as a comparator for other materials, did not report a relevant quantitative outcome, described the methods insufficiently, or reported data or addressed a question already covered more completely by an included study (Figure 1). Nine further studies were identified by hand-searching the reference lists of previous reviews [8,17,18], manufacturers' IFUs and safety data sheets, giving 69 reports in the narrative synthesis (Figure 1). Studies using an SAFRC with a separate adhesive and studies of materials outside the defined category are discussed separately where needed to explain classification, mechanisms or protocol dependence; they do not establish the effectiveness of adhesive-free SAFRC placement. English-language, peer-reviewed laboratory studies, clinical trials and systematic reviews were considered; conference abstracts and case reports were excluded. Google Scholar and publisher platforms (e.g., ScienceDirect) were used only to retrieve full texts and were not treated as bibliographic databases.

Title/abstract screening and full-text eligibility assessment were performed independently by two authors (K.M.A.B. and R.Y.), and disagreements were resolved by discussion. This is a structured critical narrative review with purposive selection and qualitative synthesis; it is not presented as a systematic review. The protocol was not registered,

and no meta-analysis or formal risk-of-bias assessment was undertaken. The PRISMA-style flow diagram (Figure 1) documents the reported selection process rather than demonstrating compliance with systematic-review methods. Interpretation considered study design, sample size, follow-up, comparator selection, ageing conditions, pre-test failures and consistency across independent studies. Clinical trials informed clinical conclusions, whereas laboratory studies informed mechanisms and hypotheses. Systematic reviews were used as contextual syntheses rather than as additional independent observations. Selective inclusion, the absence of formal bias assessment and incomplete methodological reporting limit the certainty and completeness of the conclusions; excluding a report because its question was covered more fully elsewhere does not establish that it was methodologically invalid.

A material was classified as an SAFRC when it was (a) a light-cured flowable-resin composite, (b) relied on acidic methacrylate functional monomers for adhesion and (c) was indicated by its manufacturer for placement without a separate adhesive. Materials containing polyalkenoic acids or a glass-ionomer acid–base reaction (RMGICs and poly-acid-based hybrid restoratives), compomers and giomers that require an adhesive, ionic-resin restoratives whose current IFU requires an adhesive and self-adhesive resin cements were excluded from the SAFRC data set and are discussed only for classification or an explicitly labelled mechanistic context (Section 3.2). Classification was based primarily on adhesion and setting chemistry (criteria a and b) and secondarily on the current instructions for use (criterion c), because a material that requires a separate adhesive under its current instructions is used differently in the clinic, even if its chemistry resembles that of an SAFRC. As formulations and IFUs may change, the classification refers to the IFUs and safety data sheets (SDSs) available at the time of the search. Eleven products met these criteria; this number refers to the products identified through the search, the previous mapping review [8] and manufacturers' documentation as of September 2026, not to products available in every market, because commercial availability varies geographically and some products may since have been reformulated, renamed or discontinued. IFUs and SDSs were used only to identify composition and indications and were not treated as evidence of performance; where the composition is not fully disclosed, this is indicated in Section 4.1, and the reported composition should not be regarded as exhaustive.

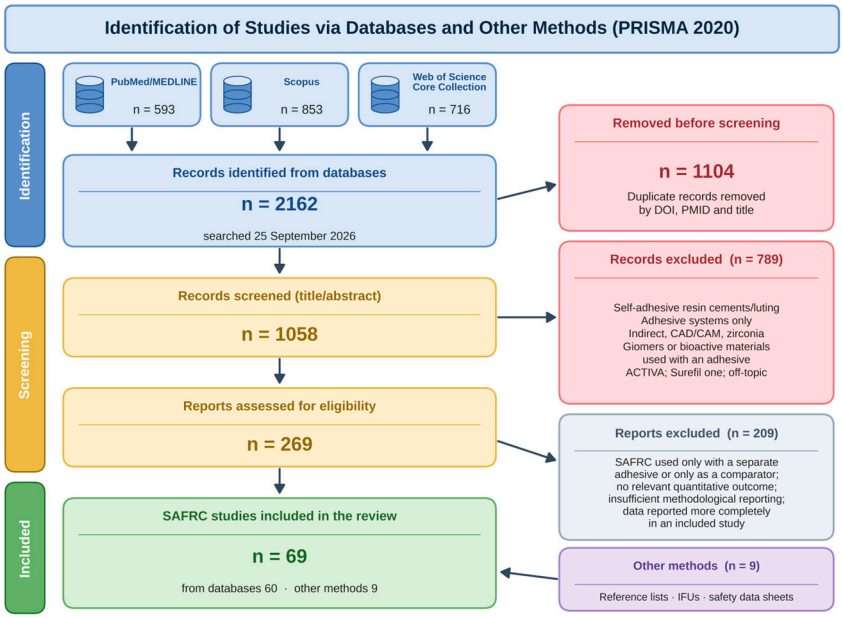


Figure 1. PRISMA 2020-style flow diagram of the literature search (PubMed/MEDLINE, Scopus and Web of Science Core Collection; 25 September 2026). The final total represents reports selected for

this narrative synthesis; it should not be interpreted as 69 independent clinical trials or independent datasets. Reasons for full-text exclusion are qualitative; category-specific counts were not tabulated. DOI, digital object identifier; IFU, instructions for use; PMID, PubMed identifier; SAFRC, self-adhesive flowable-resin composite.

3. Development and Classification of SAFRCs

3.1. From Adhesive Simplification to Self-Adhesive Composites

The acid-etch technique, the synthesis of bisphenol A glycidyl methacrylate (Bis-GMA) and the development of dentin bonding established the basis of modern adhesive restorative dentistry [5,19]. Adhesive systems were progressively simplified from three-step etch-and-rinse to two-step and one-step self-etch and, later, universal adhesives [20,21]. SAFRCs extended this trend by combining self-etch adhesive chemistry with a flowable composite. Fusio Liquid Dentin (Pentron, 2009) and Vertise Flow (Kerr, 2010; marketed as Dyad Flow in some regions, the same material) were followed by Constic (DMG, 2015), Y-Flow SA (Yller, 2018), FIT SA (Shofu, 2019), Oxford Flow SE and Profil Flow SE (2020), Beautifil Kids SA (Shofu, 2021), Fusion Flo SE (Prevest DenPro, 2022), Nova Compo SF (Imicryl, 2023) and SimpliShade Self-Adhesive Flow (Kerr, 2024) [8] (Figure 2). Earlier moisture-tolerant resins such as Embrace WetBond (Pulpdent) were marketed mainly as pit-and-fissure sealants and are not considered restorative SAFRCs here. The main differences between SAFRCs and conventional flowable RBCs used with an adhesive system are summarised in Table 1.

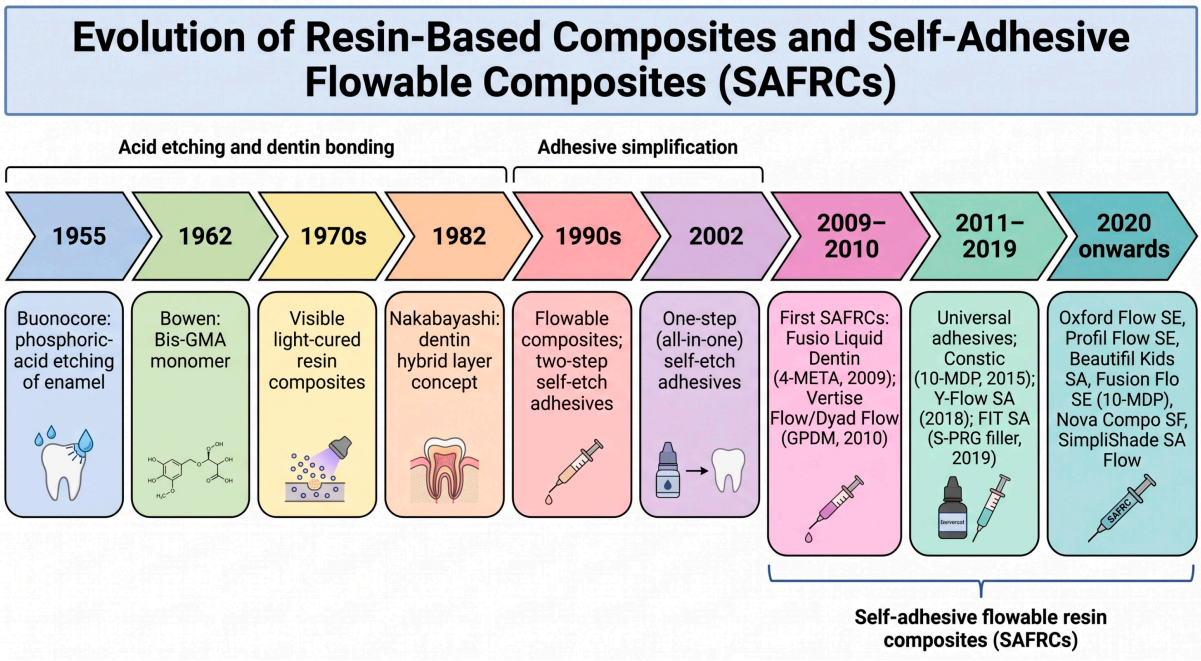


Figure 2. Evolution of resin-based composites and adhesive systems, and launch of the commercially available self-adhesive flowable-resin composites (SAFRCs) with their functional monomer or filler technology. Vertise Flow and Dyad Flow are the same material marketed under different names. Years indicate commercial launch as reported in [8] and in manufacturers' documentation; they may differ between regions and from the date of the first scientific publication. Data from [5,8]. Created in BioRender [22].

Table 1. Main differences between conventional flowable-resin composites used with an adhesive system and self-adhesive flowable-resin composites (SAFRCs). Values are typical ranges for products whose composition is disclosed and may not apply to every commercial formulation.

Characteristic	Conventional Flowable RBC + Adhesive System	SAFRC
Adhesion-promoting chemistry	Separate adhesive (etch-and-rinse, self-etch or universal) containing solvents, primers and functional monomers	Acidic functional monomer (GPDM, 4-META/4-MET, 10-MDP or phosphoric/phosphonic ester) incorporated in the composite paste; no solvent
Resin matrix	Bis-GMA, Bis-EMA, UDMA, TEGDMA and other dimethacrylates; usually no HEMA in the composite	Similar dimethacrylates plus the functional monomer and, in most disclosed formulations, ≈5–10 wt% HEMA [8]
Filler content	Generally higher, particularly in "highly filled" flowables	≈38–55 vol% in disclosed formulations [8]
Interaction with dentin	Hybrid layer and resin tags	Interaction zone ≤ 200 nm; no true hybrid layer (shown for Vertise Flow) [23]
Enamel conditioning	Phosphoric acid (etch-and-rinse or selective etch) or self-etch	Mild self-etch; selective phosphoric-acid etching of enamel recommended or permitted by most manufacturers [8]
Placement	Adhesive application, then incremental layering	Thin first layer actively brushed 15–20 s, then incremental layering (≤2 mm); not a single-step bulk procedure
Dentin bond strength	Often higher than SAFRCs in within-study comparisons; depends on adhesive, substrate and test method [8,17]	Generally lower than adhesive-based controls; values and ageing effects are product- and method-dependent [8,17]
Water sorption/solubility	Product- and protocol-dependent; compliance requires testing under the specified ISO conditions	Often higher in tested products; non-standard immersion results do not establish ISO non-compliance [24,25]
Clinical indications supported by evidence	Indications vary with the flowable formulation, adhesive protocol and loading conditions	Mainly selected small Class I cavities; predominantly short-term, product-specific trials, with one 5-year trial (Section 9.2) [8,18]

Table 1 highlights the formulation trade-off created by combining conditioning, wetting and restoration in one paste. Conventional protocols separate the adhesive interface from the bulk composite, whereas an SAFRC must balance acidic monomer activity and flow with polymerisation, strength and resistance to water uptake. The lower dentin bond strengths and greater water uptake reported for several SAFRCs are consistent with this trade-off, but their magnitude depends on the product and test conditions. Neither HEMA content nor filler loading alone predicts clinical performance. Table 1 therefore provides a framework for interpreting the product-specific evidence in Sections 4–9, rather than a uniform ranking of all conventional flowables against all SAFRCs.

3.2. Materials Outside the SAFRC Category

Several materials frequently discussed with SAFRCs differ in chemistry and should not be compared on a like-for-like basis (Table 2).

Polyacid-based self-adhesive hybrid restoratives. Surefil One (Dentsply Sirona) is a dual-cure bulk-fill restorative based on a modified, polymerisable polyacid with an acid–base (glass-ionomer-type) reaction and redox initiation [9]. Independent studies were grouped with RMGICs [10,26]. It is therefore not an SAFRC, and this review did not use clinical or laboratory data obtained with it to draw conclusions about SAFRCs.

ACTIVA products (Pulpdent). Several products must be distinguished. According to the current safety data sheet, the ACTIVA BioACTIVE line (Restorative, Base/Liner, Cement and Kids) is a "bioactive ionic resin with reactive glass filler" whose resin phase is a proprietary blend of diurethane and other methacrylates with modified polyacrylic acid (44.6 wt% in the Restorative), together with amorphous silica and sodium fluoride; the manufacturer states that it contains no Bis-GMA or bisphenol A derivatives [27,28]. Independent analyses report diurethane dimethacrylate, an acidic phosphate monomer (bis[2-(methacryloyloxy)ethyl] phosphate), a polyacrylic acid/maleic acid copolymer, reactive (ionomer) and barium glasses and a small amount of water, with a dual (acid–base plus free-radical) setting reaction. On this basis, ACTIVA BioACTIVE-Restorative has been classified as a modified RMGIC [26,29]. ACTIVA BioACTIVE-Restorative, in clinical use since 2012 [28], is dual-cured. Its original instructions recommended a short phosphoric-acid etch without an adhesive; when used this way in Class I/II cavities, it reached an annual failure rate of 24.1% versus 2.5% for a composite with a self-etch adhesive, and the trial stopped after one year [11]. The current instructions require phosphoric-acid etching (enamel 20 s, dentin 15 s) and a bonding agent [28,30]. ACTIVA BioACTIVE-Base/Liner belongs to the same product family but is indicated without etching or bonding, and only as a liner/base [30,31]. ACTIVA Presto is a newer light-cured, stackable restorative that also requires etching and an adhesive [32]. The BioACTIVE products are excluded on chemical grounds and, where applicable, because of adhesive-dependent use. Presto is excluded because its restorative protocol requires a separate adhesive; its formulation should not be assumed to be identical to BioACTIVE-Restorative.

Other categories. RMGICs, compomers, giomers requiring an adhesive (e.g., Beautifil Flow Plus) and self-adhesive resin cements are likewise excluded. When these materials are used as comparators in SAFRC studies, their results are reported as such and are not pooled with SAFRC data.

Table 2. Classification criteria used in this review to distinguish SAFRCs from other "self-adhesive" or ion-releasing restorative materials. Classification is based on adhesion and setting chemistry; the fourth column reflects the instructions for use available at the time of the search (September 2026), which may change over time.

Category	Examples	Adhesion/Setting Chemistry	Adhesive or Etching in Current IFU (September 2026)	Treated as SAFRC
Self-adhesive flowable-resin composite	Vertise Flow/Dyad Flow, Fusio Liquid Dentin, Constic, FIT SA, Nova Compo SF and others (Table 3)	Acidic methacrylate monomers; light-activated free-radical polymerisation	No adhesive; selective enamel etching recommended or permitted; dentin etching discouraged	Yes
Polyacid-based self-adhesive hybrid restorative	Surefil One (Dentsply Sirona)	Modified polymerisable polyacid; acid–base reaction plus redox/light cure (dual-cure) [9]	No adhesive required (optional)	No (RMGI-type chemistry) [10,26]
Ionic-resin BioACTIVE restorative; adhesive-dependent Presto restorative	ACTIVA BioACTIVE-Restorative (dual-cure); ACTIVA Presto (light-cure)	BioACTIVE-Restorative: ionic resin/polyacid and reactive glass [26,27,29]. Presto: distinct light-cured product; identical formulation is not assumed [32]	Etching and bonding agent required [30,32]	No: BioACTIVE-Restorative has different chemistry; Presto requires a separate adhesive

Ionic-resin liner	ACTIVA BioACTIVE-Base/Liner	BioACTIVE liner/base formulation; not assumed interchangeable with the restorative variants	No etching or bonding (liner/base only) [30]	No
RMGICs	Fuji II LC, Photac Fil	Polyacrylic acid–glass reaction plus HEMA polymerisation	Conditioner optional	No
Compomers and giomers	Dyract Flow; Beautifil Flow Plus	Acidic monomers or S-PRG filler; light cure	Adhesive required	No
Self-adhesive resin cements ("SAC")	Luting cements	Acidic monomers; dual-cure	No adhesive	No (luting agents)

Table 3. Composition and manufacturer indications of commercially available SAFRCs. Data from manufacturers' information compiled in [8], supplemented by [15,33]. Compositions are as disclosed by the manufacturers and are not necessarily exhaustive; "Not disclosed" indicates proprietary information. Except for the analyses reported in [15,33], compositions have not been independently verified.

Product (Manufacturer, Launch)	Functional Monomer	Other Monomers	Fillers	Indications (Manufacturer)	Enamel Etching per IFU
Fusio Liquid Dentin (Pentron, 2009)	4-META	UDMA, TEGDMA, HEMA	Barium glass, amorphous silica (≈52 vol%)	Small Class I, liner/base, pit and fissure	Not specified; dentin etching discouraged
Vertise Flow/Dyad Flow (Kerr, 2010)	GPDM	Bis-GMA, Bis-EMA, UDMA, HEMA	Pre-polymerised filler, barium glass, nano-silica, YbF_3 (≈70 wt%)	Small Class I, small retentive Class II, liner/base, pit and fissure	Selective enamel etching allowed
Constic (DMG, 2015)	10-MDP	Bis-GMA, TEGDMA, UDMA, HEMA and others	Barium aluminosilicate glass (≈43 vol%)	Small Class I, liner/base, pit and fissure, extended fissure sealing	Not specified
Y-Flow SA (Yller, 2018)	Acidic methacrylates (not disclosed)	Dimethacrylates	Dental glass	Small Class I, liner/base, pit and fissure	Not specified
FIT SA (Shofu, 2019)	Phosphonic/phosphoric acid monomer	UDMA, HEMA	S-PRG (fluoroboroaluminosilicate) filler, glass powder, silica	Small Class I, Class III, Class V/root, liner/base	"Do not etch dentin"
Oxford Flow SE (First Scientific, 2020)	Not disclosed	Dimethacrylates	Dental glass, SiO_2 (≈45 vol%)	Small Class I, liner/base, pit and fissure	Not specified
Profil Flow SE (Silmet, 2020)	Not disclosed	Bis-GMA, dimethacrylates	Glass, amorphous silica (≈43 vol%)	Small Class I, liner/base	Not specified
Beautifil Kids SA (Shofu, 2021)	Phosphoric acid ester	UDMA, HEMA	SiO_2, zirconium silicate, glass powder, YbF_3	Small Class I, pit and fissure, preventive resin restoration	Not specified
Fusion Flo SE (Prevest DenPro, 2022)	10-MDP	Bis-GMA, Bis-EMA, TEGDMA, HEMA	Silanated barium glass, amorphous silica (≈70 wt%)	Class I, III, IV and V, small posterior restorations	Selective enamel etching recommended
Nova Compo SF (Imicryl, 2023)	10-MDP, 4-META	Aliphatic dimethacrylates, HEMA	Barium glass, fluoroaluminosilicate (≈47 vol%)	Small Class I, Class III and V, liner/base, pit and fissure, undercut blocking	Not specified
SimpliShade Self-Adhesive Flow (Kerr, 2024)	GPDM	Bis-GMA, Bis-EMA, GDMA, UDMA, HEMA	YbF_3, fumed silica (≈38 vol%)	Small Class I, small retentive Class II, liner/base, pit and fissure, porcelain repair	Selective enamel etching allowed

Table 2 shows why a marketing term cannot substitute for chemical classification. Materials described as self-adhesive may rely on acidic methacrylates, polymerisable

polyacids or other setting mechanisms, and their results cannot be pooled as though they belong to one material class. Instructions also differ between product variants: ACTIVA BioACTIVE-Restorative requires a bonding agent, whereas BioACTIVE-Base/Liner is indicated for use as a liner/base without that step [30]. This difference does not establish identical formulations or interchangeable indications. Classification should therefore identify the exact product, its disclosed chemistry and the applicable IFU. Evidence from excluded categories is used only as labelled context, not as evidence of SAFRC performance.

4. Composition and Adhesion Mechanism

4.1. Resin Matrix, Functional Monomers, Fillers and Initiators

The composition of the commercial SAFRCs is summarised in Table 3 and Figure 3. Disclosed matrices contain combinations of conventional dimethacrylates (Bis-GMA, Bis-EMA, UDMA, TEGDMA and GDMA), an acidic functional monomer and, in several products, the hydrophilic co-monomer 2-hydroxyethyl methacrylate (HEMA), reported at approximately 5–10 wt% in selected formulations [8,15]. These descriptions are not exhaustive formulations for every product. It should be noted that HEMA is not an adhesion-promoting acidic monomer; it improves wetting and monomer miscibility but increases water uptake. Monomers used in adhesive systems but not in commercial SAFRCs (e.g., phenyl-P, PENTA or NTG-GMA) are not relevant to this category. Vertise Flow, for example, contains GPDM, HEMA, Bis-GMA, Bis-EMA and UDMA [15], whereas FIT SA combines a phosphonic acid monomer with UDMA, HEMA and surface pre-reacted glass-ionomer (S-PRG) filler [33].

Reported filler loading is approximately 38–55 vol% in disclosed formulations [8]; this range should not be assumed for products with proprietary compositions. Acidic monomers partially neutralise the tertiary amine co-initiator in the camphorquinone system and can reduce the degree of conversion; phosphine oxide initiators have been introduced, although bis-acylphosphine oxide in experimental SAFRCs increased water sorption [34,35]. The formulation is therefore a compromise: more acidic and hydrophilic monomer improves wetting and etching but increases water sorption and hydrolysis, whereas lower filler content improves flow at the expense of modulus, strength, wear resistance and shrinkage (Figure 3) [8].

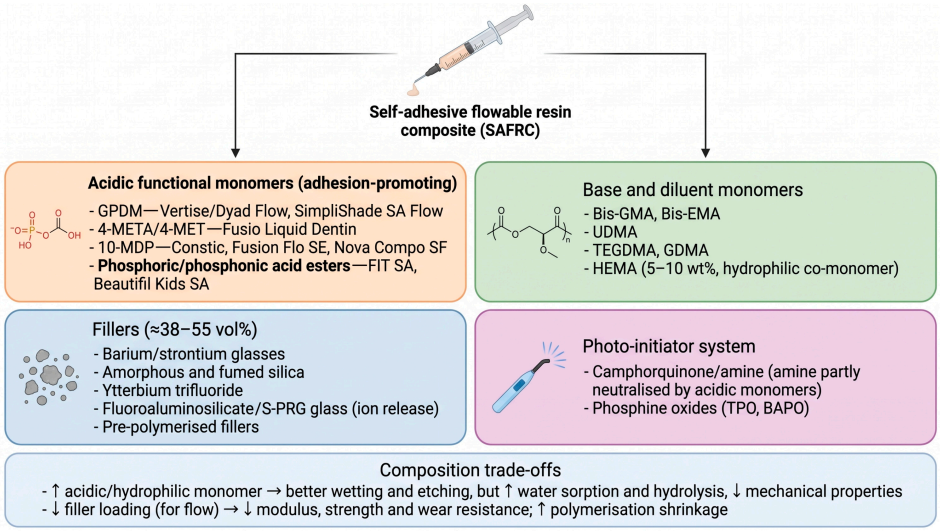


Figure 3. Compositional framework of commercial self-adhesive flowable-resin composites (SAFRCs) and the main composition–property trade-offs. ↑ increase; ↓ decrease; → leads to. Based on manufacturers' data compiled in [8,15,33]. Created in BioRender [22].

4.2. A Common General Mechanism of Self-Adhesion

Although manufacturers describe product-specific mechanisms, the adhesion of SAFRCs can be described by a common general framework of three steps (Figure 4): mild demineralisation of the smear layer and superficial hydroxyapatite by the acidic paste (pH ≈ 1.9 has been reported for Vertise Flow [8]); limited diffusion of a viscous, solvent-free resin; and ionic interaction/salt formation between the acid groups and calcium of residual hydroxyapatite. This framework does not imply equivalent interactions: the functional monomers differ in their chemical affinity for hydroxyapatite, in the stability of the calcium salts they form and, consequently, in their potential contribution to interfacial durability, and formulations also differ in acidity, monomer concentration and viscosity. According to the adhesion–decalcification concept, 10-MDP forms stable, poorly soluble calcium salts, 4-MET forms less stable salts, and phosphate monomers such as those of the GPDM type form more soluble salts that favour decalcification over durable bonding [21,36,37]. Thus, the combination of micromechanical and chemical interaction is not unique to 10-MDP; rather, the stable calcium salts associated with 10-MDP provide a mechanistic rationale for durable bonding [36], not proof that every commercial 10-MDP-containing SAFRC has superior durability. Moreover, direct evidence on the interaction of commercial SAFRCs with tooth tissue is largely limited to Vertise Flow (GPDM) [23]; the behaviour of other products is inferred mainly from studies of their functional monomers in experimental or adhesive formulations [36,37].

Transmission electron microscopy illustrates how limited this interaction is. On smear-covered dentin, Vertise Flow produced no detectable demineralisation, and even on fractured dentin the interaction zone was only 100–200 nm, without a hybrid layer or resin tags. On enamel, most areas showed distinct separation [23]. Smear-layer thickness therefore strongly influences bond strength [38], and manufacturers recommend active brushing of the first layer for 15–20 s [8]. Aprismatic and uncut enamel is poorly etched by these mild monomers, which explains the benefit of selective phosphoric-acid etching of enamel (Section 6). Conversely, manufacturers discourage phosphoric-acid etching of dentin because the viscous, solvent-free resin cannot infiltrate the exposed collagen network [8,39,40].

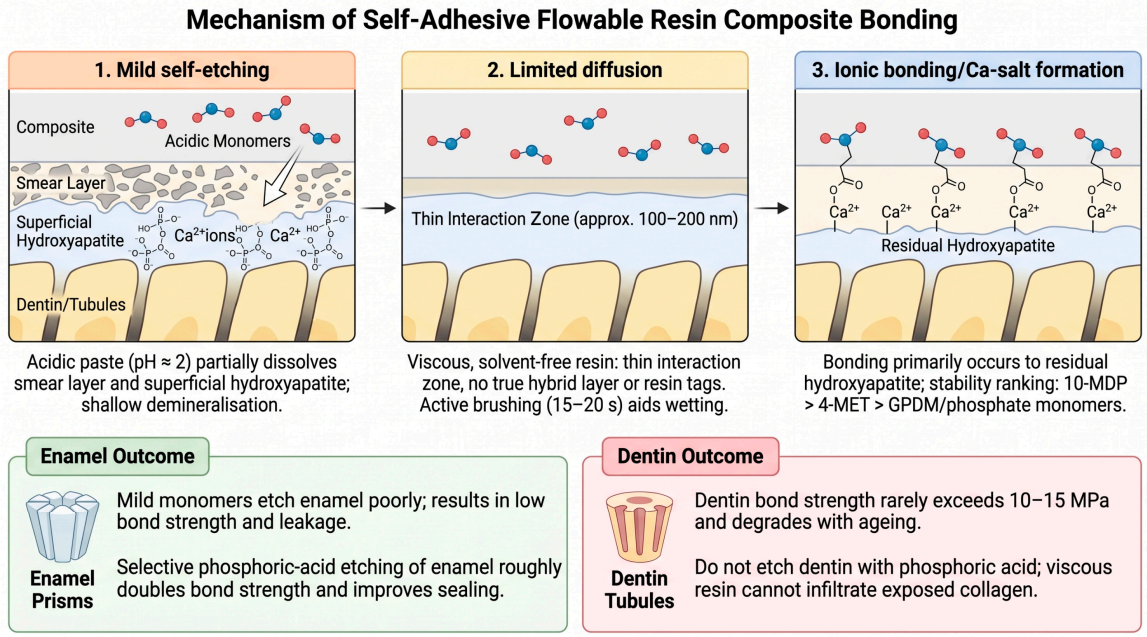


Figure 4. General framework of adhesion of self-adhesive flowable-resin composites and its consequences for enamel and dentin. The schematic is conceptual; the extent of demineralisation,

infiltration and calcium-salt stability is formulation-dependent. Based on [8,14,23,36,41]. Created in BioRender [22].

5. Physico-Mechanical Properties and Water Sorption

Because SAFRCs are low-filled flowable materials with a hydrophilic matrix, their physico-mechanical profile is best interpreted against conventional flowable RBCs rather than against packable or bulk-fill composites. The evidence is summarised in Table 4, which summarises the available studies for each property; the depth and replication of evidence vary between outcomes. Because test methods, specimen geometry, storage media and ageing protocols differ between studies (Table 4), numerical values are compared within studies or with explicit reference to the test conditions.

Flexural strength and modulus. In the largest comparison, 23 flowable RBCs (including five SAFRCs) were tested according to ISO 4049 for 12 months: three SAFRCs were below the 80 MPa threshold after 24 h and another after 6 months of storage, and flexural moduli were generally lower than those of conventional flowables [42]. For context, ISO 4049 requires a flexural strength of at least 80 MPa for Type 1 materials, i.e., those claimed to be suitable for restorations involving occlusal surfaces, and of at least 50 MPa for other materials, measured on 2 × 2 × 25 mm bars after 24 h of water storage at 37 °C [43]. The 80-MPa threshold is therefore relevant to SAFRCs only where they are indicated for occlusal restorations, and strictly only to values obtained under the 24 h ISO conditions; moreover, a value below the threshold does not by itself predict clinical failure, nor does a value above it demonstrate clinical durability. More recently, FIT SA (≈107 MPa), Constic (≈97 MPa) and Vertise Flow (≈86 MPa) exceeded 80 MPa, whereas Fusio Liquid Dentin (≈72 MPa) and Nova Compo SF (≈65 MPa) did not [15]. In a smaller study, Dyad Flow's flexural strength did not differ significantly from that of a nanohybrid RBC, although its micro-hardness was lower [44]. The test condition must be specified when modulus values are compared: the frequently quoted value of 10.81 GPa for Vertise Flow is an indentation modulus obtained by instrumented micro-indentation, which is not directly comparable with the flexural modulus obtained in three-point bending [45]. In the same study, Vertise Flow showed the highest micro-mechanical properties among the flowables tested, provided that increments ≤ 2 mm were cured for 40 s [45].

Fracture toughness, hardness and wear. Vertise Flow showed lower fracture toughness than a conventional composite, and its fracture toughness decreased significantly after 90 days of water storage [46]. Micro-hardness of SAFRCs is generally lower than that of conventional flowables and decreases further after simulated brushing [46,47], and occlusal wear of five self-adhesive flowable materials (0.099–0.447 mm^3 volume loss) was greater than that reported for a nanofilled composite [41].

Polymerisation. Degree of conversion is product-dependent: FIT SA showed the highest, and Vertise Flow the lowest conversion among five SAFRCs [13], Y-Flow SA showed markedly low conversion [48], and Vertise Flow required the full 20 s exposure to reach maximum conversion [49]. Micro-CT showed volumetric shrinkage above 5.7 vol% for Vertise Flow [50], and Vertise Flow and Fusio Liquid Dentin generated relatively high polymerisation stress (3.5–4.1 MPa) and interfacial gaps (21–27% of the interface) [51]. SAFRCs are not bulk-fill materials and should be placed in increments no greater than 2 mm [45].

Water sorption, solubility and colour stability. The hydroxyl, phosphate and carboxyl groups of HEMA and the functional monomers readily hydrogen-bond with water [52]. Vertise Flow showed a hygroscopic expansion of 4.82% at 90 days [53] and a 7-day water sorption of 55.2 $\mu g/mm^3$ in artificial saliva, numerically above the ISO 4049 limit of 40 $\mu g/mm^3$, although that limit applies to storage in water [24]. Vertise Flow and Fusio Liquid Dentin had the highest sorption in water, saliva and lactic acid, with solubility up

to 22.2 μg/mm³ compared with <9 μg/mm³ for conventional controls [25]; in a more recent comparison, Vertise Flow again showed the highest solubility, whereas Fusio Liquid Dentin and Constic had lower sorption than FIT SA and Vertise Flow [13]. ISO 4049 specifies upper limits of 40 μg/mm³ for water sorption and 7.5 μg/mm³ for solubility after 7 days of storage in water at 37 °C [43]; several of the values above were obtained in artificial saliva or lactic acid, over longer periods or with different specimen geometries, so they indicate relative hydrolytic susceptibility but cannot be judged strictly against these limits. These data are consistent with the greater discolouration of SAFRCs in staining media [54,55].

Table 4. Summary of laboratory evidence on the physico-mechanical, water-sorption and bonding properties of SAFRCs. Values were obtained with different test methods, specimens and ageing protocols and should be compared only within studies.

Property (Test)	Test Conditions	Main Findings	Refs.
Flexural strength (three-point bending)	Reported ISO-based bar tests; 24 h baseline and extended water ageing up to 12 months; aged values do not establish baseline ISO compliance	Several SAFRCs < 80 MPa at 24 h or after 6 months of storage; FIT SA, Constic and Vertise Flow ≥ 80 MPa, Fusio Liquid Dentin and Nova Compo SF < 80 MPa in a 2026 study; Dyad Flow not significantly different from a nanohybrid	[15,42,44]
Elastic modulus (flexural vs. indentation)	Three-point bending (flexural) vs. instrumented micro-indentation	Flexural modulus generally lower than conventional flowables; indentation modulus of Vertise Flow 10.81 GPa (highest among flowables tested; not comparable with flexural modulus)	[42,45]
Fracture toughness (K_{IC})	Water storage up to 90 days	Vertise Flow lower than a conventional composite; decreased significantly after 90 days in water	[46]
Hardness and wear	Micro-hardness before/after simulated brushing; occlusal wear simulation (volume loss)	Lower micro-hardness than conventional flowables, reduced further by brushing; greater occlusal wear than nanofilled composite	[41,46,47]
Degree of conversion	Spectroscopic analysis; 20–40 s light exposure	Product-dependent: FIT SA highest, Vertise Flow lowest among five SAFRCs; Y-Flow SA low; full 20–40 s exposure required	[13,45,48,49]
Shrinkage and stress	Micro-CT in Class I cavities; stress and gap measurements	Volumetric shrinkage > 5.7 vol% (Vertise Flow); stress 3.5–4.1 MPa and interfacial gaps 21–27% (Vertise Flow, Fusio Liquid Dentin)	[50,51]
Water sorption, solubility, hygroscopic expansion	7–90 days in water, artificial saliva or lactic acid; not always ISO conditions	Vertise Flow 55.2 μg/mm³ sorption in artificial saliva (numerically > ISO limit of 40, which applies to water); solubility up to 22.2 μg/mm³; 4.82% hygroscopic expansion; Fusio Liquid Dentin and Constic lower sorption than FIT SA and Vertise Flow	[13,24,25,53]
Colour stability	Immersion in staining media (e.g., tea)	Greater discolouration than conventional flowables, especially in tea	[54,55]
Dentin bond strength	SBS and μTBS (not interchangeable); 24 h to 6 months of storage, 10,000 thermal cycles, simulated pulpal pressure	Significantly lower than adhesive-based controls (meta-analysis); Vertise Flow 3.4 MPa SBS/13.1 MPa μTBS vs. 23.7/58.4 MPa after 10,000 thermal cycles; FIT SA ≈ 14, Vertise Flow ≈ 12, Constic ≈ 6 MPa μTBS; pre-test failures for Fusio Liquid Dentin and Nova Compo SF; further reduction under pulpal pressure	[13,15,17,56,57]
Enamel bond strength and effect of etching	SBS on ground vs. phosphoric-acid-etched enamel (human or bovine)	Ground enamel 7.4–15.1 MPa; selectively etched enamel 22.2–32.5 MPa; etching reduces enamel microleakage	[6,14,41]
Microleakage and marginal adaptation	Dye penetration, micro-CT and microgap analysis; Class V and Class II cavities; with/without ageing	Higher leakage than adhesive-based systems, especially at enamel margins; improved by enamel etching or adhesive preconditioning	[56,58–61]

6. Bonding Effectiveness and Marginal Sealing

Dentin. A meta-analysis of in vitro studies found that SAFRCs bond significantly less effectively than conventional composites used with adhesive systems, to both enamel and dentin [17], although absolute dentin bond strengths vary substantially by product and protocol [8]. Because shear, microshear and microtensile tests differ in stress distribution, specimen preparation and susceptibility to pre-test failures, the values below are compared within studies rather than across test methods. After 10,000 thermal cycles, Vertise Flow reached 3.39 MPa (SBS) and 13.1 MPa (μTBS), compared with 23.69 MPa and 58.4 MPa for a conventional composite bonded with a universal adhesive; preconditioning with a universal adhesive increased these values to 11.95 MPa and 26.1 MPa, which remained significantly lower than the control [56]. Similar patterns have been reported for other products and study designs [62–64]. Product differences are evident: μTBS was ≈14 MPa for FIT SA, ≈12 MPa for Vertise Flow and ≈6 MPa for Constic, whereas specimens of Fusio Liquid Dentin and Nova Compo SF debonded before testing [15]. In another study, FIT SA and Fusio Liquid Dentin bonded better than Vertise Flow and Constic, although FIT SA declined after 6 months [13]. A new experimental SAFRC performed better than the commercial products but remained inferior to a two-step self-etch adhesive system [16]. Bond strength to primary dentin is lower than to permanent dentin [65], and simulated pulpal pressure reduces the μTBS of Vertise Flow to 8.9 MPa versus 31.3 MPa for an etch-and-rinse control [57]. Failures are predominantly adhesive, whereas adhesive-bonded controls show mainly mixed and cohesive failures [62,64].

Enamel and the role of selective etching. Enamel bond strengths of SAFRCs are higher than dentin bond strengths [61] but are still limited on ground enamel (7.4–15.1 MPa). Selective phosphoric-acid etching raised enamel SBS to 22.2–32.5 MPa and reduced microleakage [14,41], consistent with earlier findings [6,39]. These data were obtained with different products, substrates (human or bovine enamel) and test methods, and the included clinical evidence does not isolate the additional benefit of etching in a randomised comparison of the same SAFRC with and without etching (Section 9.2). This is why most manufacturers now recommend or allow selective enamel etching [8], and why the protocol proposed in Section 9 includes it.

Microleakage and marginal adaptation. SAFRCs show more microleakage than multi-step adhesive systems, particularly at enamel margins of Class V and Class II restorations [58,59]. Phosphoric-acid etching of enamel before Fusio Liquid Dentin, or preconditioning with an adhesive, reduced leakage to levels comparable with conventional systems [56,59,60]. When a separate adhesive was applied beneath Vertise Flow, microleakage became similar to that of conventional flowable composites [61]. However, SAFRC filler content may increase viscosity and reduce wetting compared with an unfilled adhesive [66]. In Class II restorations, SAFRC liners showed marginal integrity similar to conventional flowable composites used with an adhesive [67], and the sealing of Class I restorations was acceptable in vitro [68]. Ageing challenges such as thermocycling and simulated pulpal pressure consistently degrade SAFRC interfaces faster than those of adhesive-based controls [57,69].

7. Biological Behaviour: Monomer Release and Cytotoxicity

Unreacted monomers can be released from all resin-based materials and may diffuse through dentinal tubules to the pulp [70–72]. The biological evaluation of SAFRCs should not be limited to HEMA and TEGDMA, because their matrices also contain Bis-GMA, Bis-EMA, UDMA and acidic functional monomers (Table 3). In studies of isolated monomers in human dental pulp cells, the order of toxicity was Bis-GMA > UDMA > TEGDMA, with Bis-GMA and UDMA depleting glutathione, inhibiting cystine uptake and inducing

oxidative stress [73]; composite eluates also induce oxidative stress in pulp cells [74]. TEGDMA and HEMA are genotoxic and can modulate immune-cell function in vitro [75,76]. These findings concern isolated monomers at defined concentrations, mostly in the context of conventional resin-based materials, and cannot be extrapolated directly to fully formulated SAFRCs, whose elution depends on composition, degree of conversion and storage conditions. By contrast, the cytotoxicity of the acidic functional monomers themselves (GPDM, 4-META and 10-MDP) in SAFRC formulations has hardly been studied, which is an important knowledge gap. Notably, HPLC analysis did not show greater monomer elution from Vertise Flow and Constic than from conventional flowable composites [77].

Cytotoxicity data obtained with eluates or specimens of fully formulated SAFRCs are summarised in Table 5. In primary human pulp cells, Constic and Vertise Flow reduced cell viability by 52% and 34%, respectively, whereas Fusio Liquid Dentin and Super Flow (Imicryl) did not reduce viability by more than 30%; one RMGIC (Photac Fil) also reduced viability by 47%, indicating that toxicity is product- rather than category-dependent [10]; Surefil One, also tested in that study, is not considered here because it is not an SAFRC. Vertise Flow and Nova Compo SF reduced the viability of bovine pulp-derived cells to 81.6% and 71.4%, respectively [78], while other studies found no mutagenic response under the particular Ames-test conditions and viability comparable to GIC and RMGIC in a direct-contact assay [79,80]. A negative mutagenicity assay does not establish overall biological safety. The presence of dentin reduced the cytotoxicity of Dyad Flow [81]. In vivo, Vertise Flow and Fusio Liquid Dentin elicited an initial inflammatory reaction in rat subcutaneous tissue that resolved by 90 days [82], and a 12-month clinical study reported gingival cytokine findings for Vertise Flow cervical restorations placed with a universal adhesive [83]; this does not establish pulpal safety or the biological response to adhesive-free placement. A recently developed experimental SAFRC showed no cytotoxicity towards dental pulp stem cells [16]. Overall, these heterogeneous experimental data support caution when SAFRCs are placed in deep cavities with little remaining dentin; in such situations, depending on the remaining dentin thickness, the material and the clinical circumstances, a protective liner or an adhesive-based approach may be preferable.

Table 5. Studies evaluating the cytotoxicity and biological response of SAFRCs. Except for the experimental material in [16], all data concern fully formulated commercial products; studies of isolated monomers are discussed in the text.

Study Design	Cells/Model	Exposure/Extraction Conditions	SAFRCs Tested	Main Findings	Ref.
In vitro (ISO 7405/10993)	Primary human dental-pulp cells	Eluates (ISO 7405/10993-12; 24 h, 37 °C), serial dilutions; 24-h exposure; untreated control	Vertise Flow, Fusio Liquid Dentin, Constic, Super Flow (Imicryl)	Constic and Vertise Flow reduced viability by 52% and 34%; late apoptosis/necrosis; no membrane damage; one RMGIC also cytotoxic	[10]
In vitro	Bovine-pulp-derived cells	24-h extracts of 2 × 5 mm specimens; untreated control	Vertise Flow, Nova Compo SF	Viability 81.6% (Vertise Flow) and 71.4% (Nova Compo SF), both lower than control	[78]
In vitro	Human keratinocytes, with/without dentin	Exposure with and without an interposed dentin barrier; 1 and 7 days	Dyad Flow	Lower viability than control at 1 and 7 days; less cytotoxic in the presence of dentin	[81]
In vitro	Cell culture, direct contact (MTT)	Direct contact; GIC and RMGIC comparators	Vertise Flow	85.7% viability, comparable to GIC and RMGIC	[79]

In vitro	Mutagenicity assay	Ames test (Salmonella typhimurium TA100, without S9); DMSO eluates of 5 × 2 mm discs (24 h and 7 days, 37 °C), 25–100 µL per plate; DMSO and sodium azide controls	Vertise Flow	No mutagenic response under the stated assay conditions	[80]
In vitro	Dental-pulp stem cells	Eluates at a range of concentrations	Experimental SA-100R vs. Fusio Liquid Dentin, Constic, Vertise Flow	Experimental SAFRC not cytotoxic at any concentration	[16]
HPLC elution	—	Eluates analysed by HPLC; conventional flowables as comparators	Vertise Flow, Constic	Monomer elution not higher than from conventional flowables	[77]
In vivo	Rat subcutaneous implantation (7–90 days)	Subcutaneous implants; histology at 7–90 days	Vertise Flow, Fusio Liquid Dentin	Initial inflammation decreasing by 90 days; thickest capsule with Fusio Liquid Dentin	[82]
Clinical (12 months)	Gingival crevicular fluid, NCCL restorations	GCF sampling over 12 months; 30 patients; selective enamel etching and universal adhesive in all groups	Vertise Flow	Gingival cytokine changes under an adhesive-assisted protocol; not evidence of pulpal safety or adhesive-free biocompatibility	[83]

Table 5 does not support a reliable safety ranking of SAFRCs. Cell viability, bacterial mutagenicity, monomer elution, subcutaneous inflammation and gingival cytokines are different endpoints and should not be treated as interchangeable measures of biocompatibility. Differences in cell model, extraction medium, dilution, exposure duration and dentin barriers can change the apparent response. The reduction in cytotoxicity observed when dentin was interposed [81] illustrates the importance of exposure conditions. Subcutaneous implantation [82] cannot reproduce the pulp–dentin complex, and the clinical cytokine study used an adhesive in all groups [83]. Thus, neither a reduction in cell viability nor a favourable result in another model directly establishes clinical pulpal harm or safety. Product-specific studies using clinically relevant exposure and dentin-barrier models are needed, particularly for deep cavities.

8. Ion Release and Bioactivity Claims

Bioactivity should be defined in relation to a specified biological function rather than used as an unrestricted material label. The tissue-bonding framework discussed by Vallittu et al. [12] emphasises apatite formation and bonding to living tissue; broader dental frameworks also investigate remineralisation, antibacterial activity and tissue responses. Here, ion release is described as a physicochemical or bio-interactive property, a demonstrated effect on mineralised tissue or bacteria as a functional biological outcome, and a reduction in secondary caries or another patient-relevant outcome as clinical therapeutic benefit. These are distinct evidentiary claims, not a universal hierarchy that excludes other definitions of bioactivity. Demonstrating one does not establish the others; in particular, apatite precipitation in a test solution does not by itself demonstrate tissue bonding or clinical benefit.

Ion release is formulation- and protocol-dependent; the available findings do not justify a single release profile for all SAFRCs. In direct comparison, Fusio Liquid Dentin released only 0.07 ppm fluoride and no detectable strontium or aluminium, whereas experimental versions of FIT SA containing S-PRG filler released 0.88–0.91 ppm fluoride, along with sodium, borate, silicate, and strontium ions [33]. FIT SA also significantly inhibited Streptococcus mutans on its surface (≈4.0 vs. 7.2–7.9 log10 CFU for other SAFRCs), an effect attributed to borate release [15]; this is an in vitro surface effect that has not been linked to clinical outcomes. However, a recent meta-analysis of S-PRG-containing dental materials in general, rather than SAFRCs specifically, found very high heterogeneity and low certainty of evidence for fluoride release and mechanical benefits [84]. Experimental calcium-phosphate-containing resin composites incorporating polylysine or nisin have shown apatite precipitation under laboratory conditions [85,86], and 10-MDP content has been varied to investigate polymerisation and flexural strength in experimental remineralising composites [87]. These are material-development studies, including a dual-cured formulation [86], and should not be treated as direct evidence for the commercial light-cured SAFRC category defined in Section 2. Similarly, ACTIVA released few ions at neutral pH and showed no evidence of apatite formation in vitro [26,88], and its clinical experience (Section 3.2) illustrates that ion-release claims do not compensate for inadequate adhesion [11]. Ion release also depends strongly on the test environment: for glass-ionomer, glass-hybrid, alkasite and resin-based restoratives, the release of fluoride, calcium, phosphate, silicon and strontium varied with pH, temperature and immersion time [89]. Although these materials are not SAFRCs, such data show that release values obtained with different protocols cannot be compared directly and that release at neutral pH may not reflect behaviour under cariogenic, acidic conditions.

Within the evidence reviewed, ion release and surface antibacterial findings for commercial SAFRCs have not established clinical remineralisation or caries prevention. Claims should therefore name the measured property and test conditions. Future studies should specify the release medium, pH, temperature, specimen geometry and exposure duration, and test whether the observed release produces a reproducible functional effect at the tooth–restoration interface before inferring clinical benefit.

9. Clinical Applications, Evidence and Protocol

9.1. Indications Claimed Versus Indications Supported

Manufacturers' indications differ considerably between products (Table 3) and include small Class I restorations, pit-and-fissure sealing and preventive resin restorations, liners/bases, small retentive Class II restorations, Class III and V restorations, undercut blocking and porcelain repair [8]. Additional off-label uses reported in vitro include orthodontic bracket bonding [90,91] and repair of CAD/CAM resin-matrix ceramics when combined with a universal adhesive [92], while one clinical study evaluated Vertise Flow for the treatment of cervical dentin hypersensitivity [93]. The clinical evidence, however, supports only a subset of these indications (Figure 5; Table 6).

9.2. Clinical Evidence

The RCTs are summarised in Table 6. In small Class I (occlusal) cavities of permanent teeth, SAFRCs performed similarly to conventional flowable composites used with an adhesive: Vertise Flow retained 91.2% of restorations at 2 years without enamel etching [94], showed no significant differences from a conventional flowable at 24 months [95] and had cumulative retention losses of 15.3% versus 7.6% for an etch-and-rinse control at 5 years, a difference that was not statistically significant [96]. Constic showed no losses but significantly more marginal-adaptation defects than adhesive-based controls at 24 months [97],

and Fusio Liquid Dentin showed 100% retention over 18 months, as did two bulk-fill protocols, although differences in several secondary criteria were reported [98]. A meta-analysis reported broadly similar short-term outcomes but highlighted the small number of studies and the short follow-up [18]. In primary molars, Vertise Flow and Fusio Liquid Dentin showed acceptable 1-year results [99,100], and postoperative sensitivity was similar to conventional composite [101]. These trials differ in product, cavity design, patient age, isolation, evaluation criteria (modified USPHS or FDI) and attrition (Table 6), so their results apply to the specific materials and conditions tested and cannot be generalised to all SAFRCs. Most trials had a follow-up of 24 months or less; the longest follow-up, 5 years, comes from a single RCT of Vertise Flow (65 restorations in 25 patients, 47 of which were evaluated at 5 years) [96]. This trial provides longer-term evidence for one product in minimally invasive Class I cavities, but its small sample, reported 68% recall and deterioration in marginal adaptation limit certainty. A non-significant between-group difference does not demonstrate equivalence or non-inferiority, and the findings cannot be extended to other products or cavity types.

Results were markedly poorer in non-retentive or less favourable situations. In a pit-and-fissure sealant trial, Vertise Flow achieved complete retention in 62.9% of evaluated teeth after 24 months, compared with 95.7% for Tetric EvoFlow with an adhesive, despite phosphoric-acid pretreatment of enamel in both flowable-composite groups [102]. These percentages refer to the evaluated cohort, not all originally treated teeth. In non-carious cervical lesions, 27 of 40 Fusio Liquid Dentin restorations failed within 6 months because of retention loss (33% success) [103], although Vertise Flow restorations were clinically acceptable except for marginal adaptation after 12 months in another study, in which selective enamel etching and a universal adhesive were applied in all groups [83]. Although enamel pretreatment was used in some studies, the included trials do not provide a direct randomised comparison of the same SAFRC placed with versus without selective enamel etching. Its incremental clinical benefit therefore remains a research gap.

Clinical longevity also depends on operator- and patient-related factors, including adherence to the IFU, isolation, caries risk and occlusal load [104]. In one RCT, rubber dam versus cotton-roll isolation did not significantly affect the 2-year performance of Vertise Flow [94], but, given the moisture sensitivity of resin-based materials, effective isolation remains advisable.

Table 6. Randomised clinical trials of SAFRCs. Studies of polyacid-based or ionic-resin restoratives are not included (see Section 3.2). The 5-year trial [96] is the only one with follow-up beyond 2 years.

Study	Indication	SAFRC vs. Control	Patients; Restorations	Enamel Etching	Follow-Up	Criteria; Recall	Main Outcome
[94]	Small Class I, permanent molars (children)	Vertise Flow vs. Premise Flowable + SE adhesive	34 children; 68 (34 SAFRC)	No	2 years	Modified USPHS; 100%	Retention 91.2% vs. 97.1%; similar performance; isolation method not significant
[95]	Conservative occlusal cavities	Vertise Flow vs. Filtek Z350 XT Flowable + universal adhesive	18 patients; 36 (18 SAFRC), split-mouth	No (SAFRC)	2 years	Modified USPHS; 100% (no dropouts)	No significant differences for any criterion
[96]	Minimally invasive Class I	Vertise Flow vs. Luxaflow + E&R adhesive	25 patients; 65 (33 SAFRC)	No (SAFRC)	5 years	FDI; 47 restorations evaluated; reported recall 68% (different denominators)	Cumulative retention loss 15.3% vs. 7.6% (n.s.); marginal adaptation deteriorated in both

[97]	Occlusal cavities	Constic vs. conventional/highly filled flowables + universal adhesive	28 patients; 114 (four groups)	No (SAFRC)	2 years	Modified USPHS; recall n.v.	No losses; significantly more marginal-adaptation defects with Constic
[98]	Class I	Fusio Liquid Dentin vs. conventional systems	20 patients; 60 (20 SAFRC)	n.r.	18 months	USPHS and SEM replicas; 60/60 restorations at 18 months (100%)	100% retention in all groups; differences in secondary criteria at 12–18 months
[99]	Occlusal, primary molars	Vertise Flow vs. universal composite + SE adhesive	31 children; 62 (31 SAFRC), split-mouth	No	1 year	Modified USPHS; 29/31 patients at 1 year (93.5%)	100% retention; no significant differences
[100]	Class I, primary molars	Fusio Liquid Dentin vs. Flow-It ALC	20 children; 40 (20 SAFRC), split-mouth	n.r.	1 year	Modified USPHS (Ryge); 16/20 restorations per group at 1 year (80%)	All restorations clinically acceptable
[102]	Pit-and-fissure sealing	Vertise Flow vs. sealants and flowable + adhesive	136 children; 544 sealants at baseline (four first molars per child); 448 evaluated	Yes: 37.5% phosphoric acid, 15 s; no adhesive for Vertise Flow	2 years	Retention and ICDAS II; 112/136 patients (82.4%); 116 Vertise Flow sealants evaluated	Complete retention 62.9% vs. 95.7% for flowable + adhesive
[103]	Non-carious cervical lesions	Fusio Liquid Dentin vs. nanohybrid + 3-step E&R	80 lesions (40 SAFRC); split-mouth; patient count n.v.	No	6 months	FDI; recall n.v.	27/40 SAFRC restorations failed (33% success) vs. 100%
[83]	Non-carious cervical lesions	Vertise Flow vs. two flowables	30 patients; 90 (30 SAFRC)	Yes (selective etching + universal adhesive, all groups)	1 year	Modified USPHS; dropouts n.r. (results reported for all 90 restorations)	Acceptable except marginal adaptation; favourable gingival cytokine profile
[101]	Deep Class I (third molars)	Vertise Flow vs. composite + SE adhesive	27 patients; 54 (27 SAFRC), split-mouth	n.r.	24 h; 15 or 30 days	VAS (postoperative sensitivity); recall n.v.	Similar postoperative sensitivity

E&R, etch-and-rinse; FDI, FDI World Dental Federation criteria; SE, self-etch; SEM, scanning electron microscopy; USPHS, United States Public Health Service criteria; VAS, visual analogue scale; n.r., not reported in the supplied extraction; n.v., not verified from the accessible primary report; n.s., not statistically significant. Patient counts and restoration counts are distinct units; multiple restorations in one patient are not independent participants. Recall percentages retain the denominators reported by the original studies. For [96], the reported recall is 68%, whereas 47/65 is the proportion of restorations evaluated; these should not be treated as the same measure. In [102], 112/136 patients attended all visits and 448/544 teeth were evaluated, including 116 Vertise Flow sealants. In [83], selective enamel etching and a universal adhesive were applied in all groups, so the trial does not test adhesive-free use. Missing verification is not evidence that a study omitted the information.

9.3. Suggested Clinical Protocol

On the basis of the evidence above, and with the caveat that most data concern individual products (mainly Vertise Flow, Constic and Fusio Liquid Dentin) in specific clinical situations, a cautious interpretation is that SAFRCs are best suited to small, retentive, enamel-bordered cavities under low occlusal stress, for example, conservative occlusal restorations in permanent or primary molars, (Figure 5). Liner/base use is a separate manufacturer indication with supporting laboratory findings; it should not be presented as established by the Class I clinical trials. They should not be used without an adhesive in non-retentive cervical lesions, in stress-bearing posterior restorations or in bulk increments. The following sequence is suggested; it is informed by laboratory findings and manufacturers' IFUs, and its clinical superiority over placement without enamel etching has not been established in RCTs: effective isolation; preparation that avoids a thick smear layer; selective phosphoric-acid etching of enamel margins where recommended or permitted by the product IFU, avoiding unapproved dentin pretreatment [8,14,41]; a thin first layer actively applied for the product-specific time; light-curing; incremental placement within the product-specific thickness limit, generally ≤ 2 mm, with curing adjusted to the prescribed exposure, irradiance and shade [45,49]; and finishing, polishing and periodic review of marginal integrity.

Two further considerations apply. First, clinical success depends on factors beyond adhesive strength, including cavity geometry, occlusal loading, adequate polymerisation, moisture control and operator technique, and the indications above assume that these are favourable. Second, the simplification offered by SAFRCs should be distinguished from actual procedural efficiency: when selective enamel etching, active brushing of the first layer, incremental placement and full curing times are followed, the time saved compared with a conventional flowable composite and a universal adhesive may be modest, and the studies included here did not quantify this difference.

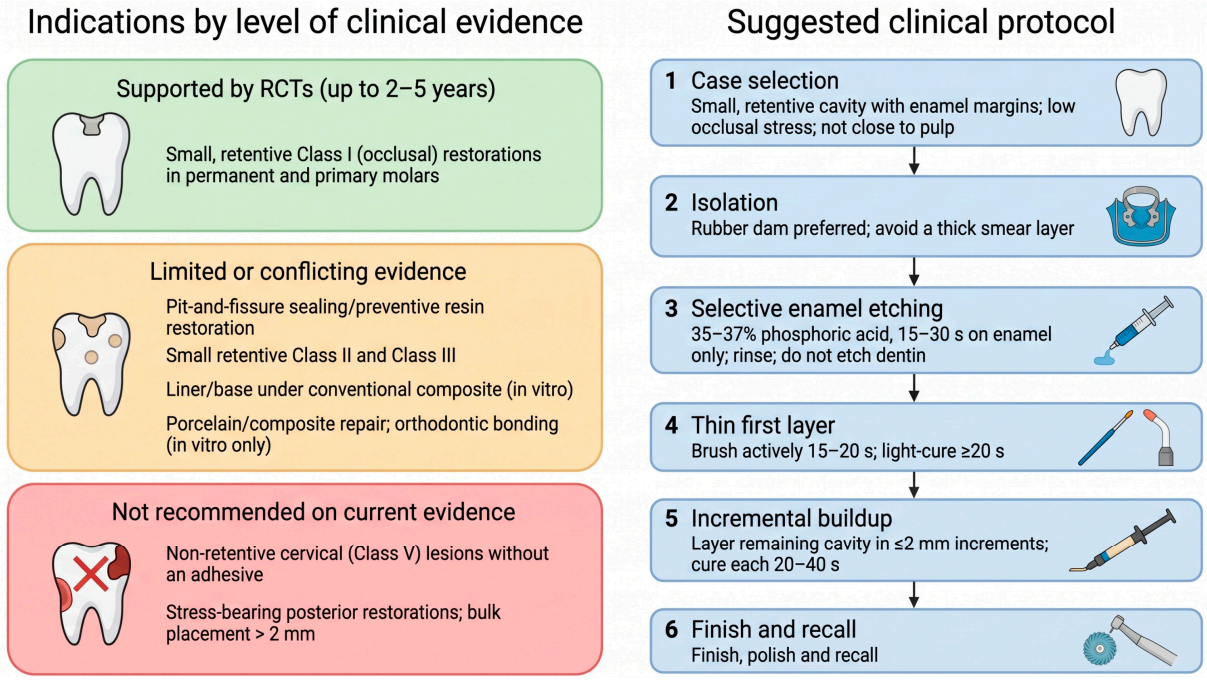


Figure 5. Indications of self-adhesive flowable-resin composites according to the level of clinical evidence, and a suggested clinical protocol including selective enamel etching. The 5-year evidence concerns one product in permanent teeth; the primary-molar trials were limited to 1 year. The sequence is a laboratory- and IFU-informed proposal, not a clinically validated superior protocol, and product-specific instructions take precedence over the illustrative timings shown. Liner/base and

repair indications have predominantly laboratory support. Based on [8,14,41,94–97,102,103]. Created in BioRender [22].

10. Evidence Gaps, Future Directions and Research Opportunities

The laboratory findings provide plausible explanations for the clinical pattern, but do not establish its causes. Limited interfacial interaction and susceptibility to water uptake may contribute to poorer performance where retention depends strongly on adhesion. Acceptable outcomes in selected small Class I cavities may also reflect cavity geometry, occlusal load, isolation and operator technique. The poorer sealant result occurred despite enamel etching [102], underscoring that improving one interfacial property does not guarantee clinical success. Table 7 distinguishes positive clinical findings, adverse clinical findings and questions for which clinical evidence is absent. Absence of a trial should not be interpreted as proof of ineffectiveness.

Table 7. Evidence-gap analysis: clinical questions on SAFRCs supported by clinical studies versus those addressed only in the laboratory or not yet studied.

Clinical Question	Clinical Evidence	Laboratory Evidence	Current Status
Small Class I (occlusal) restorations in permanent teeth, ≤2 years	Several RCTs and a meta-analysis; similar to conventional flowables for the products tested [18,94,95,97,98]	Supportive (retentive cavity, low stress)	Favourable short-term findings for tested products; equivalence not established
Long-term (>2 years) performance	One RCT (Vertise Flow, 5 years) [96]	Bond-strength reduction and hydrolytic degradation with ageing [13,56]	Limited; single product
Occlusal restorations in primary molars	Two 1-year RCTs [99,100]	Lower bond strength to primary dentin [65]	Limited; short term
Pit-and-fissure sealing	One trial; inferior complete retention despite phosphoric-acid pretreatment [102]	Low enamel bond strength without etching [6,14]	Adverse retention evidence for the tested product and protocol
Non-carious cervical lesions	One RCT of adhesive-free use (33% success at 6 months) [103]; one RCT with an adhesive in all groups [83]	Microleakage at enamel margins; low dentin bond strength [58,59]	Not supported without an adhesive
Class II and stress-bearing restorations	No direct RCT identified in the included evidence for adhesive-free definitive restoration	Marginal integrity as a liner [67]; low strength and toughness [42,46]	Insufficient clinical evidence; liner findings do not establish definitive-restoration performance
Selective enamel etching	No direct randomised comparison of the same SAFRC with versus without etching identified	Improved enamel bonding and sealing [6,14,41,59]	Laboratory evidence only; research priority
Postoperative sensitivity	One short-term RCT [101]	—	Limited
Pulpal biocompatibility in deep cavities	No long-term clinical pulpal-safety evidence in the included synthesis	Product-dependent in vitro cytotoxicity; one animal study [10,16,78,81,82]	Clinical safety remains uncertain; laboratory evidence is indirect
Ion release, antibacterial and anticaries effects	No clinical outcome data	Ion release and surface antibacterial activity of an S-PRG formulation [15,33]	Laboratory evidence only
Chairside time and cost	Not quantified in the included studies	—	Evidence gap in this synthesis

Material-development priorities include hydrolytically stable functional monomers, matrices with lower water uptake, and ion-releasing fillers assessed for both interfacial durability and biological function [8,15,33,84]. Pretreatments such as collagen depletion or alternative conditioners require validation of their effects on bonding and biological response [8,40]. Polymerisable polyacid systems offer a related route to adhesive

simplification [9], but fall outside the SAFRC definition used here when they introduce a glass-ionomer-type setting mechanism. Their development should therefore be distinguished from improving SAFRCs within the present chemical category.

Several research opportunities follow from the gaps in Table 7. In the laboratory, studies should report test methods, specimen geometry, storage media and ageing protocols in full, apply ISO 4049 conditions when results are compared with its thresholds, and assess bond durability after clinically relevant ageing rather than at 24 h only. Ion release should be measured under standardised conditions that include acidic challenges [89] and be linked to functional outcomes such as remineralisation or bacterial inhibition at the tooth–restoration interface. Biological studies should test the acidic functional monomers in isolation, and the eluates of fully formulated products in dentin-barrier models that simulate deep cavities. Clinically, the priorities are adequately powered RCTs with follow-up beyond three years, randomised comparisons with and without selective enamel etching, carefully justified evaluation of new formulations or protocols in broader indications only after satisfactory preclinical performance, outcome reporting with FDI criteria, prespecified primary endpoints, transparent patient- and restoration-level attrition and analyses accounting for clustering or split-mouth allocation, and studies that quantify chairside time and cost, since the presumed efficiency of SAFRCs has not been measured. Finally, independent disclosure and verification of composition, and a consensus on terminology, would allow results to be attributed to defined material categories and would improve the comparability of future studies and reviews [105–135].

11. Conclusions

SAFRCs are light-cured flowable-resin composites that rely on acidic functional monomers for a mild, shallow interaction with tooth structure, the chemical stability of which depends on the functional monomer and the formulation. They should be clearly distinguished from polyacid-based hybrid restoratives, ionic-resin "bioactive" materials and RMGICs. For the tested products, laboratory dentin bond strengths are generally lower than those of adhesive-based controls; selective phosphoric-acid etching improves enamel bonding and marginal sealing under laboratory conditions and is recommended or permitted by several manufacturers; and water sorption and solubility are generally higher than those of conventional flowable composites, although their magnitude depends on the test conditions. The S-PRG-filled formulation showed favourable flexural strength, degree of conversion, dentin bond strength, ion release and surface antibacterial activity in vitro, whereas 10-MDP has not consistently conferred higher bond strength on commercial products, and ion release alone establishes neither a functional biological effect nor therapeutic benefit. Current clinical evidence is heterogeneous, product-specific and largely limited to 24 months, with a single 5-year trial. It supports the use of the tested products mainly for small, retentive, low-stress cavities-particularly conservative occlusal restorations—with incremental placement; selective enamel etching can be considered where supported by the product IFU, with its additional clinical benefit still requiring direct evaluation. SAFRCs should not be regarded as general substitutes for adhesive-based composite restorations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jfb17110557/s1, Table S1: Database search strategies, dates and results.

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Abbreviations

4-META/4-MET, 4-methacryloyloxyethyl trimellitate anhydride/acid; 10-MDP, 10-methacryloyloxydecyl dihydrogen phosphate; Bis-EMA, ethoxylated bisphenol A dimethacrylate; Bis-GMA, bisphenol A glycidyl methacrylate; GDMA, glycerol dimethacrylate; GPDM, glycerol phosphate dimethacrylate; HEMA, 2-hydroxyethyl methacrylate; IFU, instructions for use; RBC, resin-based composite; RCT, randomised clinical trial; RMGIC, resin-modified glass-ionomer cement; SAFRC, self-adhesive flowable-resin composite; SBS, shear bond strength; SDS, safety data sheet; S-PRG, surface pre-reacted glass-ionomer; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate; μTBS, microtensile bond strength.

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