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Effect of Bridge Deck Placement Sequences on Cracking Performance

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GABRIEL ARCE, Ph.D., P.E.
Research Scientist

CELIK OZYILDIRIM, Ph.D., P.E.
Principal Research Scientist

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VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454
vtrc.virginia.gov

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<tr><td colspan="4">Author(s):
Gabriel Arce, Ph.D., P.E., and Celik Ozyildirim, Ph.D., P.E.</td></tr>
<tr><td colspan="4">Performing Organization Name and Address:
Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903</td></tr>
<tr><td colspan="5">Sponsoring Agencies' Name and Address:
Virginia Department of Transportation
1221 E. Broad Street
Richmond, VA 23219</td></tr>
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Abstract:

Uncertainty persists regarding the influence of continuous deck placement on cracking performance. This study evaluates the effect of bridge deck placement sequence—that is, continuous versus sequential (checkerboard)—through a literature review, a survey of state departments of transportation and Virginia Department of Transportation (VDOT) districts, and an analysis of VDOT bridge condition data. Findings consistently support that shrinkage-related mechanisms (drying, autogenous, and thermal) are the primary contributors to deck cracking, with placement sequence considered a secondary factor. Furthermore, the study underscores that achieving low cracking performance depends primarily on controlling concrete paste content (preferably below 26.5% by volume) and ensuring high-quality construction practices, particularly proper consolidation, finishing, and curing.

Although continuous placement is often perceived to cause more cracking, most survey respondents reported no significant differences in long-term deck performance for continuous placement relative to sequential placement. However, some reported taking measures to reduce the risk of cracking, such as limiting the volume or length of continuous placements, using low-shrinkage concrete, or using retarding admixtures to maintain the concrete plastic for extended times. Analysis of Condition State 2 cracking data from 76 VDOT multi-span continuous steel beam bridges, including 8 placed continuously, showed no statistically significant difference in cracking between placement methods. All the decks were constructed since 2017, reflecting modern materials and construction practices.

Overall, the results suggest that when appropriate materials and construction practices are employed, continuous deck placement may be suitable for multi-span continuous bridges with concrete volumes less than 360 yd^3, provided that the concrete can be maintained in a plastic state during the entire placement (or at least one full span behind the active placement) and the contractor has demonstrated successful experience with continuous deck placement.

Supplemental materials can be found at https://library.vdot.virginia.gov/vtrc/supplements.

FINAL REPORT

EFFECT OF BRIDGE DECK PLACEMENT SEQUENCES ON CRACKING PERFORMANCE

Gabriel Arce, Ph.D., P.E.
Research Scientist

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

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ABSTRACT

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EFFECT OF BRIDGE DECK PLACEMENT SEQUENCES ON CRACKING PERFORMANCE

Gabriel Arce, Ph.D., P.E.
Research Scientist

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

INTRODUCTION

Cracking of concrete bridge decks is a pervasive problem in Virginia and the United States, reducing the service life of the structures and increasing maintenance costs (Hadidi and Saadeghvaziri, 2005; Schmitt and Darwin, 1999). Most of these cracks occur at early ages (i.e., right after construction or soon after the bridge has been opened to traffic), widen with time, and typically exceed the suggested American Concrete Institute (ACI) Committee 224 width limit of 0.18 mm (0.007 inch) for concrete structures subjected to deicing chemicals (ACI, 2001; Hadidi and Saadeghvaziri, 2005; Schmitt and Darwin, 1999). Consequently, these cracks allow detrimental solutions (e.g., water and deicing chemicals) to penetrate the deck and accelerate deterioration of the bridge deck, supporting girders, and substructure elements, when cracks propagate through the full deck thickness, which is often the case (Hadidi and Saadeghvaziri, 2005; Schmitt and Darwin, 1999). The predominant type of cracks observed in bridge decks is transverse cracks. These cracks usually develop every 1 to 3 m (3 to 10 feet) along the span and are commonly located over the transverse reinforcement (Hadidi and Saadeghvaziri, 2005).

One of the causes of deck cracking is thought to be the concrete placement sequence, specifically whether the deck is placed continuously or in sequential stages in multi-span bridges. Sequential deck placement is typically carried out in a checkerboard-like pattern, with the positive moment regions placed first and the negative moment regions placed afterward, to control deflections and reduce deck cracking. Contractors repeatedly request that the Virginia Department of Transportation (VDOT) permit continuous bridge deck placement to improve construction productivity. However, VDOT engineers remain concerned that continuous placement may increase the risk of deck cracking and thereby reduce the service life of the structure. In response, this study aims to provide guidance on the issue for the multi-span bridges through a literature review, a survey of state departments of transportation (DOTs) and VDOT districts, and an analysis of VDOT's bridge database.

PURPOSE AND SCOPE

The purpose of this study was to gain understanding of the effect of bridge deck placement techniques on deck cracking performance. To this end, a literature review was conducted. In addition, collective knowledge and experience on the topic were gathered through a survey of state DOTs and VDOT districts. Finally, VDOT's bridge database was analyzed for decks supported by steel beams to identify evidence of the relationship between deck placement techniques and cracking outcomes.

METHODS

Overview

To accomplish the primary research objective, this project was organized into three tasks, which are detailed in the following subsections:

1. Literature review.
2. Survey of state DOTs and VDOT districts.
3. VDOT's bridge database analysis.

Literature Review

The researchers conducted a literature review of the state of the art and state of practice regarding bridge deck placement techniques and their effect on bridge deck cracking.

Survey of State Departments of Transportation and VDOT Districts

A survey was prepared and distributed to state DOTs and VDOT districts in 2024 to gather their experience and knowledge regarding the effects of bridge deck placement techniques on deck cracking performance. The survey consisted of 10 questions, with Question 5 differing between state DOTs and VDOT districts. All remaining questions were identical for both groups. Table 1 shows the survey questions.

Table 1. Survey Questions

No.	Question
1	Based on your experience, please rate the importance of the factors presented below on concrete bridge deck cracking. Rate the importance of the different factors from 1 to 10, where 1 means "not important" and 10 means "critically important." If any important factor affecting bridge deck cracking is missing, please mention it. Factors: - Concrete Properties: strength, slump, shrinkage, concrete temperature, fiber reinforcement. - Environmental/Site Conditions: ambient temperature, season (summer vs. winter), evaporation rate. - Construction Practices: time of casting (night vs. day), placement sequence (continuous vs. segmental/checkerboard), vibration/consolidation, finishing, curing. - Structural Design: girder type, deck thickness, reinforcement (size and type).
2	In your experience, does continuous concrete bridge deck placement cause more deck cracking than segmental/checkerboard placement? Yes or no?
3	In your experience, what are the main advantages and disadvantages of continuous placement of concrete bridge decks (relative to segmental/checkerboard placement)?
4	What factors do you consider when deciding whether to use continuous or segmental/checkerboard placement of concrete bridge decks?
5	**VDOT Districts:** Please list bridges in your district exhibiting significant concrete deck cracking. If known, please mention the deck placement technique (i.e., continuous vs. segmental/checkerboard).

No.	Question
	State DOTs: How do the specifications in your state influence the decision to use continuous or segmental/checkerboard placement of concrete bridge decks? Please explain.
6	Do you believe that one deck placement method (continuous vs. segmental/checkerboard) is generally more suitable for certain types of bridges or situations? Yes or no? If yes, please explain.
7	Does the span length, number of spans, and overall length of the bridge affect the decision of whether to use continuous or segmental/checkerboard placement of concrete bridge decks? Yes or no? If yes, please explain.
8	Have you observed any significant differences in the long-term performance of concrete bridge decks constructed using continuous or segmental/checkerboard placement? a. Yes, segmentally cast decks perform better. b. Yes, continuously cast decks perform better. c. No.
9	When placing concrete bridge decks continuously, how does the contractor/producer ensure that concrete stays plastic during placement?
10	When placing concrete bridge decks continuously, what measures are taken (if any) to prevent deck cracking?

VDOT's Bridge Database Analysis

VDOT's bridge condition database was analyzed to identify the potential effects of deck placement techniques on deck cracking performance. Deck cracking was evaluated using Condition State 2 (CS2), which represents the area in square feet of moderate unsealed cracks 0.012 to 0.05 inches wide or unsealed pattern (map) cracking. CS2 was used as the primary metric because nearly none of the bridges in the dataset exhibited Condition State 3 cracking, defined as wide cracks greater than 0.05 inches or heavy pattern or map cracking.

The analysis focused on bridges that have been constructed since 2017, the year VDOT fully adopted Low Shrinkage Class A4 Modified Concrete for all new deck placements, resulting in notable reductions in deck cracking. Restricting the dataset to modern decks ensured consistency with current materials and construction practices. Only multi-span continuous beam bridges were included because the question of continuous versus sequential deck placement is not applicable to single-span or simple-span bridges. Furthermore, the analysis was limited to bridges supported by steel beams because of concerns about potential diaphragm voids resulting from bar rotation during continuous placement in decks supported by concrete beams.

A total of 72 multi-span continuous steel bridges constructed since 2017 met these criteria. In addition, five bridges in the Bristol District, originally built between 1954 and 1975, were included in the analysis because their decks were replaced after 2017 and placed continuously. Accordingly, this study considered 77 bridges.

Data collected for each bridge included overall length, width, number of spans, highway system classification (interstate, primary, secondary, or urban), and CS2 deck cracking. Deck volume was also estimated assuming a deck thickness of 8.5 inches. Because the deck placement method (sequential or continuous) is not recorded in VDOT's database, the authors reviewed as-built bridge plans, examined deck placement schedules, and contacted district engineers to confirm the placement sequence used for each structure.

RESULTS AND DISCUSSION

Literature Review

Factors Affecting Bridge Deck Cracking

Four main factors have been identified as major contributors to bridge deck cracking: (1) material properties, (2) environmental and site conditions, (3) construction techniques, and (4) structural design (Hadidi and Saadeghvaziri, 2005; Schmitt and Darwin, 1995). Each of these factors possesses multiple components that affect the cracking tendency of bridge decks. **Error! Reference source not found.**2 summarizes these factors and their respective components. From Table 2, it is evident that bridge deck cracking is a complex issue given the multitude of factors involved. Consequently, rational analysis of bridge deck cracking necessitates a holistic understanding of the contribution of these factors to the cracking of concrete materials.

Table 2. Factors Affecting Bridge Deck Cracking

Factors	Strategies to Reduce Cracking
Material Properties (Hadidi and Saadeghvaziri, 2005)	***General Strategy:*** Reduce early shrinkage, heat of hydration, and Young's modulus. ***Aggregate:*** Use a low-shrinkage aggregate with high specific gravity and low coefficient of thermal expansion, larger aggregate size, and high aggregate-to-paste ratio. ***Water and cement:*** Use low amounts of water and cement (i.e., volume of paste, water + cement ≤ 27%), low water-cement ratio (i.e., up to 0.40–0.48), supplementary cementitious materials, and shrinkage-compensating cement. ***Compressive strength and slump*:** No general agreement exists on the effect of these factors on bridge deck cracking. ***Air content:*** Use high air content (i.e., ≥ 6%). ***Fibers:*** The use of fibers can help reduce and control cracking.
Environmental and Site Conditions (Hadidi and Saadeghvaziri, 2005)	***General Strategy:*** Avoid or mitigate the effects of extreme temperature conditions, low humidity, and high wind speed. ***Ambient temperature:*** Ambient temperature should be 40–90°F ***Concrete temperature:*** Maximum concrete temperature should be 80°F and at least 10–20°F lower than ambient temperature. ***Evaporation rate:*** If evaporation rate exceeds 0.2 lb/ft^2/h for normal concrete or 0.1 lb/ft^2/h for concrete with low water-cement ratio, take special precautions (e.g., use wind breaks and enclosures).

Construction Techniques (Hadidi and Saadeghvaziri, 2005)	***General Strategy:*** Use appropriate pouring, finishing, and curing techniques.
	Pour rate: Pour concrete at a rate > 0.6 span lengths/h.
	Pour sequence: Place concrete in positive moment regions first. Adhere to the following recommendations:
	• If possible, place deck at one time.
	• For simple span bridges, place one span per placement.
	  ○ If not possible, divide deck longitudinally and place each strip at one time.
	    ▪ If not possible, place center span first and then the other sections.
	• If multiple placements are necessary on continuous beams, place middle span first and observe a 72-hour delay between placements, using a bonding agent at the joint.
	Time of casting: Nighttime casting recommended.
	Vibration of fresh concrete: Appropriate vibration for proper concrete consolidation is helpful to reduce cracking.
	Finishing: Early finishing and mechanical grooving recommended.

Factors	Strategies to Reduce Cracking
	Curing: Adequate and timely curing is key. Early curing is recommended by means of fogging, water sprinkling, wet burlap, or curing compounds. Wet curing for a minimum of 7 days and preferably 14 days is recommended.
Structural Design (Hadidi and Saadeghvaziri, 2005)	***General Strategy:*** Use appropriate design practices to mitigate cracking. ***Girder Type, boundary conditions, and spacing:*** The use of concrete girders reduces cracking relative to steel girders. The girder-deck-stiffness ratio should be minimized. The use of simple spans reduces cracking relative to continuous spans. ***Deck thickness:*** Increasing deck thickness can be beneficial to reducing cracking. ***Reinforcement:*** Limit size of deck reinforcement bars to Number 5 or smaller. Use higher amount of longitudinal steel. Reduce splices and extend deck transverse steel full width.

Effect of Bridge Deck Placement on Cracking Performance

Even though studies conducted in the 1980s reported that placement length and sequence did not seem to have a significant effect on bridge deck cracking, research work conducted in the 1990s attributed bridge deck cracking to pour sequence and recommended placing concrete first in the positive moment regions to mitigate cracking (Cheng and Johnston, 1985; Hadidi and Saadeghvaziri, 2005; Issa, 1999; Ramey et al., 1997).

A study by Gara et al. (2013) using structural modeling evaluated the development of tensile stresses in steel-concrete composite bridge decks due to the effect of various placement techniques, including unique placement, continuous placement, alternated placement, continuous placement with a post-connected slab, and continuous placement with a nonsymmetrical post-connected slab. To evaluate the development of tensile stresses in bridge deck slabs, the study implemented different widely accepted material and structural models. Time-dependent characteristics of concrete, such as dimensional changes (i.e., drying shrinkage, autogenous shrinkage, thermal shrinkage, and creep) and strength development, were considered. Furthermore, for each of the five placement sequences, the structural effects associated with slab and formwork weight were carefully accounted for. The modular ratio approach suggested by Eurocode 4 was implemented to evaluate slab stress development at various construction stages. Based on the analysis conducted, the study concluded that alternate placement allows for the reduction of stresses in the bridge deck slab, especially over the inner supports, whereas continuous placement causes much higher tensile stresses, leading to the potential for significant cracking.

Bridge Deck Cracking: The University of Kansas Experience

The University of Kansas research led by Dr. David Darwin provides one of the most extensive evaluations of bridge deck-cracking performance in the United States (Bahadori et al., 2022; Dhungel et al., 2023; Feng et al., 2026; Khajehdehi and Darwin, 2019; Khajehdehi et al., 2021; Schmitt and Darwin, 1995, 1999). Across multiple studies, the work consistently identifies the concrete paste content, which governs concrete shrinkage, as the dominant factor influencing deck cracking (Khajehdehi et al., 2021). Decks constructed with paste contents below approximately 26.5% show a significantly higher likelihood of achieving low crack densities, whereas decks with paste contents above approximately 27.3% are far more likely to exhibit elevated crack densities (Feng et al., 2026; Khajehdehi et al., 2021). This relationship is observed across different states, climates, and bridge configurations, emphasizing that mixture proportioning, particularly the control of paste volume, is the most effective strategy for minimizing cracking.

Darwin's group also examined the effect of several crack-reducing technologies on deck cracking performance, including shrinkage-reducing admixture (SRA), internal curing, and fibers (particularly polymer macro- and micro-fibers at modest dosages of 0.5-5 lb/yd^3) (Bahadori et al., 2022; Dhungel et al., 2023; Feng et al., 2026). Generally, findings show that these technologies can play a role in reducing cracking in bridge decks, but they must be used together with a low paste content concrete and good construction practices to achieve decks with low crack densities. The use of SRA was evaluated on bridge decks in Virginia, making these findings particularly relevant to VDOT (Feng et al., 2026; Polley et al., 2015). Decks with low paste content (i.e., ≤ 27.3%) incorporating SRA performed very well, exhibiting a low crack density (0.16 m/m^2) comparable with that of low paste content decks in Kansas (Feng et al., 2026). In contrast, decks with high paste content (i.e., > 27.3%) incorporating SRA exhibited relatively high crack density (0.46 m/m^2), higher than that observed for a high paste content control deck in Virginia without SRA (0.26 m/m^2), although still less than that reported for high paste content decks in Kansas (0.73 m/m^2) (Feng et al., 2026). Crack density values included cracks wider than approximately 0.08 mm, which are visible to inspectors when they bend at the waist to lower their eyes toward the deck during the survey.

The studies from the University of Kansas further show that when contractors do not properly consolidate, finish, or cure the concrete, significantly higher crack densities can occur even when a low paste concrete mixture is used (Feng et al., 2026). Accordingly, strict adherence to construction procedures is essential to achieving bridge decks with low cracking potential. The findings consistently demonstrate that the use of appropriate materials alone cannot compensate for poor field execution. Furthermore, studies show that structural variables, such as girder type, span count, or deck skew, have a minimal effect on cracking compared with concrete mixture design and construction practices (Bahadori et al., 2022; Dhungel et al., 2023; Feng et al., 2026; Khajehdehi and Darwin, 2019). Across all datasets, Darwin's work emphasizes that the combination of low paste content and high-quality construction procedures provides the most reliable path to durable, crack-resistant bridge decks.

Key Findings from the Literature Review

Bridge deck cracking is the result of interacting effects from material properties, environmental conditions, construction techniques, and structural design, with shrinkage-related mechanisms consistently identified as the dominant cause. Among material factors, cement paste content governs cracking performance more than any other variable. Studies repeatedly show that decks constructed with paste contents below approximately 26.5 to 27.3% by volume exhibit significantly lower crack densities, whereas higher paste contents are associated with substantially increased cracking. Environmental factors such as high temperature, low humidity, and elevated evaporation rates further exacerbate shrinkage and early-age cracking, underscoring the importance of controlling placement conditions.

Construction practices are among the most critical and controllable factors influencing cracking. Proper placement rates and sequences, adequate consolidation and finishing, and especially timely and sustained curing are essential to limiting crack formation. Research consistently demonstrates that poor field execution can lead to high crack densities even when optimized, low-shrinkage concrete mixtures are used. Structural design variables and placement sequence can influence stress development, particularly in negative moment regions, but their effects are generally secondary compared with mixture proportioning and construction quality. Overall, the literature emphasizes that durable, crack-resistant bridge decks are most reliably achieved through low paste content concrete combined with rigorous construction and curing practices, rather than reliance on placement sequence or crack-reducing technologies alone. In this context, VDOT Low Shrinkage Class A4 Modified Concrete used in bridge decks is permitted to have a cementitious content of up to 600 lb/yd^3 when normal weight aggregates are used. For a typical water to cementitious materials ratio of 0.45 with either 20% fly ash or 40% slag cement, this corresponds to paste contents of approximately 28.0 to 28.3%, which exceed the paste content range generally recommended for optimal cracking performance. Notwithstanding, good cracking performance has been reported for decks incorporating VDOT Low Shrinkage Class A4 Modified Concrete in Virginia, which also includes SRA, relative to Class A4 General Concrete used before 2017. However, further improvements to the specification could be achieved by limiting paste content to 27.3%, or ideally 26.5%, when placing decks continuously, to further mitigate the risk of elevated deck crack densities.

Survey of State Departments of Transportation and VDOT Districts

Fifteen state DOTs, of which only 9 self-identified, completed the survey. These states were Alaska, California, Delaware, Iowa, Maine, Maryland, New York, Oregon, and Washington (Figure 1). Six of the nine VDOT districts responded to the survey: Bristol, Fredericksburg, Hampton Roads, Lynchburg, Northern Virginia, and Salem.

The supplementary documents published with this report include the complete set of survey responses, including all information respondents provided. The relevant findings from the survey responses are presented in the following subsections.

Factors Affecting Bridge Deck Cracking

Based on the responses to Question 1 from the survey, Figure 2 presents the average perceived importance of factors affecting bridge deck cracking according to VDOT and the surveyed state DOTs.

Table 3 summarizes the five most influential factors affecting bridge deck cracking. Both VDOT and the state DOTs ranked curing as the most important factor. In addition, for both groups, the top four factors—curing, evaporation rate, shrinkage, and ambient temperature for VDOT and curing, shrinkage, evaporation rate, and concrete temperature for the state DOTs—are all associated with shrinkage mechanisms, whether plastic, drying, or thermal. Both VDOT and the state DOTs ranked placement sequence as the fifth most important factor. Accordingly, although placement sequence is considered important, shrinkage-related factors—including curing, concrete shrinkage, evaporation rate, and ambient or concrete temperature—are viewed as more critical contributors to bridge deck cracking.

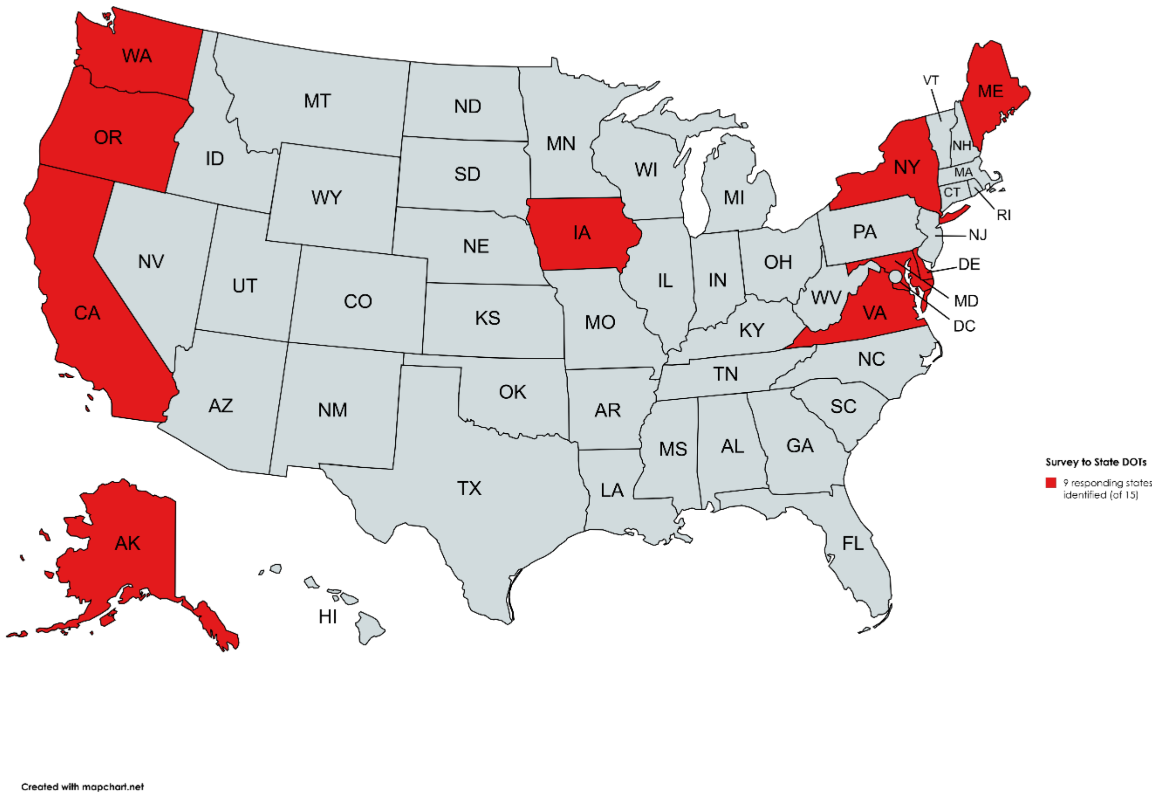


Figure 1. Survey Responses

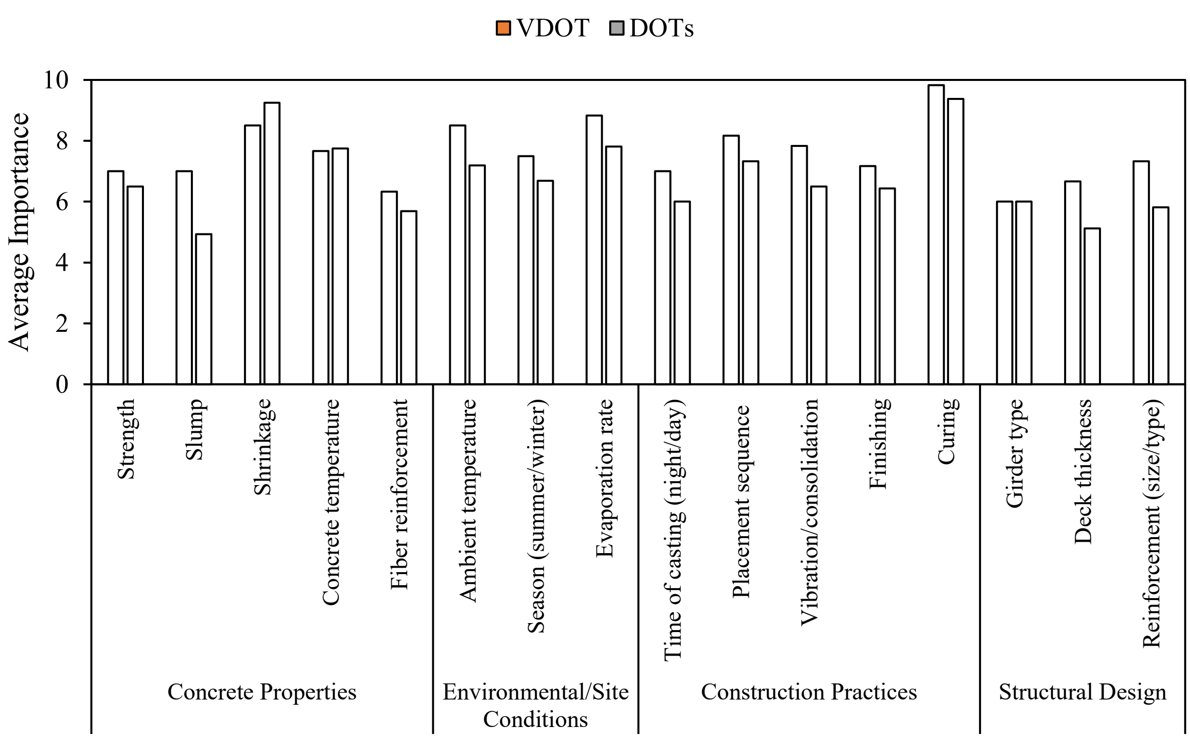


Figure 2. Importance of Factors Affecting Bridge Deck Cracking According to VDOT and Other State Departments of Transportation

Table 3. Top Five Factors Affecting Bridge Deck Cracking (Average Importance Shown in Parentheses)

VDOT	Other State Departments of Transportation
• Curing (9.8)	• Curing (9.4)
• Evaporation Rate (8.8)	• Shrinkage (9.3)
• Shrinkage (8.5)	• Evaporation Rate (7.8)
• Ambient Temperature (8.5)	• Concrete temperature (7.8)
• Placement Sequence (8.2)	• Placement Sequence (7.3)

Effect of Bridge Deck Placement Sequence on Cracking Performance

Based on the responses to Question 2 from the survey, Figure 3 illustrates the experiences of VDOT and the state DOTs with deck cracking associated with continuous placement. VDOT respondents were evenly split: 50% indicated that continuous placement results in more cracking than the typical sequential checkerboard placement, as described in VDOT's (n.d.) *Manual of the Structure and Bridge Division*, File No. 10.03-1, whereas the remaining 50% indicated it does not. In contrast, 75% of state DOT respondents reported that continuous placement leads to increased cracking. These results indicate a lack of general consensus on the issue, particularly within VDOT. The numerous interacting factors that contribute to deck cracking likely influence this lack of agreement.

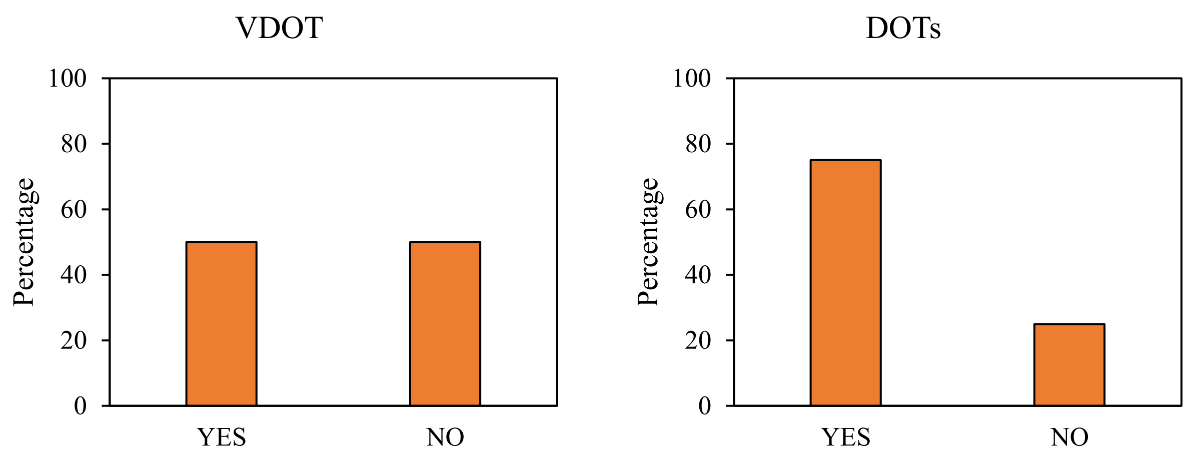


Figure 3. Answer to Question 2: In Your Experience, Does Continuous Concrete Bridge Deck Placement Cause More Deck Cracking than Checkerboard Placement? DOTs = departments of transportation.

More insights into the issue can be drawn from the responses to Question 8 (Figure 4). Interestingly, although 50% of VDOT respondents and 75% of state DOT respondents indicated that continuous placement causes more cracking, 83% of VDOT respondents and 71% of state DOT respondents reported that no difference in long-term performance is observed based on the placement sequence. Furthermore, 17% of VDOT respondents indicated that decks placed continuously perform better in the long term, whereas none indicated that sequential checkerboard placement performs better. In contrast, 7% of state DOT respondents stated that continuous placement performs better in the long term, whereas 21% indicated that sequential checkerboard placement performs better.

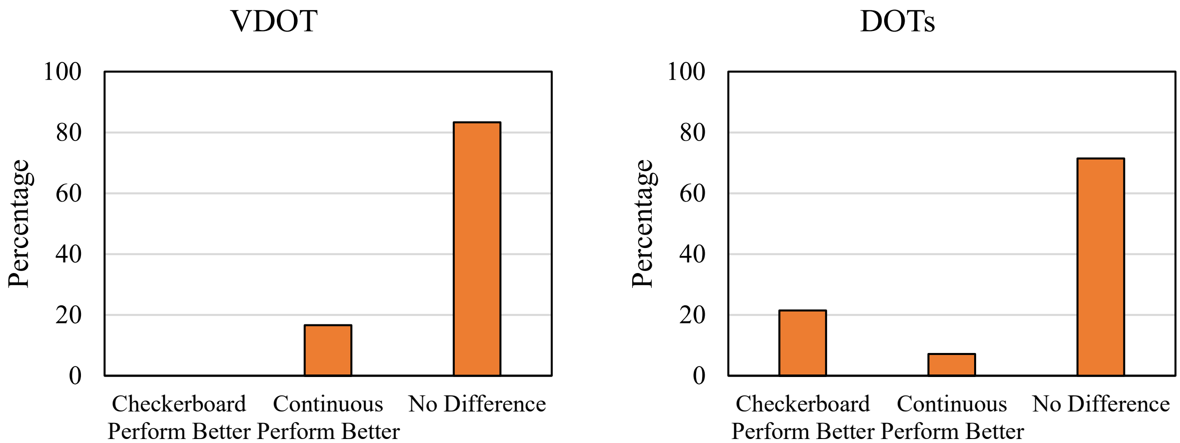


Figure 4. Answer to Question 8: Have You Observed Any Significant Differences in the Long-Term Performance of Concrete Bridge Decks Constructed Using Continuous or Checkerboard Placement? DOTs = departments of transportation.

When considering Question 8 responses alongside Question 2 responses, the findings suggest that even if continuous placement results in more cracking, this additional cracking does not appear to meaningfully affect long-term deck performance. This result may be due to the cracking not being severe enough to significantly affect durability or to competing effects because sequential placement introduces construction joints that may leak and compromise durability in a manner similar to additional cracking.

Advantages and Disadvantages of Continuous Placement

Table 4 summarizes the responses to Question 3 from the VDOT districts and state DOTs regarding the main advantages and disadvantages of continuous bridge deck placement. Because the responses were open ended, they were grouped into broad categories representing common themes. The number of times each category was mentioned is in parentheses and is presented in descending order of frequency.

Table 4. Advantages and Disadvantages of Continuous Placement

VDOT	Other State Departments of Transportation
Advantages: • Reduce or eliminate construction joints (x5) • Faster and efficient construction (x3) • Better ride quality (x1) • Less cracking (x1) **Disadvantages:** • Logistically challenging and increased risk of quality issues (x4) • More cracking (x4) • Construction joints at unexpected locations (x1)	**Advantages:** • Faster and efficient construction (x11) • Reduce or eliminate construction joints (x5) • Better ride quality (x3) • No partial composite behavior needs to be considered • Less rigorous analysis for deck dead load effects **Disadvantages:** • Logistically challenging and increased risk of quality issues (x8) • More cracking (x6) • Deflections can be an issue (x3) • Construction joints at unexpected locations (x1)

Overall, the VDOT districts and state DOTs generally agree on both the advantages and disadvantages of continuous placement. The primary advantages cited include the reduction or elimination of construction joints, faster and more efficient construction, and improved ride quality. Notably, one VDOT respondent identified reduced cracking as an advantage. Although this result appears counterintuitive, the respondent clarified that this outcome is contingent on strict compliance with VDOT Road and Bridge Specifications and maintaining the concrete plastic throughout the placement (VDOT, 2020). This observation underscores the critical role of construction practices in cracking performance, particularly when continuous placement is used.

With respect to disadvantages, respondents most frequently identified the increased logistical challenges associated with continuous placement, which substantially elevate the risk of quality-related issues. This concern was closely followed by increased cracking. Other disadvantages mentioned include construction joints at unexpected locations and issues, such as cracking, associated with deflections developing during placement. Collectively, these responses suggest that continuous placement inherently increases the risk of construction-related problems, including cracking.

Importantly, these findings do not indicate that continuous placement cannot be successfully implemented. Rather, they suggest that the likelihood of adverse outcomes increases because of the need to maintain uninterrupted concrete delivery, sustain adequate placement rates over extended durations, and manage workforce fatigue. Unforeseen disruptions, such as equipment malfunctions or concrete plant interruptions, may further compound the risk of quality issues. Maintaining concrete plastic throughout the placement is also a persistent challenge.

These considerations highlight the importance of thorough planning and the use of experienced contractors when continuous placement is selected. When properly planned and executed, continuous placement can be a viable alternative to sequential placement. However, the suitability of this approach should be evaluated on a project-specific basis, considering factors such as contractor experience and capabilities, available resources, and overall construction risk.

Factors to Consider when Choosing Placement Sequence

Table 5 presents a summary of VDOT districts and state DOTs' responses to Question 4 regarding factors considered when deciding to place a deck continuously. The responses were grouped into categories, and the frequency with which each factor was mentioned is shown in parentheses.

Table 5. Factors Considered when Deciding on Continuous Placement (Frequency Shown in Parentheses)

VDOT Districts	Other State Departments of Transportation
• Span configuration[a] (x4)	• Span configuration[a] (x10)
• Volume of pour (x4)	• Volume of pour (x6)
• Rate of pour (x4)	• Duration of placement (x4)
• Contractor (x3)	• Contractor (x4)
• Concrete setting time (x3)	• Rate of pour (x2)

[a] Length, width, number of spans, and whether the spans are continuous or simple.

Responses to Question 4 indicate strong agreement between VDOT districts and state DOTs that decisions regarding continuous deck placement are primarily driven by span configuration, deck volume, and construction-related factors, including placement rate and duration, concrete setting time, and contractor capability.

The responses to Questions 6 and 7 provide additional context for the factors influencing decisions on deck placement methods. Question 6 addresses the suitability of continuous versus sequential placement for specific situations, whereas Question 7 examines the influence of span length, number of spans, and overall bridge length on placement decisions. Table 6 provides a summary of the more relevant responses to Questions 6 and 7.

Table 6. Relevant Responses on Factors Influencing Selection of Deck Placement Sequence

State Departments of Transportation (DOTs)
• California DOT: Use continuous deck placement for simply supported superstructures. Use sequential/checkerboard deck placement for continuous superstructures, or simply supported superstructures made continuous. Exceptions considered: If the concrete deck can be placed quickly enough to remain plastic until the entire weight of the concrete deck is placed in adjacent spans, a continuous pour may be considered.
• New York DOT: Multi-span bridges and some integral abutment bridges should be placed sequentially due to negative moments. Multi-span structures with any span over 60 feet long or total deck concrete volume exceeding 360 yd^3 are done using multiple placements.
• Maine DOT: For multi-span continuous structures with less than 250 yd^3 of deck concrete, the superstructure slab concrete shall be placed in one continuous operation, and the concrete shall be plastic one complete span behind the span being placed. Consider whether changes are necessary for cast-in-place end diaphragms, semi-integral backwalls, etc.
• Washington DOT: Continuous placement is preferred for simple spans and short multi-span continuous bridges. Generally, continuous pours are not preferred for pours requiring more than 200–250 yd^3.
• Maryland DOT: If continuous placements are very long, it would be better to use a segmental/checkerboard placement. Pouring long lengths may necessitate concrete placement for excessively long times, where fatigue and equipment failure are more prone to happen.
• Iowa DOT: Would like to see more decks cast using sequential/checkerboard placement, however, the economics currently stand against this being a regular practice. We will allow continuous placement if the contractor can demonstrate that their ways and means are adequate to handle the placement.
• Oregon DOT: Use continuous placement for short-span bridges, single-span bridges, or multi-single-span bridges. Use sequential/checkerboard placement for bridges with continuous spans.
• Delaware DOT: For continuous span structures, placing the positive moment regions first should lead to less stress being locked in and less overall cracking due to that.
• Alaska DOT: Always use sequential placement.
VDOT Districts
• Fredericksburg District: Simple spans generally do not require a deck slab placement sequence other than for the integral or semi-integral back walls, if present. Longer spans and continuous multi-span superstructures may benefit from consideration of a checkerboard placement.
• Lynchburg District: Continuous placement is preferred when the rate of placement is such that all concrete remains plastic throughout entire concrete placement. Requires proper planning coordination, correct mix design, and proper use of admixtures. The total volume is the critical factor. Concrete for larger deck placements needs to remain plastic for 6–8 hrs. Minimal initial set at starting point can be acceptable (positive moment region).
• Salem District: Purely because the quality of a continuously poured deck is so much more dependent upon contractor planning and execution (which is historically an issue), we believe sequential/checkerboard placements are generally more advantageous on continuous spans. This would also be true on bridges with large deflections and other types of excessive movements during the curing process.

Responses to Questions 6 and 7 indicate that continuous placement is generally considered suitable for simple spans and short multi-span continuous bridges, whereas sequential placement is preferred for longer, multi-span continuous structures. Short multi-span continuous bridges are typically characterized by deck volumes (governed by overall bridge length and width) of less than approximately 250 to 360 yd^3, making deck volume a critical factor when determining the appropriate placement method. In addition, New York DOT referenced individual spans exceeding 60 feet as a threshold to avoid when placing decks continuously. Successful continuous placements depend heavily on maintaining concrete plasticity. To limit tensile stress development in negative moment regions, the concrete must remain plastic throughout the entire pour or, at a minimum, one full span behind the active placement, as Maine DOT suggested. Meeting this requirement is logistically demanding and necessitates significant coordination and highly capable contractors. For example, an uninterrupted 6-hour continuous placement would require placement rates of approximately 42 yd^3/hr and 60 yd^3/hr for deck volumes of 250 yd^3 and 360 yd^3, respectively. By comparison, the VDOT Road and Bridge Specifications require a minimum placement rate of 20 yd^3/hr (VDOT, 2020). Although a placement rate of 42 yd^3/hr is reasonably achievable with good coordination, a rate of 60 yd^3/hr is more challenging and requires very careful planning and execution. Nonetheless, both rates are feasible under appropriate conditions.

The Role of Specifications on Bridge Deck Placement

The following is a summary of relevant responses to Question 5 from state DOTs regarding the influence of their respective specifications on bridge deck placement:

- Iowa DOT: We have specifications that are made for both placements.
- Alaska DOT: Placement is dictated by plans.
- Maryland DOT: Our specifications do not influence the placement decision.
- Washington DOT: The decision is typically made by designers and specified in the contract plans. Standard practice and details are based on sequential/checkerboard placement to minimize tensile stress in the deck.
- New York DOT: Specifications do not influence the decision. Other design guidance documents provide instructions on when to use multiple deck placements.
- California DOT: Caltrans standard construction specifications require sequential/checkerboard placement of concrete bridge decks when the superstructure is continuous; however, this requirement can be superseded by a special design and details on the plans.
- Maine DOT: Placement decision is usually project specific, not something in the Standard Specifications. We have a few standard notes for the designer to choose from based on project details that will then be put in the plans.
- Oregon DOT: The *Bridge Design Manual* discusses deck pour sequences for concrete and steel girder bridges with continuous spans. A method similar to VDOT's sequential/checkerboard is recommended to be shown on the bridge plans.

The responses from state DOTs indicate that bridge deck placement decisions are largely determined at the project level rather than dictated by statewide specifications. Several agencies, including Alaska, Maryland, New York, and Maine, reported that their standard specifications do not govern placement methods, with decisions instead made by designers and reflected in project plans or supplementary design guidance. Iowa's specifications allow either placement approach, providing flexibility without prescribing a preferred method. In contrast, a few states, including Washington, Oregon, and California, provide more explicit direction through specifications or design manuals, typically recommending or requiring sequential/checkerboard placement for continuous superstructures to address deck stresses. Even in these cases, designers may adjust or override standard requirements when warranted by project conditions. Overall, the findings show that most state DOTs rely on engineering judgment and project-specific considerations rather than rigid specification-based requirements for bridge deck placement.

Best Practices to Prevent Cracking when Placing a Deck Continuously

Table 7 presents a summary of VDOT districts and state DOTs' responses to Question 10 regarding measures used to prevent deck cracking during continuous deck placement. Responses were grouped into categories, and the frequency with which each factor was mentioned is in parentheses.

Table 7. Best Practices to Prevent Cracking when Placing Decks Continuously

VDOT Districts	Other State Departments of Transportation

• Appropriate curing practices (x4)
   o Follow VDOT's Road and Bridge Specifications
• Use the right type of concrete (x1)
   o Low shrinkage Class A4 modified concrete
• Ensure concrete remains plastic (x1)
	• Appropriate curing practices (x6)
	   o Wet curing within 20–30 minutes of placement for 7–14 days.
	• Use low shrinkage or fiber-reinforced concrete mixtures (x3)
	• Specify maximum shrinkage limit (x2)
	• Comply with the concrete placement plan (x2)
	• Specify minimum placement rate (x1)
	• Demonstrated preparedness of the contractor (x1)
	• Keep the concrete plastic during placement (x1)
	• Internal curing (x1)
	• Use hydration stabilizers (x1)

The responses from VDOT districts and state DOTs indicate broad agreement that effective curing is the primary measure for preventing cracking during continuous deck placements. Both groups frequently emphasized timely and sustained curing, with state DOTs providing specific guidance, such as initiating wet curing within 20 to 30 minutes and maintaining it for 7 to 14 days. Material-related strategies were also noted, including using low-shrinkage or fiber-reinforced mixtures and, in some cases, specifying shrinkage limits. Additional practices that state DOTs cited, such as adherence to placement plans, maintaining adequate placement rates, ensuring contractor preparedness, and using hydration stabilizers or internal curing, highlight the importance of proper planning and execution. Overall, the findings reinforce the conclusion that minimizing cracking relies on a combination of sound curing practices, appropriate material selection, and adequate construction procedures.

Understanding the importance of keeping concrete in a plastic state during placement to limit tensile stress development and cracking, Question 9 gathered input from VDOT districts and state DOTs on the practices used to maintain concrete plastic during bridge deck placement. Table 8 provides a summary of the responses, with comments grouped into categories and the frequency of each in parentheses.

Table 8. Strategies for Keeping Concrete Plastic During Placement

VDOT Districts	Other State Departments of Transportation
• Using retarding admixtures (x6) • Materials engineer review of mix and admixtures (x1) • Providing required placement rate (x1) • Request setting time data (x1) • Provide trial batches (x1)	• Using admixtures (x9) ○ Retarders and hydration stabilizers • Providing required placement rate (x3) • Doing night pours (x2) • Controlling/monitoring concrete temperature (e.g., cooling concrete) (x2) • Avoiding hot summer or windy days (x1)

The responses show clear consensus that admixture use, particularly retarders, is the primary strategy for maintaining concrete plastic during placement. State DOTs specifically highlighted hydration stabilizers, a class of retarders designed for extended set times and well suited for large placements requiring several hours of workability (Federal Highway Administration, n.d.). VDOT districts likewise emphasized the use of retarding admixtures, supported by mix reviews, setting-time data, and trial batches. State DOTs also noted operational measures, such as maintaining required placement rates, conducting night pours, and controlling concrete temperature, along with avoiding hot or windy conditions. Overall, agencies rely on a combination of admixture use and construction-stage controls to keep concrete plastic and reduce the risk of cracking.

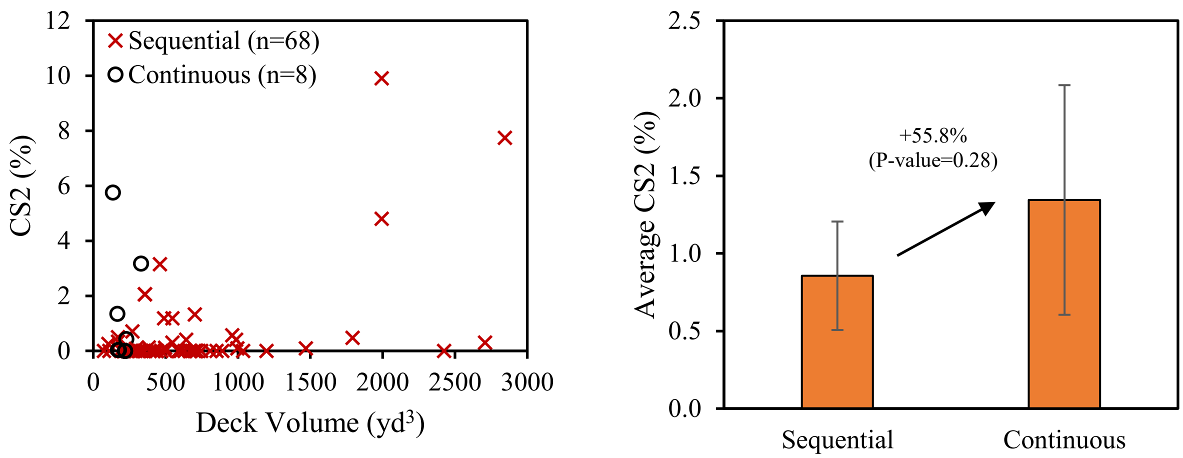
VDOT's Bridge Database Analysis

Table 9 presents the number of multi-span continuous steel bridges constructed since 2017. Median bridge length, width, and deck volume are reported for each highway system classification. In addition, the number of decks built with volumes less than 250 yd^3 and less than 360 yd^3 is reported. It is observed that 39% of the decks had volumes of less than 360 yd^3, making them potential candidates for continuous placement.

Table 9. Multi-Span Continuous Steel Bridges Since 2017

	Interstate	Primary	Secondary	Urban	All
Number of Bridges	29	24	13	6	72
Deck Volume < 250 yd^3	1 (3%)	8 (33%)	5 (38%)	1 (17%)	15 (21%)
Deck Volume < 360 yd^3	6 (21%)	14 (58%)	5 (38%)	3 (50%)	28 (39%)
Median Length (ft)	517	254	270	297	363
Median Width (ft)	45	41	53	49	43
Median Volume (cy)	674	312	593	349	479

Figure 5a shows the percentage of deck area exhibiting CS2 cracking plotted against the deck volume (in yd^3) for each of the decks considered in this study, with decks distinguished by their placement method (sequential or continuous). Importantly, one sequentially placed deck identified as an outlier was removed from the dataset. Based on the bridge plans and the inspection report, it was determined that this bridge was more prone to cracking because of specific design decisions rather than because of the particular placement sequence used. This deck had a volume of 133 yd^3 and presented a CS2 cracking area of 14.2%. Accordingly, Figure 5 is the result of 76 data points instead of 77. From Figure 5a, it is observed that decks placed continuously have smaller volumes, ranging from 135 to 330 yd^3, yet are often below 250 yd^3 (eight of nine). This observation agrees with the survey results, in which decks with volumes greater than 250 to 360 yd^3 are recommended to be placed sequentially. With respect to the effect of placement method on CS2 cracking, no obvious difference is observed between sequentially and continuously placed decks because data points generally fall within levels of CS2 cracking observed for sequential placement. Notably, five of eight continuously placed decks exhibited low CS2 cracking areas (below 0.5%), whereas the remaining three showed higher CS2 cracking areas of 1.3%, 3.2%, and 5.8%.



(a) **(b)**

Figure 5. (a) Percent Area of the Deck with CS2 Cracking for Sequentially and Continuously Placed Decks Constructed Since 2017; (b) Average Percent Area of the Deck with CS2 Cracking for Sequentially and Continuously Placed Decks. CS2 = Condition State 2.

Figure 5b shows the average percentage of deck area exhibiting CS2 cracking for decks placed sequentially (n = 68) and continuously (n = 8), with error bars representing ± one standard error. On average, continuous placement produced an increase in CS2 cracking of 55.8%. However, this difference was not statistically significant (p-value = 0.28) based on a one-tailed t-test assuming unequal variances. A one-tailed test was selected to evaluate the hypothesis that continuous placement results in greater cracking than sequential placement, providing higher statistical power for detecting an increase in CS2 cracking. Unequal variances were assumed based on an F-test, which did not support the assumption of equal variances (p-value = 0.19). Based on this finding, it can be concluded that continuous placement does not have a statistically significant effect on CS2 cracking, echoing the results from the survey and literature review. Importantly, when the outlier is included in the dataset, the outcome of the statistical analysis remains the same. However, the average CS2 cracking area for sequential placement becomes higher (1.05% instead of 0.86%), and the increase in CS2 cracking for continuous placement relative to sequential placement becomes smaller (27.6% instead of 55.8%). Although the insights from the data are valuable, it is recognized that the dataset is limited and exhibits high variability. Accordingly, as more deck placements occur, expanding the dataset would be highly beneficial to further elucidate the effect of deck placement on cracking performance.

CONCLUSIONS

- *The literature demonstrates that the primary factors influencing bridge deck cracking are the concrete paste content and the quality of construction practices, including consolidation,* *finishing, and curing*. Decks constructed with concrete containing volumetric paste contents below approximately 26.5% have a substantially greater likelihood of exhibiting low crack density, whereas those with paste contents exceeding roughly 27.3% are significantly more prone to developing high crack densities. Although crack-mitigating technologies, such as shrinkage-reducing admixtures, internal curing, and polymer fibers, can improve cracking performance, their effectiveness depends on their use in combination with low-paste mixtures and proper construction practices.

- *According to VDOT Districts and state DOTs, the primary factors influencing bridge deck cracking are shrinkage-related mechanisms (plastic, drying, and thermal shrinkage)*. Although placement sequence is recognized as an important factor, it is generally considered secondary to shrinkage-related effects.

- *State DOTs generally perceive continuous placement to result in more cracking, whereas no clear consensus exists among VDOT districts, which are evenly split*. This divergence likely reflects the dominant influence of material selection and construction practices, which may outweigh the effects of placement sequence alone.

- *VDOT districts and state DOTs broadly agree that long-term deck performance does not differ significantly between continuous and sequential (checkerboard) placement methods*. This finding may be because any additional cracking associated with continuous placement is not severe enough to adversely affect durability, or because sequential placement introduces construction joints that can leak and similarly compromise long-term performance.

- *VDOT districts and state DOTs indicate that continuous bridge deck placement offers advantages, such as reduced construction joints and improved construction efficiency, but is associated with increased logistical complexity and a higher risk of quality-related issues, including cracking*. The findings suggest that the success of continuous placement is highly dependent on construction practices, contractor experience, and volume of concrete and therefore should be evaluated on a project-specific basis.

- *Most state DOTs recommend sequential placement for multi-span continuous bridges. Nonetheless, continuous placement is considered adequate for short multi-span continuous bridges when the entire placement can be completed before concrete setting, or when the concrete can be maintained in a plastic state at least one full span behind the active placement*. Definitions of "short" multi-span bridges vary among state DOTs but typically correspond to deck volumes on the order of less than 250 to 360 yd^3.

- *For VDOT bridge decks constructed since 2017, available data indicate no statistically significant effect of continuous placement on deck-cracking performance*. This conclusion is based on CS2 cracking data from 76 multi-span continuous steel beam bridges, of which 8 were identified as having been placed continuously. Given the limited dataset and relatively high variability, collecting additional data as more deck placements occur will be important to further clarify how placement methods affect cracking. Bridges supported by concrete girders were not considered because of concerns regarding the potential formation of diaphragm voids caused by the rotation of reinforcement bars during continuous deck placement.

- *Approximately 39% of VDOT bridge decks on multi-span continuous steel beam bridges constructed since 2017 were identified as potential candidates for continuous placement*. These decks had volumes less than 360 yd^3.

RECOMMENDATIONS

1. *VDOT should consider allowing continuous placement for multi-span continuous steel bridges when the deck volume is less than 360 yd^3, the concrete can be maintained in a plastic state at least one full span behind the active placement, and the contractor has demonstrated successful experience with continuous deck placement*. Concrete is considered plastic if its penetration resistance is less than 500 psi, in accordance with ASTM C403 (ASTM International, 2023). The final determination of the placement method should remain at the discretion of the bridge engineer. The placement method should be documented to enable a more robust assessment of the effects of bridge deck placement methods on cracking performance for future projects.

2. *VDOT should limit the paste content of Low Shrinkage Class A4 Modified Concrete with normal weight aggregates used for continuous bridge deck placements to a maximum of 27% to provide an additional level of protection against cracking*.

IMPLEMENTATION AND BENEFITS

The researcher and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendations 1 and 2, within 2 years of the publication of this report, the Structure and Bridge Division, with the support of the Materials Division and the Virginia Transportation Research Council, will provide information on best practices for selecting bridge deck placement sequences to VDOT districts.

Benefits

Implementation of the recommendations from this study is expected to provide VDOT with decks that are either crack-free or contain only narrow cracks that will not adversely affect long-term performance. It will also support more efficient construction practices and reduce the number of construction joints, which can be as objectionable and detrimental as the cracks themselves.

Collectively, these benefits can enable more efficient allocation of funds and enhance the resilience of VDOT's infrastructure.

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