SYSTEMATIC REVIEW

Effect of Titanium Dioxide and Silica Nanoparticle Incorporation on the Compressive and Flexural Strength of Conventional Glass Ionomer Cement: A Systematic Review of In Vitro Studies

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Running title: TiO_2 and SiO_2 nanoparticles in conventional GIC

ABSTRACT

Background: Conventional glass ionomer cement (GIC) has low compressive and flexural strength. Titanium dioxide (TiO_2) and silica (SiO_2) nanoparticles have been added to its powder to reinforce it, but results conflict.

Objective: To assess the effect of TiO_2 and SiO_2 nanoparticle incorporation on the compressive strength (CS) and flexural strength (FS) of conventional GIC, and to compare the two additives.

Methods: The review followed PRISMA 2020 and a protocol registered in PROSPERO (CRD420261414851). PubMed, Scopus, Science Citation Index Expanded, Social Sciences Citation Index, the Cochrane Database of Systematic Reviews and Google Scholar were searched without date or language limits, supplemented by citation, thesis and conference searching. In vitro studies comparing nanoparticle-modified with unmodified conventional GIC and reporting CS or FS in MPa were included. Risk of bias was rated on seven laboratory-study domains. Where at least three studies reported means and standard deviations for the same additive and concentration, Hedges' g was pooled with a random-effects model; otherwise results were synthesised narratively.

Results: Fourteen studies met the criteria: eleven on TiO_2, two on SiO_2 and one on combined TiO_2 + SiO_2. With TiO_2, five of six studies reported higher CS at one or more concentrations, and six of nine reported higher FS; gains were concentrated at 3–5 wt% and reversed at 7 wt% or more. Exploratory pooling of 5 wt% TiO_2 favoured higher FS (g = 1.31, 95% CI 0.20 to 2.43; three studies; I^2 = 73%), whereas pooled estimates at 3 wt% were inconclusive for CS (g = 0.23, −2.07 to 2.53; I^2 = 92%) and FS (g = 2.71, −0.87 to 6.29; I^2 = 95%). Evidence on SiO_2 was sparse and inconsistent: nano-silica reduced the CS of a luting GIC at 1–5 wt%, and combined TiO_2 + SiO_2 reduced CS. No study compared TiO_2 and SiO_2 directly. Eleven studies were at moderate and three at high risk of bias, and certainty of evidence was very low.

Conclusions: Adding 3–5 wt% TiO_2 nanoparticles may increase the flexural and compressive strength of restorative conventional GIC, but effects vary by product, concentration and mixing. Evidence for silica nanoparticles is too limited for conclusions. Standardised ISO-based studies with adequate samples are needed.

Keywords: Glass ionomer cement; Titanium dioxide nanoparticles; Silica nanoparticles; Compressive strength; Flexural strength; Restorative dentistry; Biomaterials

Registration: PROSPERO CRD420261414851 (registered 03 June 2026)

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1. INTRODUCTION

Conventional glass ionomer cement (GIC) sets by an acid–base reaction between a fluoroaluminosilicate glass and a polyalkenoic acid [1]. Chemical adhesion to enamel and dentine, sustained fluoride release, a thermal expansion close to tooth structure and good biocompatibility make it a standard material for paediatric restorations, atraumatic restorative treatment, liners and luting [2]. Its brittleness and low compressive and flexural strength, however, restrict its use in stress-bearing posterior cavities [3]. A compressive strength of about 125 MPa has been proposed as the minimum for posterior permanent teeth and 100 MPa for primary teeth [6].

Nanotechnology has offered a route to reinforcement without abandoning the glass ionomer chemistry. Nanoparticles may fill spaces between the larger glass particles, provide additional sites for polyacrylate cross-linking and deflect cracks [4,5]. Titanium dioxide (TiO_2) is

chemically stable, biocompatible and antibacterial, and since 2011 several laboratory studies have reported higher strength after adding TiO_2 nanoparticles to GIC powder [13]. Silica (SiO_2) is a native component of ionomer glass and a common nanofiller in resin composites, and nano-silica has also been blended into GIC [23,26].

The findings are inconsistent. Some studies report clear gains in compressive and flexural strength, others report no change or a fall, and the optimum concentration differs between products [13,18,20]. Earlier reviews of GIC modification were narrative and covered many additives, including composite fillers such as nano-hydroxyapatite–silica [4,5]. No systematic review has focused on TiO_2 and SiO_2 nanoparticles in conventional GIC.

The objective of this review was to systematically assess the effect of TiO_2 and SiO_2 nanoparticles on the compressive and flexural strength of conventional GIC and to compare their effectiveness in improving these properties.

2. METHODS

2.1 Protocol and registration

The review was reported according to PRISMA 2020 [8]. The protocol was registered in PROSPERO on 03 June 2026 (CRD420261414851).

2.2 Eligibility criteria

Element	Inclusion	Exclusion
Population	Specimens of commercially available conventional (self-cure, acid–base) GIC: restorative, luting, lining or core build-up	Resin-modified GIC, glass hybrids, compomers, composites, experimental glasses not based on a commercial GIC
Intervention	TiO_2 and/or SiO_2 nanoparticles (any dimension below 100 nm, including nanotubes) added to the powder, at any concentration, size or incorporation method	Other nanoparticles; TiO_2 or SiO_2 only as part of a composite filler (for example hydroxyapatite–silica) or as a drug carrier; micro- or submicron particles
Comparator	Unmodified conventional GIC of the same product	No unmodified control
Outcomes	Compressive strength and/or flexural strength in MPa	Neither outcome reported quantitatively
Study design	In vitro experimental laboratory studies	Reviews, case reports, animal and clinical studies, editorials, abstracts without full data

2.3 Information sources and search

PubMed, Scopus, Science Citation Index Expanded, Social Sciences Citation Index, the Cochrane Database of Systematic Reviews and Google Scholar were searched from inception to [insert date of final search], with no language or date restriction. Reference lists and citing articles of included studies were checked, and theses, dissertations and conference proceedings were searched. The PubMed strategy, adapted for the other sources, was:

("glass ionomer cement*" OR "glass-ionomer" OR "glass polyalkenoate" OR GIC) AND ("titanium dioxide" OR TiO2 OR titania OR silica OR SiO2 OR "silicon dioxide" OR nanosilica) AND (nanoparticle* OR nano* OR nanotube*) AND ("compressive strength" OR "flexural strength" OR "mechanical propert*")

For Google Scholar, the first [insert number] records sorted by relevance were screened.

2.4 Study selection

Records were de-duplicated and screened independently by two reviewers (AC, KB) at title and abstract and then full-text level. Disagreements were resolved by discussion, with a third reviewer consulted when needed. Reasons for full-text exclusion were recorded.

2.5 Data collection

As registered, one reviewer extracted data into a piloted form: author, year, country, GIC product and indication, nanoparticle type, size, phase and source, concentration (wt%), mixing method, powder/liquid ratio, specimen dimensions, storage medium and time, test standard, crosshead speed, sample size, outcome means with standard deviations, and statistical findings. A second reviewer checked the extracted data. Authors were contacted for missing data [insert whether any replied]. Where a study reported several GIC products, each product–control pair was extracted separately.

2.6 Risk of bias

Two reviewers independently rated seven domains prespecified in the protocol: sample size calculation; randomisation of specimens; presence of an unmodified control; standardisation of specimen preparation (ISO dimensions, storage and testing conditions); blinding of the testing operator; completeness and consistency of outcome reporting; and appropriate statistical analysis. Each domain was rated yes, no or unclear. Studies with five or more yes ratings were judged low risk, three or four moderate, and two or fewer high risk.

2.7 Synthesis methods

The effect measure was the standardised mean difference (Hedges' g) between modified and unmodified GIC, chosen because specimen geometry, storage and testing protocols differed between studies. Where at least three studies reported means, standard deviations and sample sizes for the same additive, outcome and concentration, estimates were pooled with a DerSimonian–Laird random-effects model [11]. Heterogeneity was quantified with I^2 and τ^2. Because of the small number of studies, the Hartung–Knapp–Sidik–Jonkman adjustment was applied as a sensitivity analysis [12]. Pooled estimates were considered exploratory. All other data were synthesised narratively following SWiM guidance [10], grouped by additive, outcome and concentration, with the direction of effect tabulated.

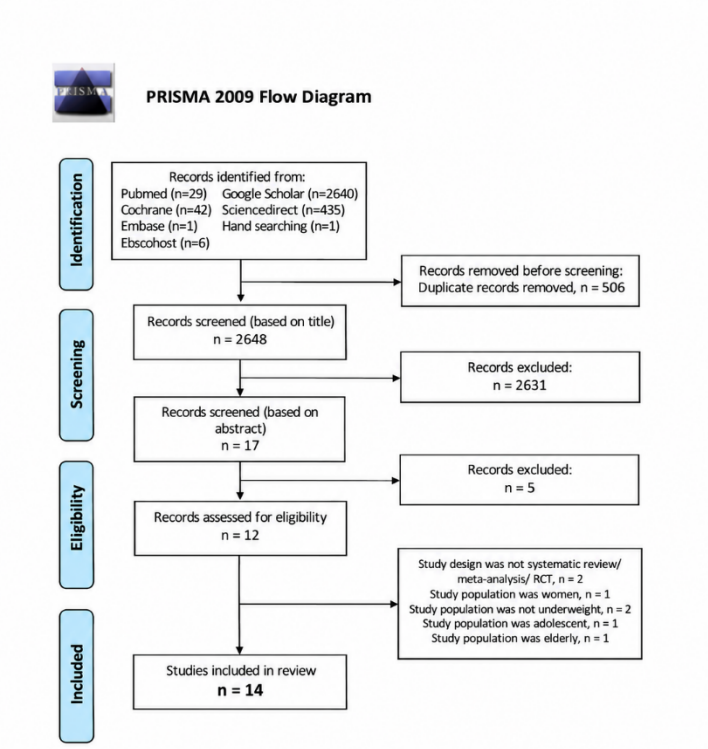
2.8 Reporting bias and certainty of evidence

Funnel plots and Egger's test were not used because fewer than ten studies contributed to any comparison. Certainty for each outcome was rated with an approach adapted from GRADE [9], considering risk of bias, consistency,

indirectness of laboratory evidence, precision and completeness of reporting. Laboratory evidence started at low certainty.

3. RESULTS

3.1 Study selection



PRISMA 2020 flow · 14 studies included

Bracketed counts are to be completed from the database exports of the final search.

3.2 Study characteristics

The fourteen studies were published between 2011 and 2026 (Table 1). Eleven tested TiO_2, two SiO_2 and one a 2.5 wt% TiO_2 + 2.5 wt% SiO_2 combination. Ten studies used restorative GIC (Fuji IX family, Ketac Molar, Kavitan Plus, Fuji II), and four included a luting, lining or core cement. Concentrations ranged from 1 to 10 wt%. Most TiO_2 particles were anatase with primary sizes of 10–25 nm; one study used TiO_2 nanotubes [17] and two used plant-mediated green synthesis [24,25]. Compressive strength was reported in nine studies and flexural strength in ten. Group sizes ranged from 3 to 20 specimens.

Table 1. Characteristics of included studies

Study	Country	GIC (indication)	Nanoparticle; size	Concentration (wt%)	Outcome(s); n per group	Main finding vs unmodified GIC
Elsaka et al., 2011 [13]	Egypt	Kavitan Plus (restorative)	TiO_2	3, 5, 7	CS, FS; [verify]	CS and FS higher at 3% and 5%; lower at 7%
Liu & Chen, 2014 [14]	China	Conventional restorative GIC [verify brand]	TiO_2	3, 6, 9	CS, FS; [verify]	CS and FS higher at 3% and 6%; lower at 9%
Garcia-Contreras et al., 2015 [15]	Mexico/Japan	Three GC cements: restorative, core build-up, base/liner	TiO_2 anatase; <25 nm	3, 5	CS, FS; 20	Restorative: CS and FS higher at 3% and 5%. Core: CS higher at 5% only. Base: no gain
Hamid et al., 2019 [16]	India	Fuji IX Gold Label (restorative)	TiO_2 anatase; 10–20 nm	3	CS; 12	CS higher (172.5 vs 140.0 MPa)
Kantovitz et al., 2020 [17]	Brazil	Ketac Molar EasyMix (restorative)	TiO_2 nanotubes	3, 5, 7	CS 10; FS 18	CS higher at 5% only; FS unchanged
Ivanišević et al., 2021 [18]	Croatia	Fuji IX GP Extra (restorative)	TiO_2 P25; 20 nm	3	CS; 4 (6 in figure)	CS lower (109.2 vs 172.7 MPa)
Showkat et al., 2023 [19]	India	GC Type IX (restorative)	TiO_2 anatase; 10–20 nm	3	FS; 12	FS higher (27.8 vs 5.3 MPa)

Study	Country	GIC (indication)	Nanoparticle; size	Concentration (wt%)	Outcome(s); n per group	Main finding vs unmodified GIC
Panahandeh et al., 2024 [20]	Iran	Fuji II (restorative)	TiO_2 sol-gel anatase	3, 5, 10	FS; 5	FS higher at 5% only; 3% and 10% unchanged
Ramić et al., 2024 [21]	Serbia	Fuji IX; Ketac Molar (restorative)	TiO_2	5	FS; [verify]	FS unchanged in both cements
Elbatanony & El Shahawi, 2024 [22]	Egypt	GC Gold Label Luting & Lining	TiO_2 + SiO_2	2.5 + 2.5	CS; [verify]	CS lower
Utama et al., 2025 [23]	Indonesia	Fuji I (luting)	SiO_2 sol-gel, diatom-derived	1, 3, 5	CS; 3	CS lower at all concentrations (3%: 64.4 vs 78.8 MPa)
Karamüftüoğlu et al., 2026 [24]	Turkey	Ketac Molar EasyMix (restorative); Ketac Cem (luting)	TiO_2 green-synthesised (hemp)	1, 3, 5	FS; [verify]	Restorative: FS higher at 1% and 3%, lower at 5%. Luting: unchanged
Abozaid et al., 2026 [25]	Egypt	Fuji IX GP (restorative)	TiO_2 green-synthesised (Citrus aurantium); 12 nm	5, 10	FS; 10	FS unchanged (P = 0.35)
Pangabdian et al., 2026 [26]	Indonesia	Fuji IX (restorative)	SiO_2 natural (beach sand, ~70 nm) or synthetic fumed	3	CS, FS; 7	CS 63.6 (natural) and 41.9 (synthetic) vs 37.1 MPa control; natural > synthetic

CS, compressive strength; FS, flexural strength. [verify] marks details not available in the accessed report.

3.3 Risk of bias

Eleven studies were at moderate and three at high risk of bias (Table 2). All had an unmodified control and used appropriate statistics, but none reported a sample size calculation, randomised allocation of specimens or a blinded testing operator. Reporting problems were found in three studies: inconsistent sample sizes [18], a transposed results table and a conflict between abstract and results [20], and a mean reported differently in text and table [23].

Table 2. Risk of bias

Study	Sample size calculation	Randomisation	Control group	Standardised preparation	Blinding	Complete reporting	Appropriate statistics	Overall
Elsaka 2011	U	U	Y	Y	U	U	Y	Moderate
Liu 2014	U	U	Y	U	U	U	U	High
Garcia-Contreras 2015	N	N	Y	Y	N	Y	Y	Moderate
Hamid 2019	N	U	Y	Y	U	Y	Y	Moderate
Kantovitz 2020	U	U	Y	Y	U	U	Y	Moderate
Ivanišević 2021	N	U	Y	Y	U	N	Y	Moderate
Showkat 2023	N	U	Y	U	U	Y	Y	Moderate
Panahandeh 2024	N	U	Y	Y	U	N	Y	Moderate
Ramić 2024	U	U	Y	Y	U	U	Y	Moderate
Elbatanony 2024	U	U	Y	U	U	U	Y	High
Utama 2025	N	U	Y	Y	U	N	Y	Moderate
Karamüftüoğlu 2026	U	U	Y	U	U	U	Y	High
Abozaid 2026	N	U	Y	Y	U	Y	Y	Moderate
Pangabdian 2026	U	U	Y	U	U	U	Y	High

Y, yes; N, no; U, unclear. Ratings for studies marked [verify] in Table 1 are based on the abstract and should be confirmed against the full text.

3.4 Compressive strength

TiO_2. Six studies reported CS [13–18]. Five found higher CS at one or more concentrations [13–17], and one found lower CS at 3 wt% when the manufacturer's powder/liquid ratio was kept unchanged [18]. Gains were seen at 3–6 wt% and reversed at 7 wt% or more [13,14]. In the multi-product study, only the restorative cement and, at 5 wt%, the core build-up cement benefited; the base/liner did not [15].

Three studies contributed to an exploratory meta-analysis of 3 wt% TiO_2 (Table 3). The pooled estimate was imprecise and non-significant, with very high

heterogeneity driven by one study with the opposite direction [18].

SiO_2 and combined. Nano-silica lowered the CS of a luting GIC at 1, 3 and 5 wt% (n = 3 per group) [23]. In a restorative GIC, 3 wt% natural nano-silica gave higher CS than the control (g = 1.69, 95% CI 0.47 to 2.91, calculated from reported data), whereas synthetic fumed silica did not (g = 0.26, −0.80 to 1.31) [26]. The combination of 2.5 wt% TiO_2 and 2.5 wt% SiO_2 lowered the CS of a luting cement [22].

3.5 Flexural strength

TiO_2. Nine studies reported FS. Six found higher FS at one or more concentrations [13–15,19,20,24], and three found no change [17,21,25]. In two studies FS fell at the highest concentration (9 wt% and 5 wt%) [14,24]. Luting, lining and base cements did not benefit [15,24].

Exploratory pooling at 5 wt% TiO_2 favoured higher FS; at 3 wt% the estimate was large but imprecise and highly heterogeneous (Table 3). The 3 wt% result depended on a study whose control FS (5.3 MPa) was far below typical values for this cement [19].

SiO_2. One study reported FS with nano-silica; natural beach-sand silica gave higher FS than synthetic silica, but values against the unmodified control were not available in the accessed report [26].

Table 3. Exploratory random-effects meta-analysis (Hedges' g, modified minus control)

Outcome; additive	Study	g (95% CI)	Weight
CS; 3 wt% TiO_2	Garcia-Contreras 2015 (restorative)	0.84 (0.19 to 1.49)	36.8%
	Hamid 2019	2.55 (1.47 to 3.62)	35.0%
	Ivanišević 2021	−3.45 (−5.64 to −1.27)	28.2%
	Pooled	**0.23 (−2.07 to 2.53); I^2 = 92%; τ^2 = 3.63**	
FS; 3 wt% TiO_2	Garcia-Contreras 2015 (restorative)	1.41 (0.72 to 2.10)	35.4%
	Showkat 2023	8.44 (5.92 to 10.96)	30.4%
	Panahandeh 2024 (24 h)	−1.04 (−2.36 to 0.28)	34.2%
	Pooled	**2.71 (−0.87 to 6.29); I^2 = 95%; τ^2 = 9.31**	
FS; 5 wt% TiO_2	Garcia-Contreras 2015 (restorative)	1.51 (0.81 to 2.21)	40.3%
	Panahandeh 2024 (24 h)	2.59 (0.91 to 4.27)	22.9%
	Abozaid 2026	0.31 (−0.57 to 1.19)	36.9%
	Pooled	**1.31 (0.20 to 2.43); I^2 = 73%; τ^2 = 0.67**	

With the Hartung–Knapp–Sidik–Jonkman adjustment all three confidence intervals included zero (CS 3%: −7.13 to 7.58; FS 3%: −9.23 to 14.65; FS 5%: −1.34 to 3.97). Ivanišević 2021 was entered with n = 4 per group as stated in its methods. No SiO_2 comparison had three studies for pooling.

3.6 TiO_2 versus SiO_2

No included study compared TiO_2 and SiO_2 nanoparticles separately against the same control. Indirectly, TiO_2 was supported by more studies and more consistent gains in restorative cements, whereas the two SiO_2 studies gave conflicting results in different cement types.

3.7 Certainty of evidence

Table 4. Certainty of evidence

Outcome	Studies	Risk of bias	Consistency	Indirectness	Precision	Certainty
CS with TiO_2	6	Serious	Serious (I^2 = 92%)	Serious	Serious	Very low
FS with TiO_2	9	Serious	Serious (I^2 73–95%)	Serious	Serious	Very low
CS with SiO_2	2	Serious	Serious	Serious	Very serious	Very low
FS with SiO_2	1	Serious	Not assessable	Serious	Very serious	Very low

Indirectness reflects the laboratory setting and short storage times (24 h to 7 days) in most studies.

4. DISCUSSION

This review found that TiO_2 nanoparticles at 3–5 wt% increased the compressive or flexural strength of restorative conventional GIC in most studies, while higher concentrations reduced it. Evidence for silica nanoparticles was limited to two studies with conflicting results, and no study compared the two additives directly. All conclusions rest on very low-certainty laboratory evidence.

Mechanism and concentration. Nanoparticles are thought to occupy spaces between the larger glass particles, act as additional bonding sites for polyacrylic acid and impede crack propagation [4,13]. The rise and fall of strength with concentration seen in four studies [13,14,20,24] is consistent with agglomeration once nanoparticle loading exceeds what the polyacid can wet and bind. Agglomerates and unreacted particles then act as flaws [24,25].

Powder/liquid ratio and handling. The study that found lower CS kept the manufacturer's powder/liquid ratio and reported difficult hand mixing and more air inclusions [18]. Nanoparticles have a low bulk density and very high surface area, so replacing part of the powder by weight changes the volume and the acid available per particle. Powder/liquid ratio is known to govern GIC strength [33]. Differences in this variable, which most studies did not report, may explain much of the heterogeneity.

Product and indication. Gains were confined to restorative cements. Luting, lining and base formulations, which have finer glass and a lower powder content, did not benefit and in some cases lost strength [15,22–24]. Results from restorative cements should not be extrapolated to luting cements.

Silica. Silica is already the main constituent of ionomer glass but is not itself acid-reactive, so added nano-silica may act only as inert filler. One luting-cement study showed lower CS at every concentration [23], while a restorative-cement study found a benefit only with natural silica [26]. The combined TiO_2 + SiO_2 study also reported lower CS [22]. These three studies used small samples and

different cements, and do not support a conclusion either way.

Clinical relevance. Even where TiO_2 raised strength, several modified restorative cements remained below the 125 MPa proposed for posterior permanent teeth [6,15]. Most studies tested specimens after 24 hours to 7 days of storage, which says little about long-term behaviour, ageing or fatigue.

4.1 Strengths and limitations

The review was prospectively registered, searched six databases and supplementary sources without language restriction, and applied a prespecified risk-of-bias framework. Limitations stem mainly from the evidence: few studies per comparison, small groups, unreported sample size calculations and blinding, internal inconsistencies in three reports, implausibly low control values in two [15,19], and missing dispersion data for several studies. The meta-analyses included only three studies each and should be read as exploratory. As registered, data were extracted by one reviewer, which may increase extraction error.

4.2 Implications for research

Future studies should follow ISO 9917-1 specimen dimensions and test conditions [7], report the powder/liquid ratio by weight and volume, describe the dispersion method, calculate sample sizes, randomise and blind testing, and report means with standard deviations for every group. Head-to-head comparison of TiO_2 and SiO_2 in the same restorative cement, ageing or thermocycling, and fatigue testing are needed.

5. CONCLUSIONS

Within the limits of very low-certainty laboratory evidence:

1. Adding 3–5 wt% TiO_2 nanoparticles may increase the compressive and flexural strength of restorative conventional GIC, but the effect is inconsistent across products and studies.
2. Concentrations of 7 wt% or more tend to reduce strength, and luting or lining cements do not appear to benefit.
3. Evidence on SiO_2 nanoparticles, alone or combined with TiO_2, is too sparse and conflicting to support their use.
4. No direct comparison of TiO_2 and SiO_2 exists; standardised, adequately powered studies are needed before either can be recommended for stress-bearing restorations.

DECLARATIONS

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Conflicts of interest: None declared.

Author contributions: AC conceived the review, designed the search, screened studies, extracted data and drafted the manuscript. KB screened studies, checked data, assessed risk of bias and revised the manuscript. All authors approved the final version. [Edit as appropriate]

Data availability: Extraction forms, risk-of-bias judgements and meta-analysis data are available from the corresponding author on reasonable request.

Ethics: Not required for a systematic review of published laboratory studies.

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