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Crack sealers for the preservation of concrete bridge decks: a synthesis of a national survey and literature review

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Abstract
Crack sealers are crucial for preserving concrete bridge decks and extending their service life. This paper presents a comprehensive national survey in the U.S., gathering responses from a total of 37 different agencies, along with literature studies on crack sealer practices in concrete bridge decks. The study covers various aspects, including available crack sealers, sealing triggers, approved product list and performance, resealing intervals, method selection, and surface preparation. Based on the study findings, epoxy, methyl methacrylate (MMA), and high-molecular-weight methacrylate (HMWM) are the most commonly used crack sealers, each offering distinct advantages. Sealing criteria are based on crack dimensions and deicing exposure. Resealing intervals vary due to sealant composition, deck age, and climate. Method selection considers deck attributes, temperature, and moisture. The study identifies gaps in consistently approved product lists and suggests future research areas, such as investigating the effects of entrapped chloride, conducting long-term performance testing, and correlating laboratory and field data. The study's findings contribute to current practices, facilitating decision-making and providing guidance for targeted future research.

Keywords Crack sealer, Concrete bridge deck, Preservation, Surface preparation, Performance evaluation

Introduction and method

Concrete cracking is a primary cause of the degradation of concrete bridges within the United States [1, 2] Cracks in bridge decks create pathways for water and corrosive agents to penetrate the concrete cover, triggering premature corrosion of underlying steel reinforcement [3, 4]. This corrosion manifests as delamination and spalling in the concrete bridge deck. The ensuing corrosive effects lead to substantial maintenance expenses, necessitate traffic diversions, and reduce the service life of these structures. In efforts to maintain the integrity of concrete bridges, agencies like the U.S. Department of Transportation (DOT) commonly use sealers to treat and safeguard decks, employing methods such as "flooding" the deck or individually "chasing" and sealing cracks [5]. Yet, DOT engineers and consultants sometimes lack awareness of prevailing practices across DOTs, such as written procedures, guidelines, and specifications. Additionally, they might remain unaware of recent research findings, case studies, and field evaluations of sealing projects conducted by other agencies. This lack of awareness regarding contemporary crack sealer practices for concrete

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bridges frequently leads to costly studies, redundant research, and extra evaluation endeavors.

Hence, this paper undertakes a comprehensive exploration, using surveys and literature studies, into general practices concerning crack sealers in concrete bridge decks within the United States. The study adopts three core methodologies:

i) An inquiry into commercially available crack sealers for concrete bridge decks provides detailed information on these crack sealers, as elucidated in Sect. 2.
ii) Sending out a comprehensive questionnaire to various agencies nationwide aims to gather essential insights about their practices and experiences with crack sealing on concrete bridge decks. Agencies are asked to share information about their crack sealing criteria, different types of sealers used, product details, qualification processes, project contracting methods, execution of sealing work, surface preparation, specifications, inspections, and performance assessment. The collected responses are then condensed and presented in an innovative map-based visualization, detailed in Sect. 3.
iii) The information gathered from the second method is combined with a thorough review of existing literature about applying sealers to concrete bridge decks. This combination includes agency specifications, relevant guidelines, research documents, and comparisons. Notable studies from the literature review, both in labs and real-world settings, are included, as they are important for assessing the effectiveness of sealer products and methods. Discrepancies between survey responses and literature reviews are also highlighted. All this information is synthesized in Sect. 4.

Drawing from the combined survey responses and literature studies, the paper concludes by suggesting possible directions for future studies related to crack sealers in concrete bridge decks.

Commercially available crack sealers and their applications

Based on the search and survey responses about commercially available crack sealers for concrete bridge decks, epoxy, methyl methacrylate (MMA), and high-molecular-weight methacrylate (HMWM) are the most commonly used crack sealers for sealing cracks in these decks. More detailed information about epoxy, MMA, HMWM, and other crack-sealing products used by different DOTs is provided in the following subsections.

Epoxy

Epoxy is a type of adhesive with low viscosity created by mixing bisphenol A and epichlorohydrin. It hardens during polymerization and has higher tensile strength and cost-effectiveness compared to other sealers [6]. To apply epoxy, cracks are first prepared using methods like compressed air, high-pressure water, sand, or shot blasting to remove debris, and the surrounding area should be cleaned. [6–8]. After application, epoxy needs to cure for a period ranging from one to twelve hours, a duration that depends on the temperature [8]. The curing process may slow down at lower temperatures, while rapid curing at high temperatures can limit the sealing depth. Hence, it's recommended to use epoxy crack sealers at temperatures between 7.2 °C and 32.2 °C[1] [9].

Methyl methacrylate (MMA)

MMA is a low-viscosity resin made of methyl methacrylate, used as a crack sealer [10]. It can be evenly spread on crack surfaces using a squeegee or roller and gets absorbed into the concrete without forming puddles [10]. By adding an MMA hardener, MMA hardens quickly, even at low temperatures, achieving early strength [10]. MMA can also be used over a similar temperature range of 7.2 °C to 32.2 °C, like epoxy [10]. However, MMA should not be applied on fresh concrete until maximum shrinkage has occurred [10]. Before applying MMA, all the substrates must be dry and free from dirt, waxes, curing agents, and other foreign materials [10].

High molecular weight methacrylate (HMWM)

HMWM is an adhesive resin made of two or more liquid methacrylate monomers, which can be poured directly onto the cracked surface [11]. By filling the resin into cracks and eliminating porosity in the surface of concrete bridge decks, chloride, and water ingression access could be blocked. HMWM sealers fill cracks and saturate the surface of the concrete as a liquid, and then transform into a plastic barrier against moisture and chlorides [12]. This type of sealant is commonly used across the surveyed agencies. According to the survey responses (Sect. 3), it is the second most used crack sealant on concrete bridge decks after epoxy crack sealers.

Other Crack Sealers

Pavon Indeck, a low-viscosity emulsified asphalt, is specifically used by Missouri DOT as a crack sealer. It's made in Kansas City and has been the main crack sealer since the mid-1990s [9]. This sealer, applied as an emulsion to the entire deck, uses electro-attraction to penetrate cracks more effectively. Reports show that the sealer can go as deep as 25.4 mm to 31.8 mm [9]. There were occasional friction issues in the past, so sand is applied to the sealed surface before curing [9]. Bridges treated with Pavon Indeck usually reopen within an hour. According

[1] All units used in this paper have been converted into the metric system.

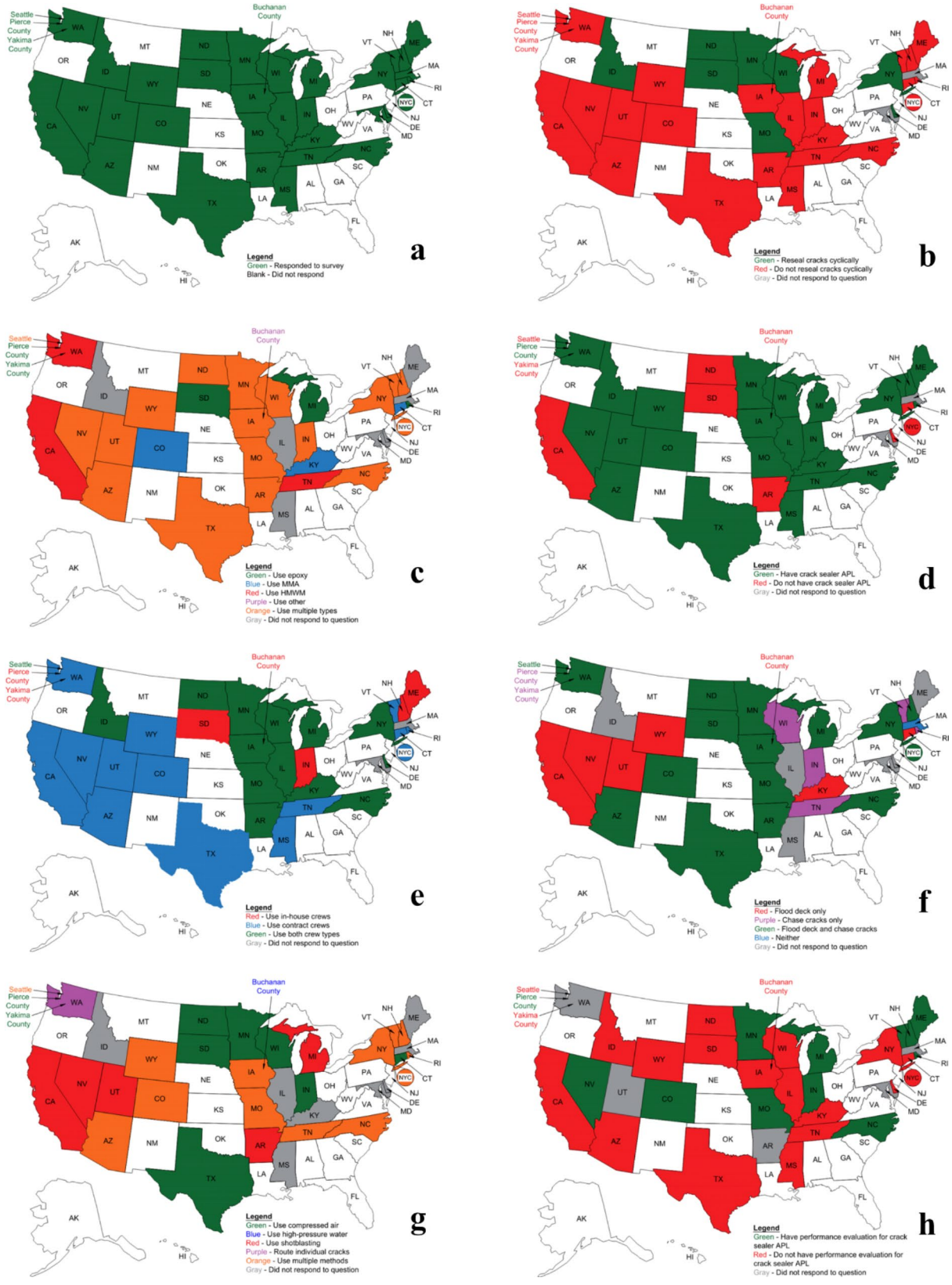

Fig. 1 (See legend on next page.)

(See figure on previous page.)

Fig. 1 Map-based representation for survey responses. (**a**) Agencies that responded to the survey (Green – Responded to survey, Blank – Did not respond); (**b**) Agencies that responded to reseal cracks or not on a cyclic basis (Green – Reseal cracks cyclically, Red – Do not reseal cracks cyclically, Gray – Did not responsd to question); (**c**) Generic crack sealing products used by agencies (Green – Epoxy, Blue – MMA, Red – HMWM, Purple – Use other, Orange – Use Multiple Types, Gray - Did not responsd to question); (**d**) Agencies that responded that whether they have an approved product list (APL) (Green – Have crack sealer APL, Red – Do not have crack sealer APL, Gray – Did not responsd to question); (**e**) Methods that are used by agencies for contracting crack sealing projects – in-house vs. contract crews (Red – in-house crews, Blue – contract crews, Green – Use both crew types, Gray – Did not responsd to question); (**f**) Methods for that are used by agencies for performing crack sealing projects – crack chasing vs. flood sealing (Red – Flood deck only, Purple – Chase deck only, Green – Flood deck and chase deck, Blue – Neither, Gray - Did not responsd to question); (**g**) Surface preparation methods that used by agencies for crack sealing (Green – Compressed air, Blue – High-pressure water, Red – shotblasting, Purple – Route individual cracks, Orange – Use multiple methods, Gray - Did not responsd to question); and (**h**) Agencies that responded that whether they have a performance evaluation for APL (Green – Have performance evaluation for crack sealer APL, Red – Do not have performance evaluation for crack sealer APL, Gray - Did not responsd to question)

to the Missouri DOT survey, Pavon Indeck is reapplied every five years. The Missouri DOT's Engineering Policy Guide and Research Investigation RI 96−005 on this sealer recommend reapplication every three to five years [13, 14].

Another type of crack sealer is hybrid polyurethane, used by Indiana DOT through Roadware 10 min Concrete Mender [15]. This sealer, a low-viscosity, two-component hybrid polyurethane, is engineered for easy application and fast curing concrete repair [16]. Its low viscosity allows it to reach deep into hairline cracks for structural fixes. Adding aggregate speeds up spall and joint repairs. Both polyurethane- and urethane-based crack sealers are also used by Wisconsin DOT.

Polyurethane methyl methacrylate (PUMMA) is reported for use by North Carolina DOT on concrete bridge decks. PUMMA is a high viscosity, flexible methyl methacrylate polyurethane hybrid resin for crack isolation and waterproofing [17]. It's made by combining polyurethane resin with MMA, creating a strong and flexible material. To apply PUMMA crack sealer, mix it using a two-component system, pour it into the crack or joint, spread it evenly with a squeegee or trowel, and let it cure. This makes a flexible, durable seal blocking water and debris from damaging the bridge deck. It works for cracks between 1.6 mm and 4.6 mm and at temperatures between −1.1 °C and 32.2 °C [17].

Synthesis of survey response and literature study

The survey responses and literature findings have been synthesized and systematically organized into seven subsections as follows: (3.1) Criteria to use crack sealers to seal cracks on concrete bridge decks; (3.2) Generic crack sealer products; (3.3) Approved product list and qualification process; (3.4) Methods of contracting for crack sealing projects; (3.5) Methods of performing crack sealing work; (3.6) Surface preparation for crack sealing; and (3.7) Performance evaluation of using crack sealers.

In each section, a map-based visualization, as illustrated in Fig. 1, has been developed to reflect the survey responses. These responses have been color-coded to facilitate distinction between responses from various agencies. Figure 1a shows that a total of 37 different agencies spanning the nation have participated in the survey, including agencies such as State DOTs, New York City, Seattle, and three additional counties within Washington State. Correspondingly, Fig. 1b to 1h align with Sect. 3.1 through 3.7, respectively.

This graphical framework emerges as a powerful instrument, elucidating state-specific practices with a degree of accessibility and comprehensibility. Beyond mere presentation, it provides useful insights into the preferences of different regions and states. The presentation can be further enhanced through other factors, such as geographical classifications (e.g., Midwest, West, East, etc.), climatic variations, population demographics, and socio-economic data. This dataset is a comprehensive collection of current practices involving crack sealers on concrete bridge decks across the United States. It helps readers analyze the topic in depth by combining the information from this study with the broader context mentioned earlier.

Criteria to use crack sealers to seal cracks on concrete bridge decks

Conditions trigger crack sealing

The primary condition for crack sealing hinges on the crack width. In the context of bridge decks exposed to deicing chemicals, Frosch et al. [18] recommended that the immediate sealing of all cracks is needed, regardless of their width, as a proactive measure to limit chloride intrusion. Soriano suggested a crack width range for sealing between 0.025 mm and 3.2 mm [19]. The Florida Department of Transportation (FDOT) employed a crack significance grading system as detailed in Standard Specification Sect. 400 [20]. This system aims to determine whether further investigation, repair, or complete removal and replacement of cracked concrete is necessary. The evaluation entails a combination of average crack widths and the computation of a "Cracking Significance Range" per evaluation lot, which is the ratio of crack area to the area of the assessed bridge deck.

Among the agencies surveyed, only 15 state DOTs have concrete deck crack sealing guidelines, including

Table 1 Crack sealing criteria specified in Agencies' guideline based on crack width

Agency	Criteria	Ref.
Illinois DOT	Cracks opening less than or equal to 12.7 mm were repaired by injecting epoxy into the cracks. Hairline cracks do not need sealing, but they should be noted in the repair plans. Cracks openings larger than 12.7 mm should be sealed by removing all loose material along the edges of the crack and then using an expansive cement grout to fill the crack	[22]
Indiana DOT	Cracks of 0.30 mm in width and wider should be sealed	[23]
Michigan DOT	Deck cracks to be sealed must be a minimum of 0.2 mm wide	[24]
Minnesota DOT	Seal cracks 0.25 mm and larger.	[25]
Missouri DOT	Deck with cracks larger than 0.2 mm should be sealed with crack sealers	[26]

Table 2 Criteria for periodic crack sealing specified in Agencies' guideline

Agency	Criteria	Ref.
Delaware DOT	Table 3.4.1 Condition State 2 and Table E10 Concrete Protective Coatings (880) in Bridge Element Inspection Manual, 2021.	[27]
Kentucky DOT	Table 2 in Developing Material Specification and Application Criteria for Sealing Concrete Bridge Decks, 2019: Decks with a condition rating of 6 or better should be sealed on a five-year cyclical basis	[28]

Arizona, Delaware, Idaho, Illinois, Indiana, Kentucky, Michigan, Minnesota, Missouri, New York City, South Dakota, Texas, Washington, Wisconsin, and Wyoming. Among these agencies, four have formulated criteria based on crack dimensions, particularly crack width. These five agencies and their corresponding criteria are outlined in Table 1. Meanwhile, the Missouri DOT has also crafted a selection matrix for sealing deck cracks. The choice of preventive maintenance treatment varies according to crack width, with different materials used for different widths [21].

Another two state DOTs, Delaware and Kentucky, employ distinct approaches to assess the condition of their bridges, outlined in their self-devised rating systems (Table 2). In the case of Delaware DOT, they have established a range of deterioration states specific to reinforced concrete deck and slab bridge elements, focusing on cracking width [27]. The progression spans from Condition State One: "Insignificant cracks or moderate cracks that have been sealed," to Condition State Four: "A condition that necessitates a structural assessment to gauge its impact on the element or bridge's strength and serviceability; alternatively, a structural review has been completed, revealing defects that influence the strength or serviceability of the element or bridge." Condition State Two refers to "Unsealed moderate cracks or unsealed moderate map cracking." The corresponding actions for these deterioration states are also defined. For instance, in Condition State Two, the actions include: Do nothing, Protect, and Repair. Consequently, Delaware DOT's criteria seem oriented towards sealing bridge deck cracks, aiming to restore them to at least moderate cracks (Condition State Two), which in this context denote cracks with widths ranging from 1.6 to 6.4 mm.

On a different note, the Kentucky DOT employs a deck preservation matrix. Their criterion for the periodic sealing of deck cracks within a five-year cycle stipulates that the deck surface must attain a condition rating of six or higher. In this context, a rating of six signifies that the surface's deficiencies are less than 10%.

Table 3 Recommended resealing interval across different agencies

Agency	Resealing Interval
Delaware DOT	No interval recommended
North Dakota DOT	3 years
Minnesota DOT	3–5 years
New York DOT	3–5 years
Wisconsin DOT	3–5 years
Idaho Transportation Department	5 years
South Dakota DOT	5 years
Missouri DOT	5 years for Pavon Indeck 10 years for MMA/HMWM

Recommended intervals for resealing

In Fig. 1b, the survey responses are visually represented, showing instances of whether agencies engage in cyclical crack resealing practices or not. From the pool of surveyed agencies, only 8 state DOTs have established programs for cyclically resealing cracks. The recommended intervals for such practices across various agencies are tabulated in Table 3, drawn from their responses to the national survey. Conversely, agencies that do not engage in cyclical resealing projects have formulated their resealing strategies based on various situations. For instance, Maine, Michigan, New Hampshire, North Carolina, Rhode Island, Texas, Utah, and Vermont adopt a case-by-case approach contingent on the observed conditions. In Arizona, crack resealing is undertaken exclusively on bridges incorporated within pavement rehabilitation projects. Meanwhile, California has recently embarked on crack sealing projects but has not yet instituted a comprehensive program, instead prioritizing high-impact projects. Yakima County in Washington state selects to reseal cracks upon reaching a width greater than 3.2 mm, while Pierce County, also in Washington state, undertakes resealing of recurrently appearing cracks.

Mamaghani et al. [29] studied the manufacturers' guidelines regarding crack sealers, underlining that the concrete must attain a minimum age of 28 days before

any crack sealing operation can commence. Their study further suggested a resealing cycle of four years. Rahim et al. [12] suggested prompt sealer treatment for bridge decks to avert the infiltration of chloride and other contaminants as soon as feasible within acceptable sealing conditions. Soriano [19] recommended that crack and surface sealing activities on bridge decks be executed within 3 to 6 months post-bridge completion, with subsequent resealing every five years. Washer et al. [30] developed a Bridge Maintenance Program for the City of Columbia, Missouri, advising a crack sealing interval of four to five years. Krauss et al. [31] conducted an assessment of various crack sealer products, revealing their diminished efficacy after three years of application and consequently advocating a resealing cycle of three years. Oman [32], in evaluating epoxy and MMA products, advised a service life of 2 to 4+years for epoxies and 3 to 4+years for MMA products. Oman also mentioned that, in Minnesota, bridge crews typically engage in crack resealing every five years [32]. Conversely, Johnson et al. [9] studied Wisconsin and Montana's practices and indicated that they reseal cracks at four-year intervals and every 15 years, respectively [9]. However, concerns surround the recommended sealing intervals. Notably, scant research has been undertaken to ascertain whether the age of a bridge deck (or crack) could influence the adhesive properties of sealers, thus impacting resealing intervals. Meggers [33] concluded that sealers could more easily penetrate newer bridges compared to older ones, due to the relatively shorter time and narrower cracks available for contaminants to accumulate.

Table 4 Survey respondents using multiple generic sealers

Agency	Epoxy	MMA	HMWM	Other
Arizona DOT	X		X	
Arkansas DOT	X		X	
Indiana DOT	X			X
Iowa DOT	X		X	
Minnesota DOT	X	X	X	
Missouri DOT	X	X	X	X
Nevada DOT	X		X	
New Hampshire DOT	X		X	
New York DOT		X	X	
New York City DOT	X	X	X	
North Carolina DOT	X		X	
North Dakota DOT	X		X	
Seattle DOT	X	X		
Texas DOT	X	X		X
Utah DOT	X		X	
Vermont Agency of Transportation	X	X		
Wisconsin DOT	X			X
Wyoming DOT	X		X	

Generic crack sealer products

As illustrated in Fig. 1c, the responses received from 26 state DOTs substantiate their active involvement in crack-sealing endeavors. Table 4 compiles the entities employing multiple generic sealers. A comprehensive analysis including the agency-standard specifications, bridge maintenance manuals, and preservation protocols facilitates the aggregation of the generic crack sealer products currently in utilization. Among these 26 state DOTs, the prevailing choice for crack sealer is epoxy. Following closely is HMWM, while MMA claims the third position. Alongside these common choices, several other products appear within the framework of specific DOTs. To elaborate, the Indiana DOT integrates polyester and urethane in their crack sealing strategy [34]; the Missouri DOT adopts in-deck sealer [35], and the North Carolina DOT employs polyurethane methyl methacrylate [36].

In addition to the survey response, a review of studies by McGettigan [37] and Weyers et al. [38] asserts that HMWM has superior crack sealing performance, evident in terms of crack penetration, bonding/bridging, and sealing. Johnson et al. [9] found that HMWM products tend to exhibit deeper crack penetration, while epoxy products exhibit higher bond strength and heightened resistance to freeze-thaw cycles. Similarly, Liang et al. 2014 [39] found HMWM to outperform MMA in terms of the sealers' capacity to hinder chloride penetration into the deck. Alternative generic sealing materials like epoxy, modified polyurethane (MPU), and urethane sealers are also viable for crack sealing. These sealers share similar rheological attributes with methacrylates but offer enhanced extensibility characteristics. For example, epoxies are not recommended for cracks narrower than 1.0 mm due to their lower extensibility compared to MMA and MPU [30]. Furthermore, Soriano [19] demonstrates that while MMA and epoxy exhibit a comparable crack penetration depth of 2.5 mm, MPU displays a lesser depth of 1.5 mm.

The width of cracks constitutes a pivotal criterion for selecting appropriate crack sealers. Wenzlick [40] recommended epoxy sealers for cracks exceeding 0.64 mm. Frosch et al. [41] advocate the choice of crack sealing products based on crack width, product characteristics, and field conditions, including temperature and humidity. For cracks spanning 0.2 to 1 mm, methacrylates, due to their deeper penetration into cracks compared to epoxies, should be considered [41]. In the NYSDOT Bridge Manual, epoxies or HMWM are stipulated for working cracks greater than 0.18 mm and nonworking cracks exceeding 0.30 mm [42]. Working cracks are defined as cracks with widths that fluctuate over time due to deck load or concrete temperature variations [43]. For cracks greater than 0.41 mm, epoxies are preferred due to their higher bond strength and demonstrated

performance. Mamaghani et al. [29] discuss the association between HMWM and crack widths, highlighting that HMWM proves ineffective for cracks wider than 2 mm, which should instead be pre-treated following ACI 224.1R (2001) guidelines [44]. When crack widths are below 2 mm, HMWM is recommended, often in tandem with silane sealers. Rahim et al. [12] indicate that HMWM is applicable for sealing cracks spanning 0.05 mm to 12.7 mm. Additionally, reactive methyl methacrylate (MMA) catalyzed by 50% dibenzoyl peroxide powder is another popular generic product category. Mamaghani et al. [29] highlight that MMA and HMWM exhibit comparable performance. The suggested crack width ranges for using distinct crack sealers can vary based on specific product and manufacturer recommendations. It is advised to consult manufacturer technical data sheets and installation instructions for insights into temperature constraints and recommended application methods.

Several other parameters could also influence the efficacy of crack sealing, including product viscosity, bond strength, and repair quality. Oman [32] demonstrates that epoxy sealers exhibit superior bond strength, while HMWM and MMA sealers show improved penetration characteristics attributed to their lower viscosities. Notably, epoxy products are continuously adapted for specific applications, including super low viscosity scenarios. Temperature and relative humidity could also affect the efficacy of crack sealing. For example, many products mandate application within specific temperature and humidity ranges, often shortly after application [32]. If specifications are not followed, the crack repair/cleaning may be inadequate. Therefore, products with wider temperature and humidity tolerances are preferred. Standard temperature ranges for applying crack sealers can vary, based on product specifics, manufacturer recommendations, and site conditions. Relying on manufacturer technical data sheets and installation instructions is crucial to determine temperature limitations and optimal application processes. Cost and health considerations are also relevant in comparing different sealing products. Johnson et al. [9] conclude that epoxy crack sealants are more cost-effective and cause fewer health concerns in comparison to HMWM products.

Table 5 Responded agencies using crack sealer approved product list or product evaluation program

Agency	Have Approved Product Lists	Have Product Evaluation Program	Ref.
Arizona	X		[50]
Arkansas	X	X	[51, 52]
Colorado	X	X	[53]
Idaho	X	X	[54]
Indiana	X	X	[34]
Michigan	X		[55]
Minnesota	X	X	[45]
Missouri	X	X	[35]
Nevada	X	X	[56]
New Hampshire	X	X	[57]
New York	X	X	[58]
North Carolina	X	X	[36]
Rhode Island	X	X	[59]
Tennessee	X	X	[60]
Texas	X		[61, 62]
Vermont	X	X	[63]
Washington	X		[64]
Wisconsin	X		[65]

Approved product list and qualification process

Based on the survey responses depicted in Figs. 1d and 31 state DOTs responded to the question regarding approved product lists (APLs) and product performance evaluation programs. The specific state DOTs that have established APLs and programs for evaluating product performance can be found in Table 5. Among these 31 DOTs, a total of 18 possess approved product lists, with a subset of 13 DOTs having dedicated product evaluation programs.

Among the state DOTs, merely four have delineated the criteria for evaluating APLs. These include the Minnesota DOT [45], New Hampshire DOT [46], Rhode Island DOT [47], and Tennessee DOT [48]. This set of requirements includes critical properties such as viscosity, gel time, 14-day bond strength, compressive yield strength, tensile strength, tensile elongation, track-free time, and shear bond adhesion. For example, Johnson et al. [9] asserted that crack sealers are ideally characterized by a viscosity below 500 cP, with HMWM sealers, for instance, showcasing a remarkable viscosity of less than 25 cP. Furthermore, they advocate the crack sealers to ideally have a tensile strength surpassing 8 MPa, coupled with a tensile elongation exceeding 10%. New Hampshire DOT mirrors these parameters closely, excluding tack-free time. Rhode Island DOT and Tennessee DOT have opted for the AASHTO National Product Evaluation Program (NTPEP) as their chosen avenue for product evaluation.

Conversely, other states refrain from conducting acceptance tests on crack-sealing products when formulating APLs [9]. Instead, some states rely on existing literature that has scrutinized these products. For example, Wisconsin employs the laboratory study endorsed by Pincheira [49] as the foundation for approving crack sealer products. In certain instances, field performance becomes the benchmark for APL selection, as observed in the practices of South Dakota [9].

Methods of contracting for crack sealing projects

Based on the survey responses depicted in Figs. 1e and 31 state DOTs have utilized in-house crews and/or contractors to carry out crack-sealing projects. The agencies that exclusively employ contract crews are predominantly situated in the southern and western regions, with a handful also found in New England, including Connecticut, New York City, Rhode Island, and Vermont. Conversely, the midwestern agencies exhibit a prevalent practice of combining contract crews and in-house crews. Notably, Indiana and South Dakota are exceptions within the midwestern region, relying solely on in-house crews. Moving to the east coast, the respondents showcased a balanced distribution regarding crew utilization strategies. Among them, four reported exclusive reliance on contract crews, two indicated sole utilization of in-house crews, and three affirmed their adoption of both crew types. Table 6 summarizes these agencies' practices of using in-house crews and/or contract crews.

Table 6 Methods that are used by agencies for contracting crack sealing projects – in-house vs. contract crews

Agency	In-house Crews	Contract Crews	Ref.
Arizona		X	[7]
Arkansas	X	X	[68]
California	X		[69]
Colorado		X	[70]
Delaware	X	X	[71]
Idaho	X	X	[72]
Illinois		X	[78]
Indiana	X	X	[74]
Iowa	X	X	[66]
Kentucky	X	X	[75]
Maine		X	[76]
Massachusetts		X	[77]
Michigan	X	X	[67]
Minnesota	X	X	[78]
Mississippi		X	[79]
Missouri	X	X	[80]
Nevada	X	X	[81]
New Hampshire		X	[82]
New York		X	[83]
New York City	X	X	[84]
North Carolina	X	X	[85]
North Dakota		X	[86]
Rhode Island		X	[87]
South Dakota		X	[88]
Texas	X	X	[89]
Utah		X	[90]
Vermont		X	[91]
Washington		X	[92]
Wisconsin	X	X	[93–95]
Wyoming		X	[96]

While agencies employing contract crews typically have established standard specifications and general information available on their DOT websites, detailing the overarching procedures for contractor selection, these processes often lack specificity pertaining to bridge deck crack sealing. This study focuses on the process of identifying the scope of work. A case in point is the Iowa DOT's project development process manual "Sect. 3.1.1.3 Maintenance Bridge Projects" [66], which specifies the needs of the biannual inspection reports. Michigan DOT's Local Bridge Asset-Management Guide [67], on the other hand, not only rates preventive maintenance tasks, including concrete crack sealing, but also offers a Bridge Repair Cost Estimate Workbook, replete with unit prices for diverse preventive maintenance actions. This workbook serves as a valuable resource for cost estimation.

In instances where contract execution involves private sector firms, it primarily involves projects of significant size or specialized nature, which is often beyond the capacity of in-house crews. The estimation of contracted work often hinges on Michigan DOT's Capital Scheduled Maintenance Cost Estimate Workbook, which provides a unit price guide. Oman [32] recommends that product evaluations could be incorporated into the contractor's warranty evaluation period, enhancing overall quality assurance.

Methods of performing crack sealing

The methods employed for performing crack sealing can be categorized into two distinct approaches: "chasing cracks," also recognized as crack chasing, and "flooding the deck with crack sealer," also acknowledged as flood sealing. In the context of crack chasing, individual cracks are addressed one at a time, ensuring a thorough sealing process [8]. Conversely, flood sealing involves applying a concrete sealer over a large section of cracked concrete, enabling the simultaneous coverage, and sealing of numerous cracks [8]. The illustration of various agencies' adoption of these methods is illustrated in Fig. 1e. Further insight into the criteria utilized by certain individual agencies and their corresponding practices can be found in Table 7, which compiles information extracted from the survey responses.

Drawing from the survey and literature study, the following research efforts pertaining to crack sealing methods for concrete bridge decks have been undertaken or are currently underway. Table 8 presents the most recent research endeavors carried out by various state agencies.

In addition to the survey responses, the literature study provides more in-depth insights into the methods of performing crack sealing. Deruyver et al. [97] reported

Table 7 – Responded agencies' current practice for determining crack chasing or flood sealing

Agency	Current Practices	Ref.
Arizona DOT	Based on the engineer's judgment, crack width, and volume of cracks	[7]
Indiana DOT	Crack chasing is done as part of bridge deck sealing and bridge deck epoxy injection programs. When there's a large number of cracks, they place a thin deck overlay	[23]
Michigan DOT	Refer to Section of "Thin Epoxy Overlay and Healer Sealer Treatments on Bridge Decks"	[97]
Minnesota DOT	In-house Crews: Crack chase with low density of cracks (spacing > 0.92 m); flood seal with high density of cracks (spacing < 0.92 m) Contract Crews: Refer to MnDOT Standard Specification Sect. 2433.3.C.1 Bridge Deck Crack Sealing Process	[98]
Mississippi DOT	Usually flood seal	N.A.
New Hampshire DOT	Use visual observations and engineering judgement based on number and frequency of cracks	N.A.
New York DOT	Depends on size and frequency of cracks	N.A.
New York City DOT	Case by case basis by the design engineer	N.A.
North Dakota DOT	Typically try to crack chase before the level of cracking gets to the flood seal requirements	N.A.
Seattle DOT	Reference qualified products used by state agency and from various subject matter experts with the industry	N.A.
South Dakota DOT	Consider flood seal for bridge decks with pattern cracking	N.A.
Texas DOT	Evaluates on a case-by-case basis	[89]
Washington DOT	Methods determined by contractor based on the extent of cracking	N.A.

Table 8 Research endeavors carried out by various state agencies

Agency	Year Completed	Topic/Title	Ref.
Michigan DOT	Ongoing	Ongoing Research with Western Michigan University - Effects of concrete cure time on Thin Epoxy Overlays and Healer Sealers - Effects of applying a Silane to the deck surface immediately prior to application of Thin Epoxy Overlay and Healer Sealers.	N.A.
Illinois DOT	2022 (expected)	R27-224 - Developing an Effective Crack Sealing Procedure by Leveraging Chemistry and Computer Vision	N.A.
Iowa DOT	2022	TR-782 - Guide to Remediate Bridge Deck Cracking	[43]
Nevada DOT	2018	Improving the Long-Term Performance of Concrete Bridge Decks using Deck and Crack Sealers	[99]
Indiana DOT	2016	Development of a Cost-Effective Concrete Bridge Deck Preservation Program: Volume 1 - Development and Implementation of the Experimental Program	[18]
Indiana DOT	2016	Development of a Cost-Effective Concrete Bridge Deck Preservation Program: Volume 2 - Final Results and Recommendations	[100]
Minnesota DOT	2014	Concrete Bridge Deck Crack Sealant Evaluation and Implementation	[32]

that the selection of crack-sealing application methods should consider both crack width and the causes of crack formation. For instance, cracks resulting from local stresses in the deck should be sealed using crack chasing to ensure adequate material penetration and to facilitate future crack monitoring. MnDOT [78] specifies the use of crack chasing for decks with a low density of cracks (spacing > 0.91 m) and flood sealing for those with a high density of cracks (spacing < 0.91 m [78]; or where crack mapping of 6.7 m^2 of representative area results in 6.1 m, as listed in The Standard Specification for Construction Volume 2 Sect. 2433.3.C.1 Bridge Deck Crack Sealing Process [98].

Johnson et al. [9] investigated the impact of temperature on crack sealing effectiveness and found that high temperatures could hinder the proper curing and penetrating time for the sealers to develop their performance, while low temperatures could result in prolonged curing times, causing seepage issues and environmental concerns when the resin drains into a river beneath the bridge deck. Prolonged curing times can also affect traffic control. Sprinkel [101] tested the gel time of five different crack sealers, including three epoxies, one polyurethane, and one HMWM sealer, to assess the influence of temperature on these sealers. Their findings demonstrated that the gel time of all five sealers decreased as the temperature increased. Rodler [102] noted that gel time could also impact the bond strength of sealers. They tested three different HMWM sealers on a cracked slab at a temperature of approximately 46.1 °C, revealing a 12% reduction in bond strength and an 8.5% reduction in penetration depth.

Johnson et al. [9] also highlighted the significance of considering thermal expansion in application methods due to the varying crack widths throughout the day resulting from thermal expansion. Typically, crack width is smallest around midday and largest at midnight. This variance in crack width expansion and contraction necessitates different requirements for the extensibility of crack sealers. Their recommendations include: (a) applying crack sealers between temperatures of 7.2 °C to 32.2 °C ; (b) applying crack sealers between 11:00 PM and 7:00 AM, when temperatures are lowest and crack width is largest; (c) performing surface preparation, such as

cleaning, before sealing; and (d) ensuring the bridge deck is dry for two to three days before sealing.

Surface preparation for crack sealing

To guarantee the effective adhesion of crack sealers to concrete surfaces, several preparation methods are available for treating cracks in bridge decks. These methods include compressed air, high-pressure water, sandblasting, shotblasting, and routing individual cracks. Figure 1 g illustrates the distribution of these methods across different regions, indicating that no specific method is predominantly preferred throughout the country. However, compressed air emerges as the most frequently employed technique. Table 9 provides a comprehensive compilation of agencies that employ multiple methods for surface preparation in crack sealing. It is evident that the information is either from the survey responses or from the official documents supporting their practices.

The literature studies concerning surface preparation and its impact on the durability of sealer effectiveness are summarized below. Johnson et al. [9] emphasized that cleaning cracks enhances the efficacy of crack sealing. Contaminants like dirt, dust, and carbonation can accumulate in cracks, affecting both new and old bridges. Failure to clean can significantly diminish bond strength and depth of penetration. Contaminants impede proper sealer infiltration, reduce penetration depth, obscure the crack surface, and decrease bond strength. The study also identified two effective cleaning methods: high-pressure water and compressed air. Megger [33] documented decreased penetration depth due to excessive contaminants in cracks. Mamaghani et al. [29] cited Alberta DOT's practice of annual high-pressure water washing for bridge decks, underscoring the importance of clean, dry, open capillary surfaces, free of curing compounds and pore-blocking contaminants. Frosch et al. [41] asserted that proper surface preparation, such as sandblasting or shot blasting, is integral for sealers to attain full penetration and establish a proper bond. Krauss et al. [31] highlighted sandblasting, shot blasting, and compressed air as effective cleaning methods. However, Frosch et al. [18] contended that surface roughening via sandblasting might not be necessary due to existing deck surface features created by thinning and abrasion. Soriano [19] shared this view, suggesting blasting could damage surface pore structure and encourage water penetration. They indicated that surface preparation's impact on penetration depth is negligible without debris. However, they noted that power broom/forced air might be preferable in debris-laden situations.

Nevertheless, if high-pressure water is used or the deck becomes wet from rainfall, adequate drying time is necessary before applying crack sealers to avoid potential impacts on penetration depth and bond strength [9]. Rodler [102] employed laboratory ovens to explore drying time for cracked slabs to retain 95% of their dry bond strength and penetration depth. Results showed three days of drying for 95% dry bond strength retention and two days for 95% dry penetration depth retention. Mamaghani et al. [29] similarly suggested a two-day

Table 9 – Responded agencies using multiple methods for surface preparation

Agency	Compressed Air	High-Pressure Water	Sandblast	Shotblast	Route Individual Cracks	Ref.
Arizona DOT	X		X	X	X	Survey
Arkansas DOT			X			[68]
Colorado DOT	X	X	X	X		Survey
Indiana DOT	X					[23]
Iowa DOT	X		X	X	X	Survey
Michigan DOT	X	X	X	X		[24]
Minnesota DOT	X	X	X	X		[98]
Missouri DOT	X	X		X		Survey
New Hampshire DOT	X	X	X	X		Survey
New York DOT		X	X	X		Survey
New York City DOT	X	X				Survey
North Carolina DOT	X	X	X	X	X	Survey
North Dakota DOT	X					[86]
Rhode Island DOT	X	X			X	Survey
Seattle DOT	X	X				Survey
South Dakota DOT	X					[88]
Tennessee DOT	X		X			Survey
Texas DOT	X				X	[87]
Utah DOT	X		X			[88]
Vermont Agency of Transportation	X		X			Survey
Wyoming DOT			X	X		Survey

drying period after cleaning or rain, aligned with most sealer manufacturers' and Highway Agencies' recommendations. Johnson et al. [9] also recommended two to three days of deck drying before sealing, though it's noted that laboratory oven tests might not precisely mirror field conditions. Michigan DOT mandates moisture testing on all contracted projects [8]. They employ a polyethylene sheet affixed to the deck at least two hours before sealing for moisture assessment, following ASTM D4263 [103]. And Cady 1994 [104] stressed the need to eliminate the carbonated layer on the concrete surface before sealing work.

Performance evaluation of using crack sealers

As depicted in Fig. 1h, approximately half of the agencies with an APL, as summarized in Sect. 3.3, implement a performance evaluation of new products before inclusion in the APL. A performance evaluation may be part of the APL qualification process or a research study to monitor the sealed crack's condition. Johnson et al. [9] indicated that two common QA/QC tests for bridge evaluation are depth of penetration and chloride ion concentration tests. However, states do not uniformly employ these QA/QC tests. Mamaghani et al. [29] concluded that various factors, including environmental conditions, traffic wear, penetration depth, ultraviolet light exposure, exposure type, and the quality of concrete used, influence the service life of a sealer.

Krauss et al. [31] described three methods used to gauge crack sealant performance: permeability tests, visual observation, and petrography of samples extracted from decks. Giannini et al. [105] introduced two testing methods: NCHRP Report 244 Series II tests and standards developed by the Alberta Ministry of Transportation (BT Series). The former evaluates sealer waterproofing performance pre- and post-abrasive conditioning, simulating traffic wear. The latter assesses products' resistance to chloride penetration and their waterproofing performance in a saltwater solution. Pincheira [106] advised conducting ponding tests in the field during early spring or late fall, followed by coring samples for further lab-based ponding tests, to measure depth of penetration and chloride ion concentration. They also recommended initial core extraction two or three years after sealing, followed by subsequent extractions every five or six years. Johnson et al. [9] introduced four primary performance measures for crack sealers: penetration depth, bond strength, chloride content/resistance to corrosion, and seepage rate. Penetration depth can be tested via coring, microscopy, and fluorescent dye. Tensile splitting tests (ASTM C496) are commonly used to determine sealer bond strength. Another method for assessing repair strength is the three-point bending flexural test (ASTM C293), typically performed on laboratory-cast beams, both with and without freeze-thaw effect.

Due to the challenge of replicating field conditions in the lab, Johnson et al. [9] noted substantial inconsistencies between test results from lab-prepared samples and cored field samples. Pincheira and Dorshorst [49] recommended conducting field tests using core samples on recently sealed bridge decks, enabling effective product performance monitoring. To determine resealing requirements for decks, they also proposed periodic chloride ion analysis tests. In 1992, Meggers [33] applied HMWM and epoxy crack sealer to eight Kansas bridges aged one to 29 years and conducted field tests in 1992 (pre-sealing) and 1995 to assess crack chloride concentration. Their findings suggested that sealing older cracks might trap existing chloride near reinforcement bars, potentially exacerbating adverse effects post-sealing. However, inconclusive field test results arose due to inconsistent chloride concentration levels in sealed and unsealed portions. Further investigation in this area is warranted.

Summary and recommendations for future study

Crack sealers play a crucial role in enhancing the service life of concrete bridge decks. In response to a national survey, over half of the participants undertake crack sealing to prolong the service life of their concrete bridge decks. Based on the survey responses, an innovative map-based visualization has been developed to provide a graphical framework, which emerges as a powerful instrument to explicate state-specific practices with a degree of accessibility and comprehensibility. A comprehensive review of literature and research has been conducted to delve further into the application of crack sealers. Drawing insights from both survey results and literature findings, the key conclusions are summarized below.

HMWM and MMA sealers exhibit superior performance in terms of crack penetration, bridging, and sealing, whereas epoxies offer elevated bond strength and excellent resistance to freeze-thaw cycles. Conversely, polyurethane resin struggles to achieve satisfactory penetration depths at elevated temperatures and experiences diminished bond strength under freeze-thaw conditions. Current practices and prior studies consider factors such as crack width, area, and exposure to deicing chemicals as triggers for crack sealing. Recommended resealing intervals vary widely among states, spanning from 3 to 15 years. This broad range can be attributed to variations in the chemical composition of sealants, deck age, and varying climatic conditions.

Selecting application methods hinges on parameters including deck dimensions, crack width, traffic control, cost, crack density, crack causes, and deck surface

roughness. Temperature, thermal expansion, and deck moisture levels influence the application process. While some State DOTs lack an APL, others include qualified crack sealers in their APLs. Only four states provide detailed criteria for crack sealer product qualification. Several states rely on products tested by prior research without a defined qualification system. Contracting work is necessary based on the recommended work scope outlined in inspection reports.

Universal consensus supports thorough surface preparation, involving debris and contaminant removal. Drying periods of two to three days are recommended prior to sealer application. Following this drying period, it is advisable to measure moisture content. Consideration of traffic impacts may be necessary when selecting surface preparation and sealing application methods.

The inclusion of post-application product performance evaluation in contracts is recognized as a quality assurance measure. Discrepancies between laboratory-prepared samples and field samples are significant due to complex and variable field conditions. Climatic factors, traffic loads, and deicing chemicals significantly impact sealer performance. The entrapment of existing chlorides in cracks near reinforcement bars post-sealing may further deteriorate sealer performance.

Based on the summary, the following future study areas are recommended:

1. The lack of consistent APLs and product qualification systems among State DOTs may lead to improper crack sealer application and potentially impact performance. Further research is needed to develop a suitable qualification system for crack sealer products listed on State DOT APLs, tailored to each state's criteria.
2. Limited study exists regarding the adverse effect of entrapped chlorides on crack sealer performance and bridge deck longevity. Considering the influence of chlorides on reinforcement, further research should investigate the correlation between entrapped chlorides, crack sealer performance, and concrete deck durability.
3. The large variation of resealing intervals could be addressed by testing the long-term performance of the available crack sealers. Compatibility and bonding/adhesion impacts could also be considered.
4. Research aimed at establishing a robust system correlating lab and field test data is recommended, accounting for diverse field conditions encountered during crack sealing. Comprehensive experimental studies, considering climatic factors, traffic loads, and deicing chemicals, should be designed. Non-destructive testing methods should be devised for field tests, reducing adverse effects on bridges when compared to coring samples. This data can offer valuable insights for predicting the efficacy of crack sealing and choosing appropriate preservation and maintenance treatments for decks.

Authors' contributions

Xiaoqiang Ni: Data Curation, Formal Analysis, Investigation, Methodology, Visualization, Writing - Original Draft, Writing - Review & Editing. Matias Leon-Miquel: Data Curation, Formal Analysis, Investigation, Methodology, Writing - Original Draft. Quentin R. Greiner: Data Curation, Formal Analysis, Investigation, Methodology, Writing - Original Draft. Alvaro Paul: Methodology, Visualization. Qingxu Jin: Conceptualization, Data Curation, Formal Analysis, Supervision, Investigation, Methodology, Visualization, Writing - Original Draft, Writing - Review & Editing.

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Data Availability

None.

Declarations

Competing interests

The authors declare no competing interests.

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