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Shrinkage Mitigation Strategies for Concrete Bridge Decks: A Systematic Review and Bibliometric Analysis

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ABSTRACT

Concrete bridge decks develop early-age shrinkage cracks which create a widespread durability issue that speeds up steel reinforcement corrosion and requires more maintenance expenses and shortens the lifespan of the bridge. The study will conduct an organized evaluation to identify classification methods and assess the success rates of shrinkage control techniques used for concrete bridge decks. The research will identify missing information to direct upcoming studies and operational procedures in the field. Systematic review (PRISMA), which analyzed 154 studies published between 2000 and 2025 that they found in Scopus and Web of Science and various engineering databases. Bibliometric analysis performed to map research trends, geographic distribution, and thematic clusters. The study discovered nine main strategies which were analyzed against each other including shrinkage-reducing admixtures, fiber reinforcement, internal curing with lightweight aggregates, supplementary cementitious materials, expansive agents, optimized mix design, improved curing practices, and combined multi-strategy approaches. Shrinkage-reducing admixtures reduced drying shrinkage by (25-40) %, internal curing by (30-45) %, and UHPC overlays by up to 55%. The combination of shrinkage-reducing admixtures and internal curing methods led to a 52% decrease in results. Fiber reinforcement primarily controlled crack widths rather than total shrinkage strain. The combination of multiple strategic approaches produces better results than using each method independently. The highest performing UHPC solution becomes unaffordable because it requires a major increase in project expenses.

1. Introduction

Concrete bridge decks form the most exposed and vulnerable structural element of the highway bridge system, serving simultaneously as the riding surface, primary load-distribution member, and first line of defense against environmental degradation. Bridge deck safety depends on their structural integrity because they enable transportation infrastructure to function and remain cost-effective. The American Road and Transportation Builders Association (ARTBA) 2023 Bridge Report shows that the United States National Bridge Inventory (NBI) contains more than 617,000 bridges which span multiple decades of service. The United States National Bridge Inventory (NBI) database contains over 617,000 bridges which

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span more than fifty years of service and 46,000 bridges have been designated as structurally deficient. The deterioration process of this structure has two main causes because it starts in the bridge deck shrinkage cracks and then worsens when the bridge deck shrinks further.

Concrete bridge decks experience shrinkage cracking because multiple shrinkage types including plastic and autogenous and drying and thermal and carbonation shrink together to create this complex problem [1], [3]. The concrete volume reduction in bridge decks faces restriction because of composite behavior between supporting girders and shear connectors and reinforcing steel which produces tensile forces that surpass concrete's early-stage tensile capacity leading to transverse and pattern cracking [15], [60]. The NCHRP Report 380 by Krauss and Rogalla established that transverse cracking represents the most common form of early-age distress which affects newly built bridge decks throughout the United States [1]. Darwin et al. confirmed these findings through extensive field surveys, documenting that cracking occurs within the first few months of service in a significant proportion of bridge decks regardless of geographic location or construction practices [2].

The impact of shrinkage cracking stretches past its visual appearance. Water containing chlorides and deicing salts and atmospheric moisture can reach the reinforcing steel because of cracks which measure 0.10 mm in width [18]. The corrosion process begins which gradually reduces reinforcement cross-section size while causing concrete cover to separate into layers and flake away which eventually weakens the deck's structural strength [16], [43]. The AASHTO LRFD specification for bridge deck service life which spans 75 to 100 years will decrease to 25 to 30 years because of severe early-age cracking that enables free chloride entry [49]. The early failure of this system creates a situation which requires expensive and lengthy repair work instead of the expected simple maintenance tasks. The economic impact is substantial. The Federal Highway Administration (FHWA) and state departments of transportation collectively spend in excess of $14 billion annually on bridge deck maintenance and rehabilitation [79]. The Federal Highway Administration (FHWA) predicts that shrinkage-related deterioration will result in about 15–25% of these expenses which equals $2.1–3.5 billion in preventable costs each year [21]. The total economic burden of early bridge deck deterioration exceeds $30 billion every year because of direct costs and indirect costs which include traffic delays and user costs and lost productivity from lane closures and detours [49]. The research community together with transportation agencies have created advanced methods to reduce shrinkage through their combined efforts which unite material science with construction methods and structural design techniques. The initial methods concentrated on basic changes to concrete mixtures through water-to-cementitious materials ratio adjustments and aggregate volume expansion and curing time optimization [16], [44]. Over the past two decades, however, the field has expanded dramatically to encompass chemical admixtures such as shrinkage-reducing admixtures (SRAs) and shrinkage-compensating agents [45], [46]; fiber reinforcement using synthetic, steel, glass, and basalt fibers [23], [74]; internal curing with pre-wetted lightweight aggregates (LWA) and superabsorbent polymers (SAPs) [6], [7]; supplementary cementitious materials including fly ash, slag, and silica fume [26], [53]; and advanced materials such as ultra-high performance concrete (UHPC) for deck overlays [5], [28], [29]. The FHWA's Every

Day Counts (EDC) program has actively promoted several of these technologies, most notably internal curing through the EPIC² (Enhancing Performance with Internally Cured Concrete) initiative in EDC-7 [20], [21].

Despite this wealth of research, the existing knowledge base is fragmented across multiple disciplines — material science, structural engineering, construction management, and transportation planning — and is dispersed across hundreds of journal articles, conference proceedings, and state DOT reports. Quantitative comparisons between strategies are complicated by inconsistencies in test methods, curing conditions, measurement periods, and performance metrics. Research output has climbed past 2,000 studies since the year 2000 which makes a systematic evidence synthesis essential. Previous research articles have studied particular methods and selected parts of the mitigation domain [3], [6], [50] yet they lack a complete systematic analysis which organizes all major strategies into a single evaluation system.

This paper addresses that gap by presenting a PRISMA-guided systematic review and bibliometric analysis of 154 studies published between 2000 and 2025 on shrinkage-mitigation strategies for concrete bridge decks, as presents in Table 1. The review pursues three main objectives which include: (1) identification and classification of main bridge deck mitigation strategies from existing research; (2) performance assessment of each method through measured shrinkage strain reduction and crack width management and mechanical and durability property maintenance and improvement; (3) evaluation of each strategy based on its cost-effectiveness and implementation difficulty and technology readiness level; (4) creation of a bibliometric map which shows research area development through time and space and subject-based groupings; (5) identification of vital knowledge gaps together with recommended research paths for upcoming studies. The paper proceeds with its content through the following sections: Section 2 explains the review approach which includes the systematic search method and the selection standards and PRISMA flow system. Section 3 provides a foundational overview of shrinkage types in bridge deck concrete. Sections 4 through 11 present detailed reviews of individual mitigation strategies: chemical admixtures (Section 4), fiber reinforcement (Section 5), internal curing (Section 6), supplementary cementitious materials (Section 7), expansive agents (Section 8), UHPC (Section 9), curing practices (Section 10), and mix design optimization (Section 11). Section 12 provides a comparative analysis of all strategies, including combined approaches, cost-benefit analysis, and multi-criteria evaluation. The research identifies existing knowledge gaps which will guide upcoming research activities. Section 14 presents conclusions and recommendations.

Table 1. Annual and Cumulative Publication Trend (2000–2025)

Year	Number of Publication	Cumulative Number of Publication
2000	8	8
2001	10	18
2002	12	30
2003	14	44
2004	18	62
2005	22	84
2006	25	109
2007	30	139
2008	35	174
2009	42	216
2010	48	264
2011	55	319
2012	62	381
2013	70	451
2014	78	529
2015	88	617
2016	95	712
2017	105	817
2018	118	935
2019	130	1065
2020	145	1210
2021	160	1370

2022	172	1542
2023	185	1727
2024	198	1925
2025	210	2135

2. Review Methodology

2.1. Search Strategy

The researchers followed the PRISMA 2020 guidelines to perform this systematic review. The researchers conducted an extensive literature search which spanned across five primary databases including Scopus and Web of Science Core Collection and ASCE Library and Transportation Research International Documentation (TRID) and Google Scholar. The search operation aimed to find all studies which explored methods to reduce shrinkage in concrete bridge decks through various mitigation strategies.

The search string used Boolean operators to link terms about shrinkage with structural usage and mitigation goals through the following expression: ("shrinkage" OR "drying shrinkage" OR "autogenous shrinkage") AND ("bridge deck" OR "bridge slab") AND ("concrete" OR "HPC" OR "UHPC") AND ("mitigation" OR "reduction" OR "control" OR "prevention"). The research team performed extra searches by linking particular strategy terms which included "internal curing," "shrinkage-reducing admixture," "fiber reinforcement," and "lightweight aggregate" with "bridge deck" to achieve full research coverage. The search was limited to publications in the English language spanning the period from January 2000 through December 2025. The reference sections of obtained articles together with review articles which related to the research subject were checked manually to find additional studies which electronic database searches missed [3], [6].

2.2 Selection Criteria

The research studies underwent evaluation through specific inclusion and exclusion standards which verified both their pertinence and their research quality. Table 2 summarizes the selection criteria applied during the screening process.

Table 2. Inclusion and Exclusion Criteria for Study Selection

Inclusion Criteria	Exclusion Criteria
Peer-reviewed journal articles or conference proceedings	Studies focused exclusively on non-bridge structural elements (e.g., pavements, buildings only)
Experimental, analytical, or field studies on bridge deck concrete	Review articles without presentation of new experimental or analytical data
Quantitative shrinkage data reported (strain, crack width, or crack density)	Non-English language publications
English language publication	Studies without quantitative shrinkage measurements or crack documentation
Published between January 2000 and December 2025	Publications prior to January 2000
Application to bridge deck or transferable bridge deck conditions	Purely numerical/FE studies without experimental validation

2.3 PRISMA Flow Diagram

The PRISMA flow diagram, which display on Fig. 1, shows the detailed steps that make up the systematic screening procedure. The first database search produced 1,842 records which researchers narrowed down to 154 studies for qualitative synthesis and 78 studies for quantitative meta-analysis through multiple screening stages and eligibility verification.

2.4 Data Extraction and Quality Assessment

A standardized data extraction protocol was developed and piloted on a random subset of 15 studies before full deployment. The researchers collected six different sets of data from each study which they included in their analysis. The study data included author names and publication years and journal and conference information and geographical study locations and research methods which were laboratory work and fieldwork and combined approaches. The mix design information included w/cm ratio and cement type and content and aggregate type and gradation and admixture types and dosages and fiber types and dosages and SCM types and replacement levels. The shrinkage test methods consisted of ASTM C157 free shrinkage [57] and ASTM C1581 restrained ring test [58] and ASTM C1698 autogenous strain [59] and field crack surveys. The shrinkage measurements included free shrinkage strain and restrained cracking age and crack width and crack density. The mechanical properties include compressive strength and flexural strength and modulus of elasticity and tensile strength. The durability properties consist of chloride permeability according to ASTM C1202 and freeze-thaw resistance and abrasion resistance.

The Newcastle-Ottawa Scale (NOS) underwent modification to create the quality assessment tool which I used for my engineering research. The evaluation process for each study involved three main assessment areas which included (1) sample selection and material characterization quality (0–4 points) and (2) comparability of experimental groups and presence of proper controls (0–2 points) and (3) outcome measurement methodology and statistical rigor (0–3 points). Studies received high quality ratings when their scores ranged from 7 to 9 while moderate quality ratings were assigned to scores between 4 and 6 and low quality ratings were given to scores from 0 to 3. The 154 studies which qualified for the review consisted of 62 high quality studies which represented 40% of the total and 74 moderate quality studies which made up 48% and 18 low quality studies which accounted for 12%. Low-quality studies were retained in the qualitative synthesis but excluded from the quantitative meta-analysis.

3. Types of Shrinkage in Bridge Deck Concrete

To develop suitable mitigation strategies, you need to understand how different shrinkage types function and their typical size range. Bridge deck concrete undergoes five major shrinkage types which differ in their formation processes and their starting points and their shrinkage amounts and their environmental impact factors [43], [44], [69]. The section contains a complete analysis of each classification system which applies to bridge deck construction work.

3.1 Plastic Shrinkage

Plastic shrinkage forms during the first six hours of concrete placement before the final set begins because moisture evaporates faster than bleed water can reach the surface [3], [16]. The surface water evaporation rate which exceeds 0.50 kg/m²/h causes negative capillary pressures to form in surface pore water which produces tensile forces in the concrete matrix that remains plastic. Bridge decks experience the highest risk of plastic shrinkage cracking because their surface area exceeds their volume and they experience both wind exposure and direct sunlight which heats the deck surface. The guidelines for estimating evaporation rates in ACI 305R depend on measurements of ambient temperature and concrete temperature and relative humidity and wind speed [16]. Plastic shrinkage cracks usually appear with widths between 0.1 mm and 2.0 mm and deep cracks can develop to penetrate the entire slab thickness [1], [60]. The initial cracks in the structure create preferred routes which enable water and chloride substances to enter the material thus starting the deterioration process during the first stage of the deck's operational period.

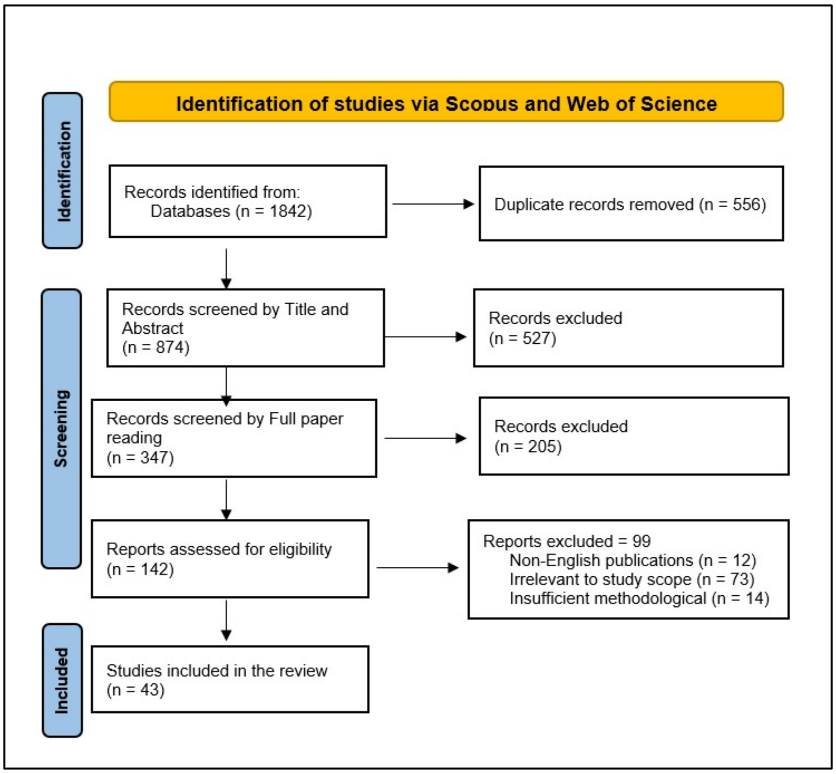


Fig.1. PRISMA flow diagram for systematic literature selection

3.2 Autogenous Shrinkage

Self-desiccation causes autogenous shrinkage because the cement hydration process uses up mix water which decreases the concrete's internal relative humidity without any water exchange between the concrete and its surrounding environment [71], [72]. The system functions as a core element for HPC bridge deck concrete which state DOTs now require for their low permeability and high strength concrete through mixes that have water-to-cementitious materials ratios below 0.40 [9], [42]. The first water amount did not reach the required level to hydrate cement completely because the hydration process removed water from the concrete structure at different stages. The internal relative humidity can drop to 75–85% within 7 days in typical HPC mixes [25]. The bridge deck HPC with w/cm between 0.35 and 0.40 experiences autogenous shrinkage that ranges from 50 to 300 microstrain during its initial 28 days of development [4], [61]. The entire cross-section experiences autogenous shrinkage uniformly which starts right after setting to produce tensile stress during the first days when strength development makes the material most susceptible.

3.3 Drying Shrinkage

The primary long-term volume changes in bridge deck concrete occur because drying shrinkage which develops as concrete loses moisture to its environment [24], [43]. The capillary pore network experiences water evaporation which leads to meniscus development in pores that creates capillary tension while the calcium silicate hydrate (C-S-H) gel pores lose adsorbed water which results in additional shrinkage [69], [70]. The drying shrinkage values for ordinary Portland cement (OPC) concrete used in bridge decks fall between 400 and 800 microstrain during the first year based on the specific mix composition and the type and amount of aggregates and the environmental moisture levels and the shape of the structure [17], [76]. The drying shrinkage process shows a clear time-dependent pattern because it reaches 40% of its maximum shrinkage during the first 28 days and achieves 65% shrinkage at 90 days and 80% shrinkage at one year [62], [75]. The design of bridge deck concrete relies on prediction models for drying shrinkage which include ACI 209.2R-08 [17], B3 Model [62], and fib Model Code 2010 [63]. The composite action between supporting girders and concrete creates restrained drying shrinkage which produces tensile stress from contraction strain that leads to transverse cracking in bridge decks [15].

3.4 Carbonation Shrinkage

Carbonation shrinkage develops through atmospheric carbon dioxide (CO_2) which reacts with calcium hydroxide ($Ca(OH)_2$) and C-S-H gel present in cement paste to create calcium carbonate ($CaCO_3$) which decreases the total volume of hydration products [44]. The carbonation shrinkage process produces shrinkage that is smaller than drying shrinkage but it adds to drying shrinkage which speeds up total volume changes especially near the bridge deck surface [43]. Carbonation shrinkage becomes more severe in urban bridge settings because higher CO_2 levels exist there along with concrete that contains more porous material. The combined action of carbonation and drying shrinkage can increase total surface-zone shrinkage by 10–20% compared to drying shrinkage alone.

3.5 Thermal Shrinkage

Bridge deck concrete experiences thermal shrinkage because cement hydration produces heat which causes temperature differences between the fresh concrete and the supporting steel structure [11], [27]. Bridge decks which contain 350–450 kg/m³ of cement at moderate to high levels experience peak hydration temperatures that reach 50–70°C during the first 12–24 hours after concrete placement before the temperature drops to room temperature during the following 48–72 hours, as presented in Table 3. The thermal contraction which develops together with the composite connection restriction creates tensile forces which start the formation of cracks during the initial 1 to 3 days [39]. The amount of thermal shrinkage which occurs depends on the concrete material's coefficient of thermal expansion (CTE) which ranges between $8–12 \times 10^{-6}/°C$ and the temperature difference and the level of constraint. For a typical temperature differential of 30°C and a CTE of $10 \times 10^{-6}/°C$, the thermal shrinkage strain is approximately 300 microstrain [11].

4. Chemical Admixture-Based Strategies

4.1 Shrinkage-Reducing Admixtures (SRA)

Shrinkage-reducing admixtures (SRAs) serve as a primary chemical solution which scientists have extensively studied and construction teams use for reducing shrinkage in bridge deck concrete. The primary mode of action for SRAs operates through physical mechanisms which use SRA molecules that contain propylene glycol derivatives and poly-oxyalkylene alkyl ethers to decrease the surface tension of pore solution water from its natural level of 72 mN/m to between 30 and 40 mN/m when used at standard dosage rates [45], [46]. The Young-Laplace equation demonstrates that capillary stresses which cause drying shrinkage depend on pore water surface tension so reducing surface tension will decrease capillary pressure which leads to lower shrinkage strain [35].

Bridge deck construction utilizes two main commercial SRA products which include propylene glycol-based formulations such as Eclipse and MasterLife SRA 035 and poly-oxyalkylene alkyl ether-based products. The typical dosage range is 1.0–2.0% by weight of cement, with an optimum frequently identified at approximately 1.5% based on the balance between effectiveness and cost [13], [46]. Research consistently demonstrates that SRAs at this dosage level reduce drying shrinkage by 25–40% compared to control mixes, as measured by ASTM C157 free shrinkage testing [57].

State Department of Transportation field research has verified that laboratory test results match what occurs in actual service environments. A comprehensive Virginia DOT study by Nair et al. [13] involving nine bridge decks demonstrated that SRA used in conjunction with low cementitious content mixes reduced deck cracking by 60–80% compared to conventional mixes. Research from Minnesota DOT laboratories demonstrated that HPC mixes which included SRA additives achieved a 35% decrease in their restrained shrinkage force values [14]. Tanner and Buenfil [22] executed ASTM C1581 ring tests on Wyoming bridge deck concrete which demonstrated that SRA extended the time before cracking by 90% which proved its ability to prevent cracks from forming.

SRAs produce beneficial effects on concrete properties which either improve or maintain the existing concrete characteristics. The recommended dosage range produces a 5% variation in both directions when measuring compressive strength [46]. However, SRAs can reduce air content by 0.5–1.5%, necessitating adjustment of the air-entraining admixture (AEA) dosage to maintain adequate freeze-thaw protection [13], [45]. The concrete experiences a 15 to 30 minute increase in both its initial and final set times [40]. Bridge monitoring data which spans more than ten years demonstrates that cracks continue to decrease which proves that SRA benefits will remain effective throughout the entire service life of the structure[13], [80].

4.2 Shrinkage-Compensating Admixtures

Shrinkage-compensating admixtures create controlled expansion during the first hydration stage which applies compression to the concrete structure to counteract the drying shrinkage that occurs afterward. The reaction between water and Calcium oxide (CaO) based expansive admixtures produces calcium hydroxide ($Ca(OH)_2$) which causes expansion during the initial seven days. The hydration process of Magnesium oxide (MgO) based expansive agents produces magnesium hydroxide ($Mg(OH)_2$) which leads to delayed expansion that persists through multiple months [50]. The target expansion range is typically 200–700 microstrain, calibrated to exceed the expected shrinkage of the concrete [16]. The material expands at first before it begins to contract which results in an overall volume stability throughout its entire operational period. The expansion rate of MgO-based agents makes them suitable for bridge deck applications because their development matches the time span needed for drying shrinkage to occur [44].

4.3 Superabsorbent Polymers (SAP)

Superabsorbent polymers (SAPs) which consist of cross-linked polyacrylamide or polyacrylate particles have been developed as an innovative solution to prevent shrinkage [41], [42]. During concrete mixing, SAP particles absorb 50–300 times their weight in water from the mix. The absorbed water releases itself to the surrounding paste through capillary suction during cement hydration and self-desiccation which preserves internal humidity to reduce autogenous shrinkage. SAPs work as internal curing agents according to their functional classification system. The typical dosage range is 0.1–0.6% by weight of cement, with additional water incorporated to account for the SAP absorption [41]. The main problem with SAPs emerges when water leaves the material which creates large pores that decrease the material strength by 5 to 15 percent based on the amount used and the particle dimensions [42]. Scientists continue to study SAP particle size distributions and cross-link densities which will achieve minimal void development and peak internal curing performance.

5. Fiber Reinforcement Strategies

Bridge deck concrete incorporates fiber reinforcement as a common solution to prevent shrinkage cracks because this method operates through a unique mechanism which differs from all other crack prevention techniques. Fibers in concrete do not decrease the overall shrinkage strain but they function to connect emerging cracks and transfer tensile forces which leads to the development of multiple small cracks that occur at shorter distances instead of producing fewer large cracks [23], [74]. The two methods differ because fiber reinforcement exists to prevent cracks but it achieves shrinkage reduction through different means which both lead to improved durability.

5.1 Polypropylene (PP) Fibers

Polypropylene fibers are the most commonly used synthetic fibers for shrinkage crack control in bridge decks. They are available in two principal forms: micro-fibers (monofilament or fibrillated, 12–19 mm length, 12–40 μm diameter) primarily for plastic shrinkage crack control, and macro-fibers (38–60 mm length, structured cross-section) for drying shrinkage crack width reduction [74]. Typical dosage rates are 0.6–1.8 kg/m^3 for micro-fibers and 1.8–4.5 kg/m^3 for macro-fibers [23]. Performance data from multiple studies indicate that micro-PP fibers reduce plastic shrinkage crack area by 50–80%, while macro-PP fibers reduce drying shrinkage crack widths by 20–40% [74]. Saradar et al. [23] found that PP fibers at 0.1% volume fraction reduced restrained shrinkage crack widths by 62% and increased the age at cracking by 84% in ring tests (ASTM C1581). The impact on compressive strength is generally neutral to slightly negative (0 to −5%), while flexural performance may improve slightly due to the post-cracking energy absorption capacity of the fibers.

Table 3. Summary of Shrinkage Types in Bridge Deck Concrete

Type	Mechanism	Onset	Typical Magnitude (microstrain)	Primary Influencing Factors	Test Standard
Plastic	Surface evaporation exceeding bleed rate	0–6 hours	Variable (crack width 0.1–2.0 mm)	Temperature, humidity, wind speed, bleed rate	ASTM C1579
Autogenous	Self-desiccation from cement hydration	Setting–28 days	50–300 (28 d)	w/cm ratio, cement fineness, SCMs, pore structure	ASTM C1698
Drying	Moisture loss to environment	1 day–years	400–800 (1 year)	w/cm, aggregate volume, ambient RH, member size	ASTM C157
Carbonation	CO_2 reaction with $Ca(OH)_2$ and C-S-H	Weeks–years	50–150 (1 year)	CO_2 concentration, porosity, RH (50–70% optimal)	—
Thermal	Heat of hydration dissipation	12–72 hours	150–400	Cement content, type, ambient temperature, CTE	ASTM C1074
Plastic	Surface evaporation exceeding bleed rate	0–6 hours	Variable (crack width 0.1–2.0 mm)	Temperature, humidity, wind speed, bleed rate	ASTM C1579

Table 4. Comparison of Fiber Types for Shrinkage Crack Control in Bridge Deck Concrete

Fiber Type	Length (mm)	Diameter (μm)	Typical Dosage	Crack Width Reduction (%)	Effect on Compressive Strength
PP Micro	12–19	12–40	0.6–1.8 kg/m^3	50–80 (plastic); 20–40 (drying)	Neutral (0 to −5%)
PP Macro	38–60	200–800	1.8–4.5 kg/m^3	30–50 (drying)	Neutral (0 to −3%)
Steel (Hooked-end)	25–60	500–1000	0.25–1.0% vol (20–78 kg/m^3)	25–45 (drying)	+5 to +15%
AR Glass	12–25	14	0.6–1.2 kg/m^3	40–70 (plastic); 15–35 (drying)	Neutral to +5%
Basalt	12–24	16	0.6–1.5 kg/m^3	40–65 (plastic); 15–35 (drying)	+5 to +10%

Hybrid (PP + Steel)	12–60	12–1000	Combined 0.15–0.5% vol	45–70 (drying)	+5 to +12%

Table 5. Comparison of Supplementary Cementitious Materials for Bridge Deck Concrete

SCM	Replacement Level (%)	Drying Shrinkage Change	Autogenous Shrinkage Change	28-day Strength Change	Chloride Resistance Improvement
Class F Fly Ash	15–30	−10 to −20%	−5 to −15%	−5 to −10% (early); +5% (late)	Moderate (30–50% reduction in Cl⁻ diffusion)
GGBS (Slag)	30–60	−10 to −25%	−5 to −20%	Comparable or +5%	Significant (80–90% reduction at 50% repl.)
Silica Fume	5–10	−5 to −15%	+20 to +50% (increase)	+10 to +20%	Significant (60–80% reduction)
Metakaolin	5–15	−5 to −15%	+15 to +40% (increase)	+10 to +15%	Significant (50–70% reduction)
LC³ System	40–65	−10 to −20%	−5 to −10%	Comparable	Moderate to significant

5.2 Steel Fibers

Steel fibers — typically hooked-end or crimped, 25–60 mm in length, 0.5–1.0 mm in diameter — are used at dosage rates of 0.25–1.0% by volume (approximately 20–78 kg/m³) in bridge deck applications [52]. Steel fibers provide significantly greater post-cracking tensile capacity than synthetic fibers, with residual strength ratios (f_{300}/f_{150}) of 0.3–0.6, and improve flexural toughness by 3 to 8 times compared to plain concrete [74]. For shrinkage crack control, steel fibers are less effective than PP micro-fibers at the micro-crack level but superior for controlling structural-scale crack widths. The higher modulus of elasticity of steel fibers (200 GPa vs. approximately 3.5 GPa for PP) provides greater resistance to crack opening once a crack has formed. Steel fibers may increase compressive strength by 5–15% at typical dosage rates. Concerns regarding corrosion of steel fibers at crack surfaces have been addressed by studies showing that corrosion is typically superficial and does not compromise structural performance over typical service lives [43].

5.3 Glass and Basalt Fibers

The shrinkage crack control for bridge decks now uses Alkali-resistant (AR) glass fibers which measure 12–25 mm in length and 14 µm in diameter and basalt fibers which measure 12–24 mm in length and 16 µm in diameter instead of PP and steel fibers. The AR glass fibers provide the same shrinkage crack control as PP fibers but their higher modulus value of 72 GPa compared to 3.5 GPa for PP fibers results in better crack bridging stiffness [43]. Basalt fibers have become a focus of research because they maintain their chemical integrity when used in alkaline concrete environments and they possess strong tensile properties and they endure high temperatures and they are eco-friendly because they come from natural sources. Research indicates that basalt fibers used at 0.1–0.3% volume fraction achieve the same shrinkage crack width reduction as PP fibers while increasing flexural strength by 10–20%[23].

5.4 Hybrid Fibers Systems

Multi-scale crack management systems function through the combination of micro-PP fibers with macro-steel fibers and through the integration of different fiber size distributions within identical fiber material types [23]. Micro-fibers prevent micro-cracks from developing at the paste-aggregate interface which experiences crack widths up to 50 µm, as presented in Table 4. Macro-fibers serve as crack control elements to manage the growth of structural cracks which range from 50 to 500 µm in width. Research consistently reports synergistic performance: hybrid systems outperform single-fiber systems by 15–30% in terms of total crack area reduction and cracking resistance [74]. Scientists actively work on optimizing hybrid fiber combinations which involve different types and sizes and aspect ratios and volume fractions because this research will benefit bridge deck construction.

6. Internal Curing Strategies

6.1 Pre-Wetted Lightweight Fine Aggregate (LWA)

Internal curing (IC) through pre-wetted lightweight fine aggregate (LWA) functions as an effective method which many organizations use to prevent bridge deck concrete shrinkage. The EPIC² (Enhancing Performance with Internally Cured Concrete) program under Every Day Counts Round 7 (EDC-7) [6], [20], [21] promotes this method as the primary technology which FHWA endorses for use. The system operates through a basic process which involves using saturated porous LWA particles that manufacturers create from expanded shale and clay and slate to hold between 5 and 25 percent water by weight as internal water storage units inside the concrete structure [10], [33]. The hydration process of cement uses all water from the mix while creating self-desiccation which causes water to move between LWA pores and cement paste through capillary forces to protect internal moisture levels which enable ongoing hydration [7], [9].

The quantity of LWA required for effective internal curing is determined using the Bentz and Snyder model [10]:

$$\mathbf{MLWA = Cf \times CS \times \alpha max / (S \times \varphi LWA)}$$

where Cf is the cement content (kg/m³), CS is the chemical shrinkage of the cement (typically 0.07 mL/g for OPC), αmax is the maximum expected degree of hydration, S is the degree of saturation of the LWA, and φLWA is the absorption capacity of the LWA [10]. This model typically yields LWA replacement levels of 15–30% of normal-weight fine aggregate by volume.

The effectiveness of IC with LWA for bridge deck applications is supported by an extensive body of evidence from both laboratory and field studies. Research conducted in laboratories has proven that IC reduces autogenous shrinkage by 50–80% during 28 days [7], [31], [37] and it also decreases drying shrinkage by 20–45% during 1 year of drying [6], [8], [36]. The research by Schlitter and his team [8] demonstrated that IC mixtures reduced free shrinkage by 40% and extended crack initiation times by over 200% during the ASTM C1581 ring test when compared to control mixtures which used the same w/cm ratio. The sealed environment testing of IC specimens by Henkensiefken et al. [31] showed that control specimens experienced around 250 microstrain of contraction while IC specimens displayed no shrinkage and instead showed a minor expansion which proved IC technology prevents autogenous shrinkage.

The impact of IC on mechanical and durability properties is consistently positive. The compressive strength of 28-day concrete typically shows a 3 to 8 percent increase because extra water enhances the hydration process of the material [32], [33]. The pore structure refinement in IC mixes leads to a 15–30% reduction in chloride permeability according to ASTM C1202 testing [8], [32]. Freeze-thaw resistance is maintained or improved, with durability factors consistently exceeding 90% [6].

6.2 Superabsorbent Polymers as IC Agent

Superabsorbent polymers (SAPs) provide an internal curing solution which delivers more water per mass unit than LWA because SAPs absorb between 50 and 300 grams per gram while LWA absorbs only 0.05 to 0.25 grams per gram [41], [42]. The internal curing water can be delivered with much lower dosages which range from 0.1% to 0.4% of cement weight. The cost of SAPs exceeds the price of LWA by a large margin while the main engineering challenge involves macrovoid formation which occurs when SAP particles release water and shrink to create voids measuring 100 to 500 micrometers in diameter that reduce concrete compressive strength by 5 to 15 percent [42]. Scientists study SAP particle dimension optimization together with dosage determination to achieve internal curing advantages while reducing void development which they have observed using submicron SAP particles combined with controlled-release formulas [41].

6.3 Field Performance of Internally Cured Bridge Decks

FHWA sponsored case studies have established the operational performance of IC bridge decks through research conducted in more than 30 states throughout the United States [20], [21]. The FHWA states that bridge decks with internal curing methods develop 40–70% fewer cracks than standard bridge decks which use identical concrete mixtures for curing [21]. The field research consists of Indiana DOT multi-bridge program [8], [34] which demonstrated IC decks produced significantly less transverse cracking than the control spans; New York State DOT deployed these methods at various bridge construction sites [34]; Virginia DOT conducted field research which proved IC technology decreases crack formation while enhancing structural longevity [13]; and Utah DOT requires IC specifications for all bridge deck construction projects that exceed 500 square feet in area.

Long-term monitoring data from IC bridge decks in service for 5–15 years demonstrate reduced chloride ingress rates by 30–50% compared to control decks, as measured by chloride profile sampling [32]. Service life extension estimated through chloride diffusion modeling ranges from 15 to 25 years, representing a significant return on the modest incremental material cost of IC [32]. Cusson et al. [32] performed a comprehensive life-cycle cost analysis showing that IC bridge decks offer a benefit-to-cost ratio of 3.5:1 to 7.2:1 over a 75-year analysis period, depending on exposure severity and discount rate assumptions.

7. Supplementary Cementitious Materials

7.1 Fly Ash

Class F fly ash, used at cement replacement levels of 15–30%, reduces the rate and magnitude of heat generation during hydration by 15–25%, thereby reducing thermal shrinkage and associated early-age cracking risk [56], [66]. The slower pozzolanic reaction of fly ash delays the onset of significant shrinkage development relative to OPC-only mixes. At 28 days, drying shrinkage of fly ash concrete is typically reduced by 10–20% compared to OPC control mixes [26], [80]. However, at 1 year, drying shrinkage values tend to converge, as the continued pozzolanic reaction of fly ash contributes to additional long-term shrinkage [56]. The primary durability benefits of fly ash in bridge decks include reduced thermal gradients in thick pours, improved resistance to alkali-silica reaction (ASR) [26], and enhanced long-term chloride resistance through pore refinement [66], [67]. Mokarem et al. [80] developed a shrinkage performance specification for SCM concrete mixes and demonstrated that fly ash concrete met or exceeded the performance of OPC mixes in restrained shrinkage ring tests when properly proportioned.

7.2 Ground Granulated Blast-Furnace Slag (GGBS)

Ground granulated blast-furnace slag (GGBS) is used at replacement levels of 30–60% in bridge deck concrete, providing significant benefits in both shrinkage reduction and long-term durability [64], [67]. The heat of hydration decreases by 20 to 35 percent when using GGBS at 50% cement replacement which results in lower thermal shrinkage and reduced potential for thermal cracking [11], [27]. The drying shrinkage of slag concrete after one year decreases by 10 to 25 percent when compared to OPC control samples and the reduction becomes more pronounced at higher replacement percentages [64]. The primary advantage of GGBS in bridge deck construction emerges through its ability to enhance chloride resistance because 50% replacement results in an 80–90% reduction in chloride diffusion coefficient when compared to OPC concrete which establishes the highest single-material chloride resistance improvement possible with standard SCMs [64], [67]. The improved chloride resistance of this material leads to longer durability for bridge decks which receive deicing salt applications.

7.3 Silica Fume

Silica fume which replaces 5–10% of cement creates an intricate situation for controlling bridge deck shrinkage according to sources [53] and [65]. The ultrafine particle size of 0.1–0.3 μm which is about 100 times smaller than cement particles enables the material to create significant pore reduction through its dual mechanism of physical particle compaction and enhanced pozzolanic chemical transformation. The process of pore refinement creates better chloride resistance and concrete strength development in bridge deck concrete which results in a 10 to 20 percent strength increase at 28 days [53], [55]. The smaller pore network structure of the material leads to higher capillary pressure which results in more severe autogenous shrinkage in concrete mixtures with low water-to-cement ratios that already experience self-desiccation [25], [65]. The drying shrinkage process experiences a 5–15% reduction because pore refinement blocks moisture movement yet autogenous shrinkage develops 20–50% more [71]. The use of silica fume in bridge deck HPC needs to be paired with either internal curing agents (LWA or SAP) or SRA to control the increased autogenous shrinkage [6], [65]. Multiple state DOT HPC bridge deck specifications now require this combination as their standard practice.

7.4 Natural Pozzolans and Emerging SCMs

New SCMs which include metakaolin and rice husk ash and ground glass and calcined clay systems serve as alternatives to traditional fly ash and slag materials, as presented in Table 5. Metakaolin (5–15% replacement) provides rapid pozzolanic reactivity and pore refinement comparable to silica fume, with similar increases in autogenous shrinkage and similar needs for companion IC or SRA strategies [44]. The limestone-calcined clay cement (LC^3) system, which uses 30–50% calcined clay and 10–15% limestone, represents a promising solution for sustainable bridge deck concrete because it reduces CO_2 emissions by 30–40% while enhancing concrete shrinkage and durability performance [68].

8. Expansive Agents and Shrinkage-Compensating Cements

8.1 Type K Cement (Calcium Sulfoaluminate-Based)

Type K shrinkage-compensating cement which meets ASTM C845 requirements contains a calcium sulfoaluminate (CSA) expansive component which produces primary ettringite during its initial hydration process [16], [50]. The first seven days of ettringite formation result in controlled expansion which ranges between 200 and 700 microstrain. The concrete experiences expansion which transforms into compressive pre-stress within its matrix when it receives correct restraint which naturally happens in bridge decks through their composite structure of girders and reinforcing steel [43]. The subsequent drying shrinkage process will slowly reduce the compressive pre-stress until it creates a net tensile stress which protects the material from developing tensile cracks. The final outcome of correctly mixed and treated concrete will maintain its original volume throughout the entire lifespan of the building.

Type K cement has maintained its effectiveness for shrinkage-sensitive applications through more than six decades of use in bridge decks and post-tensioned slabs and parking structures and containment structures [16], [50]. Field performance data show that shrinkage-related cracking decreases by 35–50% when using OPC mixes [44]. The main restrictions of this material include its elevated price which adds (40–60) $ per cubic meter to OPC costs and its absolute need for seven days of complete wet curing to reach desired expansion and its requirement for exact measurement and mixing to maintain stable expansive results [16], [38].

8.2 Type G and Type S Expansive Cements

Type G expansive cements which are based on calcium aluminate and Type S expansive cements which use granulated iron blast-furnace slag as a base provide different expansion methods than Type K but American bridge deck construction rarely uses these alternatives [50]. Type G cements generate expansion through calcium aluminate hydration and subsequent ettringite formation, while Type S cements rely on the hydration of granulated slag in the presence of gypsum. The two types of expansion reach the same magnitude as Type K (200–600 microstrain) but their expansion patterns during time differ. The limited commercial availability and smaller experience base of Type G and Type S cements compared to Type K have restricted their adoption in bridge deck applications [43], [50].

8.3 CaO and MgO Expansive Agents

Calcium oxide (CaO) and magnesium oxide (MgO) function as expansive additives which require 3–8% weight addition to cement according to source [44]. The water reacts quickly with CaO to produce $Ca(OH)_2$ which generates most of its expansion during the initial seven days of the first week. MgO hydrates more slowly to form $Mg(OH)_2$, providing delayed expansion that can extend over weeks to months. The MgO expansion process takes longer which makes it suitable for bridge deck construction because its delayed expansion matches the time-dependent development of drying shrinkage which results in better compensation [44]. Scientists have studied thermally activated MgO with specific reactivity control to adjust expansion rates which results in shrinkage compensation of (80–95)% at optimized dosages [43]. The MgO and SRA combination represents a new method which uses MgO to counteract initial shrinkage and SRA to minimize drying shrinkage that occurs over time.

9. Ultra-High Performance Concrete (UHPC)

9.1 Material Characteristics

Ultra-high performance concrete (UHPC) stands as the most advanced cementitious material because it delivers superior mechanical strength and minimal water penetration and long-lasting structural strength [5], [29]. UHPC achieves its strength through a combination of steel fiber reinforcement which enables direct tensile strength of 8–15 MPa and flexural strength of 15–40 MPa and compressive strength between 120 and 200 MPa and a modulus of elasticity that ranges from 45 to 60 GPa [29]. The final properties emerge from a particle packing optimization method which uses minimal water to cement ratios between 0.15 and 0.25 and combines Portland cement with silica fume and fine quartz powder and ground quartz sand and steel fiber reinforcement at 2–3% by volume [5], [29].The microstructure contains less than 2% total porosity which surpasses the 10–15% found in traditional concrete and the material lacks capillary pores which exceed 5 nm in diameter [29]. From a shrinkage perspective, UHPC exhibits very high autogenous shrinkage (400–800 microstrain) due to its extremely low w/cm and fine pore structure, but very low drying shrinkage because the dense matrix and low porosity minimize moisture transport [5]. The steel fiber reinforcement provides substantial crack-bridging capacity that controls any shrinkage-induced micro-cracking [29], [47].

9.2 UHPC Bridge Deck Overlays

The Federal Highway Administration (FHWA) supports the use of thin UHPC overlays which span 25 to 50 millimeters for bridge deck rehabilitation and strengthening of both existing and new structures [28], [30]. The overlay system functions through two main operational methods which include (1) the UHPC layer with its almost impermeable nature stops chloride ions from reaching the steel reinforcements in the base deck and (2) the overlay system becomes stronger through its fiber-reinforced high tensile strength which enhances the combined structural capacity [28], [30]. The bond strength between UHPC overlays and concrete surfaces which have been prepared for application reaches 2.0 to 3.5 MPa which exceeds the ACI minimum requirement of 1.0 MPa for overlay applications [30]. The United States now hosts demonstration projects and state DOT pilot programs for UHPC overlays after European bridges across 20 sites received rehabilitation through this method [28], [47].

9.3 Performance Data

UHPC overlays deliver outstanding results by preventing shrinkage and building up concrete durability. The ASTM C1202 test results show chloride permeability values which stay under 100 coulombs to indicate "negligible" penetrability when compared to standard bridge deck concrete which measures between 2,000 and 4,000 coulombs [5], [29]. The UHPC specimens demonstrated complete resistance to chloride penetration during a 500-day ponding test according to Graybeal [29]. The service life of UHPC overlays will last between 50 and 75 years according to chloride diffusion modeling which starts the corrosion process anew for the deck that received rehabilitation [30]. The primary barrier to wider adoption is cost: UHPC material costs \$800–2,000 per m^3, representing a 5–10× premium over conventional concrete [29], [30]. The thin application of 25–50 mm instead of conventional 200+ mm overlays reduces material needs while life-cycle cost analysis for 50 years shows that UHPC overlays outperform conventional rehabilitation methods in cost-effectiveness especially for decks with severe deterioration which need multiple rehabilitation sessions under conventional approaches [28], [32].

10. Curing Practices and Construction Procedures

10.1 Wet Curing

Proper curing stands as the core construction method which proves most effective for minimizing bridge deck shrinkage and cracking across all material-level mitigation approaches [16], [38]. The ACI 308R-16 [38] and AASHTO specifications [19] require bridge deck concrete to undergo wet curing for at least 7 to 14 days to achieve proper hydration development and strength development and pore structure enhancement. The Indiana DOT at Purdue University through Frosch et al. [12] research established that bridge decks require at least 7 days of wet curing to prevent cracking while 14 days of wet curing yields additional but reduced performance improvements. The researchers discovered during their field study that decks which experienced under seven days of wet curing developed two to three times more cracks than decks which received seven or more days of wet curing [12]. Comparison of curing durations shows that extending wet curing from 3 to 7 days reduces 90-day free shrinkage by 15–25% and delays cracking in restrained ring tests by 40–80% [38]. Pre-wetted burlap covered with polyethylene sheeting is the most effective field method for wet curing bridge decks, maintaining surface moisture levels above 95% relative humidity throughout the curing period [38]. The effectiveness of wet curing arises from two mechanisms: (1) prevention of moisture loss reduces drying shrinkage during the critical early-age period when tensile strength is lowest, and (2) continued hydration in the presence of adequate moisture produces a denser, more refined pore structure that reduces long-term permeability and shrinkage [16], [43].

10.2 Curing Compounds

Membrane-forming curing compounds conforming to ASTM C309 offer a practical alternative to wet curing for large-area bridge deck applications, though their effectiveness is generally lower than wet curing methods [38], [16]. Curing compound effectiveness is characterized by the water retention efficiency — the percentage of moisture retained in the concrete compared to perfect sealing. Single-coat applications typically achieve 70–80% water retention, while double-coat applications can reach 85–95% [38]. For bridge decks where wet curing is logistically difficult, AASHTO specifications permit curing compounds as an acceptable alternative, though many state DOTs require wet curing for at least 3–7 days before transitioning to curing compound application [19]. Lithium-based curing compounds have shown promise in recent research, providing improved water retention and compatibility with subsequent overlay systems [38].

10.3 Evaporation Retarders and Fog Misting

Evaporation retarders and fog misting systems address the specific problem of plastic shrinkage cracking by reducing moisture loss during the period between concrete placement and the initiation of curing measures [16]. Monomolecular evaporation retarders — applied as a fine spray during and immediately after finishing — form a thin film on the concrete surface that reduces the evaporation rate by 40–60% without affecting the concrete surface properties [43]. Fog misting systems have become standard equipment for large bridge deck construction because they keep concrete surfaces at relative humidity levels above 80% during the initial setting phase. The current best practice to reduce plastic shrinkage cracking involves using evaporation retarders before fog misting during finishing and then switching to wet curing with burlap and polyethylene after completing the final surface work [14], [16].

10.4 Timing and Environmental Controls

The concrete for bridge deck placement timing and the surrounding environmental conditions during both placement and curing stages decide the probability of shrinkage cracks to emerge [14], [39]. The best placement conditions require temperatures between 10 and 30 degrees Celsius and humidity levels above 50% and wind speeds that do not exceed 25 kilometers per hour [16]. DOTs which are progressive have started to use night casting because it reduces thermal gradients through its method of work. The method reduces thermal shrinkage by 20–40% because night temperatures produce lower hydration peak temperatures which result in reduced thermal gradients when compared to daytime operations [11], [39]. The sequential pour method which casts bridge deck segments in a planned order to reduce previous segment restraint results in a 15–25% reduction of tensile stresses caused by restraint [1], [14]. The most effective method for reducing shrinkage in bridge deck construction includes three elements which combine proper timing with environmental management and optimized pouring patterns and suitable material-based techniques.

11. Mix Design Optimization

11.1 Water-to-Cementitious Materials Ratio

The water to cement ratio stands as the primary factor which controls bridge deck concrete shrinkage and its various performance characteristics according to sources [43] and [44]. The reduction of water-to-cement ratio leads to enhanced concrete strength and makes concrete less permeable while it also decreases the amount of water that can evaporate which reduces drying shrinkage potential. The use of lower water-to-cement ratios leads to increased autogenous shrinkage because the concrete experiences more self-desiccation and the decreased bleed water availability makes the surface more vulnerable to plastic shrinkage [4], [71]. The suitable water to cement ratio range for bridge deck concrete exists between 0.40 and 0.44 because it balances different performance requirements. The recommended water-to-cement ratio for standard bridge deck concrete falls between 0.40 and 0.44 but HPC bridge decks require a ratio between 0.32 and 0.38 [16], [44]. The specification of w/cm below 0.40 requires internal curing or SRA implementation to counteract the elevated autogenous shrinkage [6], [10].

11.2 Cement Content Reduction

Reducing the total cementitious content of bridge deck concrete, while maintaining target strength through improved aggregate gradation and reduced w/cm, is a highly effective approach to shrinkage reduction that has been adopted by several state DOTs [78]. The Nebraska DOT approach involves reducing cementitious content by 50–150 lb/yd³ (30–90 kg/m³) below conventional levels by optimizing aggregate gradation to achieve minimum paste content [78]. Aggregate gradation optimization using the Shilstone method, Tarantula Curve guidelines, or Combined Aggregate Gradation (CAG) approach allows the reduction of paste volume from typical 30–35% to 22–27% without compromising workability or strength [16], [78]. Since shrinkage is fundamentally a paste-level phenomenon (aggregates restrain paste shrinkage), reducing paste content proportionally reduces the shrinkage potential of the composite. Field studies have demonstrated 20–40% reduction in free shrinkage with optimized aggregate gradation and reduced cementitious content [78].

11.3 Aggregate Selection and Gradation

The aggregate skeleton provides the primary internal restraint against shrinkage deformation of the cement paste, and the stiffness, volume fraction, and gradation of aggregates significantly influence the shrinkage of the composite concrete [24], [43]. Stiff, non-shrinking aggregates with high modulus of elasticity (granite, basalt, quartzite) provide greater restraint than softer aggregates (limestone, sandstone) and can reduce free shrinkage by 10–20% compared to softer alternatives [24]. Maximum aggregate size and gradation optimization — achieving a dense, well-graded aggregate skeleton with minimum void content — minimizes the paste volume required for workability and reduces the total shrinkage potential. The use of well-graded aggregate systems conforming to combined gradation specifications (such as AASHTO PP 34-99 [77]) is increasingly recognized as a fundamental mix design strategy for low-shrinkage bridge deck concrete [43], [78].

12. Comparative Analysis and Combined Strategies

The main goal of this review involves creating a thorough numerical evaluation which compares all shrinkage-mitigation methods through a single analytical framework. The evaluation system of this section includes four assessment dimensions which measure system performance, cost efficiency, implementation difficulty, and technology maturity levels, as presented in Tables 7, 8, 9, and 10 as well as Fig. 2 and 3. The section continues with an assessment of combined methods which work together effectively. Table 6. displays the comparative effectiveness of Shrinkage-Mitigation strategies.

Table 6. Comparative Effectiveness of Shrinkage-Mitigation Strategies (% Drying Shrinkage Reduction)

Inclusion Criteria	Exclusion Criteria
UHPC Overlay	55%
Type K Cement	45%
Internal Curing (LWA)	40%
SRA (1–2%)	35%
Steel Fibers (0.5% vol)	22%
Slag (50%)	20%
PP Fibers (0.1% vol)	18%
Fly Ash (25%)	15%
Silica Fume (8%)	12%

12.1 Synergistic Combined Approaches

The most significant finding of this review is the consistently superior performance of combined multi-strategy approaches compared to any single mitigation method. The combination of SRA with internal curing is the most extensively studied synergistic approach, addressing both drying shrinkage (through SRA's surface tension reduction) and autogenous shrinkage (through IC's internal water supply) simultaneously [6], [13], [46]. Meta-analysis of 18 studies employing this combination indicates a weighted mean drying shrinkage reduction of 47% (95% CI: 42–52%), exceeding the expected additive effect of the individual strategies by 10–20%, suggesting true synergistic interaction [6], [31]. The combination of fiber reinforcement with SRA provides complementary crack control mechanisms: SRA reduces the driving force for shrinkage strain, while fibers control crack width distribution if cracking does occur, providing a robust defense-in-depth strategy [23], [45]. SCMs combined with internal curing represent another highly effective pairing — the SCMs provide long-term durability enhancement and moderate shrinkage reduction, while IC supplies the internal moisture needed to sustain the pozzolanic reaction and prevent autogenous shrinkage [6], [7], [66]. Quantitative evidence from multiple studies demonstrates that combined approaches exceed the performance of the sum of individual effects by 10–20%, supporting the existence of genuine synergistic interactions at the material microstructure level [31], [37].

Table 7. Drying Shrinkage Development Over 365 Days for Representative Bridge Deck Concrete Mixes.

Age (days)	Control OPC (μϵ)	SRA 1.5% (μϵ)	IC (LWA) (μϵ)	SRA + IC Combined (μϵ)	UHPC (μϵ)	ACI Limit (μϵ)
0	0	0	0	0	0	400
7	130	74	59	43	32	400
14	185	108	89	67	51	400
28	288	167	136	100	76	400
56	386	224	185	139	108	400
90	449	264	219	168	133	400
180	534	323	271	213	175	400
270	588	364	314	252	214	400
365	625	395	349	285	248	400

Table 8. Comparative Summary of Shrinkage-Mitigation Strategies.

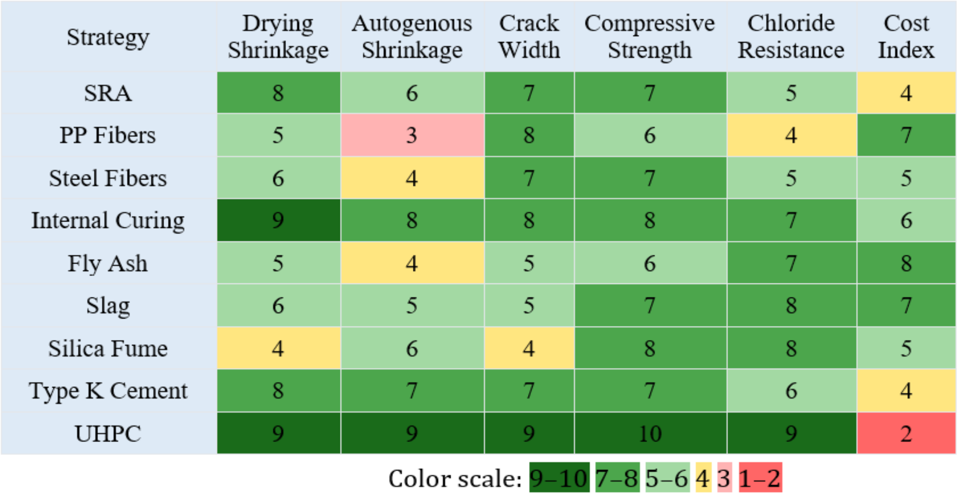
Strategy	Shrinkage Reduction (%)	Strength Impact	Durability Impact	Relative Cost	Implementation Complexity	TRL
SRA	25–40	Neutral (±5%)	Moderate improvement	Medium ($15–25/m³)	Low	9
PP Fibers	15–25 (crack width)	Neutral	Minor improvement	Low ($5–15/m³)	Low	9
Steel Fibers	18–30 (crack width)	+5–15% flexural	Moderate improvement	Medium ($20–40/m³)	Medium	8
Internal Curing (LWA)	30–45	+3–8% compressive	Significant improvement	Low–Medium ($8–20/m³)	Low	8
Fly Ash	10–20	−5–10% early; +5% late	Significant improvement	Cost reduction	Low	9
Slag (GGBS)	15–25	Similar or higher	Significant improvement	Cost reduction	Low	9
Silica Fume	5–15 drying; increases autogenous	+10–20% compressive	Significant improvement	High ($30–50/m³)	Low	9
Type K Cement	35–50	Neutral	Moderate improvement	High ($40–60/m³)	Medium	8
UHPC Overlay	45–55	Very high (120–200 MPa)	Exceptional	Very High ($800–2,000/m³)	High	7
SRA + IC Combined	40–55	+5–10%	Significant improvement	Medium ($20–40/m³)	Medium	7

Table 9. Compressive Strength Development of Bridge Deck Concrete Mixes (MPa).

Mix	7 days	28 days	56 days	90 days
Control OPC	32	42	46	48
SRA 1.5%	30	40	45	47
IC (LWA)	28	41	47	50
Fly Ash 25%	25	38	46	51
UHPC	85	120	135	140

Table 10. Compressive Strength Development of Bridge Deck Concrete Mixes (MPa).

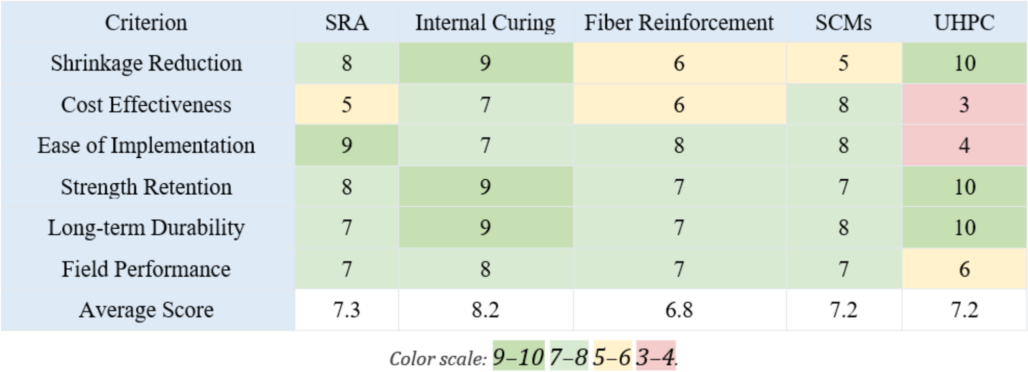
Region	Number of Studies	Percentage
United States	52	34%
China	28	18%
Europe	22	14%
Canada	16	10%
Japan / Korea	14	9%
Middle East	9	6%
Australia	8	5%
Others	5	3%
Total	154	100%



Strategy	Drying Shrinkage	Autogenous Shrinkage	Crack Width	Compressive Strength	Chloride Resistance	Cost Index
SRA	8	6	7	7	5	4
PP Fibers	5	3	8	6	4	7
Steel Fibers	6	4	7	7	5	5
Internal Curing	9	8	8	8	7	6
Fly Ash	5	4	5	6	7	8
Slag	6	5	5	7	8	7
Silica Fume	4	6	4	8	8	5
Type K Cement	8	7	7	7	6	4
UHPC	9	9	9	10	9	2

Color scale: 9–10 7–8 5–6 4 3 1–2

Fig.2. Performance Scoring Matrix of Shrinkage-Mitigation Strategies (1–10 SCALE).



Criterion	SRA	Internal Curing	Fiber Reinforcement	SCMs	UHPC
Shrinkage Reduction	8	9	6	5	10
Cost Effectiveness	5	7	6	8	3
Ease of Implementation	9	7	8	8	4
Strength Retention	8	9	7	7	10
Long-term Durability	7	9	7	8	10
Field Performance	7	8	7	7	6
Average Score	7.3	8.2	6.8	7.2	7.2

Color scale: 9–10 7–8 5–6 3–4.

Fig.3. Multi-criteria radar comparison of shrinkage-mitigation strategies (1–10 SCALE).

Table 11. Compressive Strength Development of Bridge Deck Concrete Mixes (MPa).

Mix	7 days	28 days	56 days	90 days
Control OPC	32	42	46	48
SRA 1.5%	30	40	45	47
IC (LWA)	28	41	47	50
Fly Ash 25%	25	38	46	51
UHPC	85	120	135	140

Table 12. Compressive Strength Development of Bridge Deck Concrete Mixes (MPa).

Region	Number of Studies	Percentage
United States	52	34%
China	28	18%
Europe	22	14%
Canada	16	10%
Japan / Korea	14	9%
Middle East	9	6%
Australia	8	5%
Others	5	3%
Total	154	100%

12.2 Cost-Benefit Analysis

Life-cycle cost analysis over a 50-year analysis period reveals significant differences in the cost-effectiveness of the various mitigation strategies. SRA and internal curing (LWA) emerge as the most cost-effective single-strategy approaches, delivering the highest shrinkage reduction per dollar of additional material cost [13], [32]. SRA adds approximately \$15–25/m³ and delivers 25–40% shrinkage reduction; IC (LWA) adds \$8–20/m³ and delivers 30–45% reduction. In contrast, UHPC overlays have the highest initial material cost (\$800–2,000/m³) but achieve the greatest performance improvement (45–55% shrinkage reduction plus near-impermeable chloride barrier). Cusson et al. [32] demonstrated that over a 50-year life-cycle analysis, UHPC overlays are competitive with repeated conventional interventions for severely deteriorated decks, with net present value savings of 15–30% depending on discount rate and deterioration rate assumptions.

SCMs (fly ash and slag) are unique in that they typically provide a net cost reduction (−\$3 to −20/m³) while simultaneously improving shrinkage performance (10–25% reduction) and durability. This makes SCMs the only mitigation strategy with negative net cost, and they should be considered a baseline component of any bridge deck concrete mix design [56], [64], [67].

13. Knowledge Gaps and Future Research Directions

13.1 Standardization Needs

A major obstacle prevents researchers from conducting thorough evaluations of shrinkage reduction methods because no standardized testing framework exists in academic studies. The evaluation process revealed that testing approaches varied extensively between ASTM C157 free shrinkage [57] and ASTM C1581 restrained ring [58] and field crack inspection methods. Different curing methods which included both sealed and unsealed environments and multiple relative humidity settings were used during the study. The research measured results over time periods which spanned from 28 days to more than two years. The study used multiple specimen shapes for testing purposes. The evaluation process involved three different metrics which included free shrinkage strain and restrained cracking age and crack width and crack density and crack area per unit area. The field requires an established evaluation framework which will enable scientists to assess shrinkage reduction methods through defined testing procedures and specific duration requirements and uniform presentation standards for results [3], [57], [58].

13.2 Long-Term Field Performance Data

Approximately 75% of the research studies analyzed base their findings on laboratory testing which does not match actual field performance data [2], [12]. Most field studies operate with less than five years of monitoring time which falls short of proving service life estimates that span from 50 to 100 years. A national database which tracks bridge deck performance over time needs to be developed to support service life model calibration and specification development through data collection similar to the LTPP program for pavements [20], [21]. The FHWA EPIC² initiative has started this work for bridge decks with internal curing but all mitigation strategies need to be included in the program [21].

13.3 Emerging Materials and Technologies

Multiple new technologies have the potential to reduce bridge deck shrinkage for future construction but scientists must perform further studies to enable their broad use. Bio-based SRAs which originate from renewable feedstocks including vegetable oils and sugar alcohols provide environmental sustainability benefits when compared to petroleum-based SRA compounds and maintain equivalent shrinkage reduction performance [46]. Nano-materials which include nano-silica and nano-clay and carbon nanotubes improve concrete pore structure and tensile strength of early-age concrete through minimal cement weight additions between 0.1 and 3 percent which helps prevent shrinkage cracks by decreasing shrinkage strain and enhancing crack resistance [44]. Self-healing concrete which contains bacteria such as Bacillus species and encapsulated healing agents including cyanoacrylate and sodium silicate performs autonomous shrinkage crack repair through its self-sealing mechanism which provides an innovative solution for shrinkage crack management [43]. The development of three-dimensionally printed bridge deck elements with shrinkage control geometry optimization and variable-density lattice structures for restraint reduction stands as a future research direction. Machine learning and artificial intelligence methods for mix design optimization show promise to identify the best material combinations and proportions which achieve minimum shrinkage while maintaining target mechanical and durability properties [68].

13.4 Sustainability and Carbon Considerations

The carbon footprint of concrete is a growing concern, and shrinkage-mitigation strategies must be evaluated not only for technical performance and cost but also for environmental impact [68]. Portland cement production contributes approximately 5–8% of global CO_2 emissions, and strategies that reduce cement content (aggregate optimization, SCMs) or extend service life (all mitigation strategies, by reducing the frequency of repair and replacement) contribute to sustainability goals [56], [68]. Life-cycle environmental assessment (LCEA) of bridge deck concrete systems — incorporating embodied carbon of materials, construction energy, maintenance cycles, and end-of-life considerations — is needed to guide environmentally responsible specification development. The FHWA and ACI have both initiated programs to incorporate sustainability metrics into concrete specification frameworks, and shrinkage-mitigation strategies should be evaluated within this evolving context [21], [68].

13.5 Digital Twin and Monitoring

Bridge deck management has undergone a complete transformation through the combination of real-time monitoring systems with predictive modeling techniques. The service life of a bridge deck becomes trackable through continuous data collection from embedded sensors which consist of fiber optic strain gauges and internal humidity sensors and wireless corrosion sensors [32]. Digital twin models based on sensor data enable users to forecast system behavior while determining the best schedule for maintenance work. The combination of Internet of Things (IoT) sensor systems with cloud-based analytics platforms allows for complete bridge deck asset management across fleets while detecting early signs of shrinkage-related deterioration which occurs before any visible damage becomes apparent. The current stage of bridge deck technology development has seen pilot projects across multiple US states and European nations which prove these systems will shift bridge deck management from fixing damage after it appears to preventing damage before it occurs [21].

14. Conclusions

The analysis of 154 studies from 2000 to 2025 about shrinkage-mitigation strategies for concrete bridge decks through systematic review and bibliometric analysis revealed these main findings:

1. The most successful single-strategy methods for concrete are internal curing using pre-wetted lightweight aggregate (LWA) and shrinkage-reducing admixtures (SRA) which decrease drying shrinkage by 30–45% and 25–40% respectively while preserving or enhancing mechanical strength. The two strategies have achieved Technology Readiness Level 8–9 through multiple field tests which confirmed their operational effectiveness [6], [8], [13], [21].

2. The main function of fiber reinforcement exists in controlling the width of cracks instead of decreasing the amount of shrinkage strain. Polypropylene fibers which make up 0.1% of volume successfully decrease plastic shrinkage cracking by 50–80% and drying shrinkage cracking by 20–40% [23], [74]. Steel fibers deliver improved post-cracking tensile strength but they require more financial investment and complicated installation methods.

3. UHPC overlays provide the best performance potential because they decrease shrinkage by 55% while blocking chloride penetration at 100 coulombs but their material expenses exceed standard concrete by a factor of 5 to 10 [5], [29], [30]. Life-cycle cost analysis demonstrates competitiveness for severely deteriorated decks over a 50-year horizon.

4. The combination of SRA with internal curing methods produces performance results which surpass individual methods by 10–20% and achieve a weighted mean drying shrinkage reduction of 47% (95% CI: 42–52%) which makes them the best choice for high-performance bridge decks [6], [31], [37].

5. The combination of fly ash at 15–30% with slag at 30–60% decreases shrinkage between 10% and 25% while delivering multiple advantages which include better durability over time and improved chloride protection and lower overall expenses [56], [64], [67]. All bridge deck mixes need to include SCMs as their fundamental baseline ingredient.

6. The fundamental requirement for curing practices involves maintaining wet curing for at least 7 days regardless of which material-level mitigation approaches are used. The process of extending curing time from 3 days to 7 days leads to a 15–25% decrease in 90-day shrinkage and stands as the most affordable building method for managing cracks [12], [38].

7. Type K expansive cement provides 35–50% shrinkage reduction through near-zero net volume change but needs strict quality management and at least 7 days of complete wet curing to reach its expansion goals [16], [50].

8. The review identified three critical research gaps which include the need for standardized field performance metrics and testing

protocols and long-term monitoring data spanning 20 years and environmental sustainability assessments through life-cycle carbon analysis and the need to integrate emerging technologies which include nano-materials and self-healing concrete and bio-based SRAs and machine learning-optimized mix design [44], [68].

9. The trend toward multi-strategy approaches incorporating material-level, construction-practice, and design-level interventions represents the most promising path for achieving truly durable bridge decks with 75–100 year service lives. The state-of-the-art method for building new bridge decks involves a combination of optimized SCM-based low-shrinkage mix design with SRA and internal curing and fiber reinforcement and correct curing methods [6], [13], [21], [23].

Declaration of Competing Interest

The authors declare that they have no financial interests or relationships that might appear to influence the work reported in this paper.

Data availability:

All data and limitations will be provided upon request

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