Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
PU-23-RP-01	N/A	N/A

4. Title and Subtitle	5. Report Date
Holistic Quality Management of Precast Concrete Construction for Transportation Infrastructure	December 2024
	6. Performing Organization Code N/A
7. Author(s) Hubo Cai, PhD, https://orcid.org/0000-0003-4527-1974, Dulcy Abraham, PhD, Phillip Dunston, PhD, https://orcid.org/0000-0002-2809-8893, Jiansong Zhang, PhD, https://orcid.org/0000-0001-5225-5943	8. Performing Organization Report No. PU-23-RP-01
9. Performing Organization Name and Address Lyles School of Civil Engineering Purdue University 550 W Stadium Ave, West Lafayette, IN 47907	10. Work Unit No. N/A
	11. Contract or Grant No. 69A3552348333
12. Sponsoring Organization Name and Address Transportation Infrastructure Precast Innovation Center (TRANS-IPIC) University of Illinois Urbana-Champaign Civil & Environmental Engineering 205 N Mathews Ave, Urbana, IL 61801 US Department of Transportation Office of Research, Development and Technology (RD&T) 1200 New Jersey Avenue, SE Washington, DC 201590	13. Type of Report and Period Covered Final Report (September 2023 - December 2024)
	14. Sponsoring Agency Code N/A

15. Supplementary Notes

For additional reports and information visit the TRANS-IPIC website https://trans-ipic.illinois.edu

16. Abstract

Precast concrete (PC) is manufactured in a controlled environment to provide desired quality, durability and efficiency to build transportation assets that address significant infrastructure challenges faced by the nation. Quality deficiencies during any lifecycle phase can easily off set the expected benefits, leading to premature failures and excessive repair costs. Currently, PC quality management heavily relies on a manual approach and remains isolated within each life cycle stage. This multi-phase research project develops and validates a holistic quality management framework for precast construction of transportation infrastructure that collects,measures, and evaluates quality data of the precast process across its life cycle. It integrates building information modeling (BIM), laser, radar, vision sensing, extended reality (XR) along with advanced computational tools to create a digital twin for lifecycle PC quality control and management. Phase 1 deliverables include BIM templates and a tested implementation mechanism for precasters to more safely manufacture high-quality PC products in plant.

17. Key Words		18. Distribution Statement	
Precast, Concrete, Transportation, Infrastructure, building information modeling (BIM)		No restrictions.	
19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	25	N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Disclaimer:

Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Holistic Quality Management of Precast Concrete Construction for Transportation Infrastructure
PU-23-RP-01

FINAL REPORT

Submitted by:
Hubo Cai, hubocai@purdue.edu
Lyles School of Civil Engineering
Purdue University

Collaborators / Partners:
Norwalk Concrete Industries
Indiana Department of Transportation

Submitted to:
TRANS-IPIC UTC
University of Illinois Urbana-Champaign
Urbana, IL

Executive Summary:

Precast concrete (PC) is manufactured in a controlled environment to provide the desired quality, durability, and efficiency to build transportation assets that address significant infrastructure challenges faced by the nation. Quality deficiencies during any lifecycle phase can easily offset the expected benefits, leading to premature failures and excessive repair costs. Currently, PC quality management (QM) heavily relies on a manual approach and remains isolated within each lifecycle stage. To address these problems, this research project developed a holistic quality management framework/model for precast construction of transportation infrastructure to collect and evaluate quality-related data of the precast concrete system across its life cycle. Building information modeling (BIM) was utilized for continuous collection of quality data and creating a digital twin of PCS to provide a 'seamless' method for information management and sharing for lifecycle quality control and management of precast concrete systems. The framework is aligned with the business process of the precast concrete systems and is flexible to integrate with multi-model sensor data with the potential to automate the quality control and management of precast concrete systems from a lifecycle perspective.

The specific objectives of this project are to 1) design a system-level framework for lifecycle quality management of PC systems (PCS), and 2) exploit BIM for precast concrete systems in the stage of precast at the plant. To achieve these objectives, the project consists four research tasks. In task 1, a framework was designed to enable continuous data collection and seamless data exchange for PCS QM across the stages of design, manufacturing, transportation, installation, and operation and maintenance (O&M). The state-of-the-art practice by the precast industry was reviewed and compiled. The current state of BIM practice in the quality management of precast concrete systems was reviewed and assessed. Based on the findings, a BIM-based digital twin system was designed. In task 2, an expandable BIM approach was adopted to meet the data and information needs of lifecycle PCS QM. After identifying the data needs in the stages of precast production, transporting, installation, and O&M, the research team designed expandable BIM templates using Industry Foundation Classes (IFC) to accommodate the identified data needs. In task 3, a panel discussion at 2024 Purdue Road School was organized. Four panelists from an owner organization, a precast manufacturer, and an engineering company shared their insights in six aspects: 1) the growth of PCS, 2) common types of structure, 3) common challenges, 4) specific perspectives on QM, 5) Stakeholders and involved parties, and 6) Inspection, identification, and correction of defects. In task 4, the newly designed framework and BIM templates were validated through a case study with one of the project partners in the precast-at-plant stage.

The key findings of this project and the main merits of the newly designed BIM framework for PCS QM are as follows. First, using BIM automates the compliance checking process during precast quality inspections. By comparing as-built and as-designed BIM models, discrepancies are identified and compared against specified tolerances to determine compliance. All the comparisons can be automated within BIM. Second, using BIM as the central hub for documenting QC data enables the accumulation and lifecycle sharing of QM data. Besides the as-designed and as-built data, BIM stores additional fine-grained quality data (e.g., raw inspection data, compliance checking results, and corrections and repairs), which is impossible with traditional paper-based documentation approaches. Third, customization of IFC property is effective in incorporating project-specific QC information without changing the fundamental structure of IFC schema. The QC data is stored as the properties of associated BIM objects by specifying the property name, property value, and value type. Lastly, the case study finds that the precast plant simplifies industry standards to streamline the inspection tasks and inconsistencies exist in the practice. Such inconsistencies can be eliminated by using the newly developed BIM-based framework to lower the risk of missing certain inspection items.

Table of Contents:

1. Statement of Problem

Precast concrete (PC) is manufactured in a controlled environment and is a promising alternative to cast-in-place concrete providing desired quality, durability, adaptability, efficiency, and (with embedded sensors) real-time performance monitoring capacity to construct transportation assets. PC systems (PCS) such as mechanically stabilized earth (MSE) retaining walls, bridge beams and deck panels, and precast concrete pavements have been widely used by US State Departments of Transportation (DOTs). High-quality PCS provide several benefits including shorter lane closures and reduced traffic congestion attributed to accelerated construction with shorter project duration, and increased road user and worker safety when such systems are utilized correctly [1]. However, quality deficiencies during any PCS lifecycle phases (i.e., design, manufacturing, transporting, lifting and installation, and operation and maintenance (O&M)) can easily offset the expected benefits, leading to premature failures and excessive repair costs. Therefore, there is a *critical need* for holistic quality management (QM) of PCS in transportation infrastructure from the lifecycle perspective.

The current practice in quality management (QM) of PCS (PCS QM) heavily relies on manual approaches and remains isolated within each lifecycle stage. For instance, quality control (QC) during the precast-at-plant stage is done using labor-intensive performance audits and sporadic inspections with the potential to miss critical defects and thus violate specifications [2]. The resulting quality deficiencies can impact the transportation of precast elements, their installation and connections with other components at transportation projects, and their life-cycle performance and maintenance. Some of the quality-related issues are documented using inspection forms and checklists, but mechanisms to share the data with downstream stages are lacking. These limitations can offset the expected benefits of using PCS.

To address the aforementioned problems, this research project aims to develop, validate, and test a holistic quality management framework/model (see Fig. 1) for precast construction of transportation infrastructure. The framework collects, measures, and evaluates data of the precast process across its life cycle, from design to manufacturing, transport, installation/construction, and O&M. Building information modeling (BIM) is utilized as a central data hub for continuous collection of quality data and creating a digital twin of PCS, providing a 'seamless' method of information management and sharing that can be used for quality control and management of the precast systems from the life-cycle perspective.

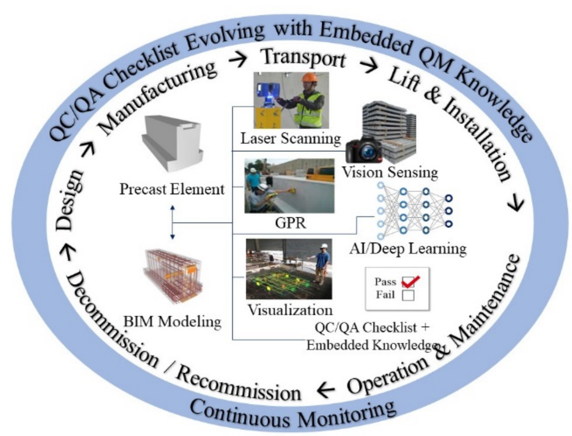

Fig. 1. Digital twin for holistic QM in PCP

2. Research Tasks

The specific research objectives are to 1) design a system-level framework for lifecycle quality management of PCS, and 2) exploit BIM for precast concrete systems in the stage of precast at the plant. The research plan includes four research tasks detailed as follows. As proof of concept, this project focuses on the following PCS: MSE walls, bridge beams, and pavement sections/bridge deck panels.

2.1 Design of BIM-based framework

Task 1 aims to design a system-level framework for lifecycle data/information/knowledge acquisition and data exchange in PCS. This task focuses on framework design and workflow and process modeling. It consists of three steps: 1) compiling knowledge of field practice of PCS QM, 2) assessing the state-of-the-art BIM practice in PCS QM, and 3) designing a BIM-based digital twin system.

2.1.1 Current practice of PCS QM

(1) Manufacturing stage

The current practice of in-plant QC for precast manufacturing consists of four main QC operations: shop drawing review, raw material testing/acceptance, aggregate and concrete testing, and inspections [3]. Fig. 2 illustrates the overall procedure.

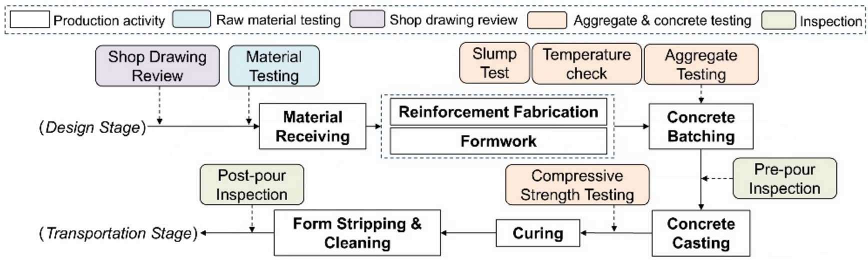

Fig. 2. In-plant QC procedure for precast manufacturing.

Review of shop drawings by the project's engineer of record ensures that detailed plans for manufacturing, handling, and installation of produced PC elements align with project specifications. Shop drawings are usually furnished by precast manufacturers for approval by the customers, and typically contain design values such as concrete dimensions, rebar size, and concrete compressive strength to guide practical manufacturing operations. Also, they serve as a reference for checking actual measurements during inspections to assess the quality conformance of the PC elements.

Testing of raw materials such as cement and aggregates is necessary to 1) verify the conformance of the used materials to product specifications, and 2) provide records to isolate the problems that may occur in the following casting operations or in future product service. Suppliers normally furnish test records that specify the materials' technical properties per shipment. Upon receiving the orders, plant inspectors review the shipped materials regarding their general condition and properties (e.g., size and steel grade of rebars) and check them against the reports/certificates.

Aggregate and concrete testing is performed to determine the workability, durability, and strength of the concrete used in the PC elements. Aggregate testing focuses on examining aggregate gradation, deleterious substances, and moisture content [3]. Concrete testing includes tests for slump, temperature, density, air content, and compressive strength [3]. All concrete test results along with mix design information (e.g., mix designation, quantity, and type of used materials) are documented in concrete batch reports for an easy check on concrete quality conformance.

Inspection focuses on the products and is categorized into pre-pour inspection and post-pour inspection (see Fig. 3). Pre-pour inspections are performed before each casting to check formwork-related aspects, including form cleanliness, form dimensions, application of release agent, positioning of reinforcement, and miscellaneous embedment. Post-pour inspections are intended to detect and correct damage (e.g., cracks, spalls, honeycomb), poor dimensional tolerances (e.g., concrete dimensions, squareness, bowing), or other problems such as exposed reinforcing after the concrete pour. Visual checks are used to check conditions (e.g., form cleanliness, misalignments) or detect damage. Tape measurements are used to verify dimensional accuracy and check against tolerances. Defects identified during pre-pour inspections are corrected immediately to make forms ready for casting. Defects identified during the post-pour inspection are analyzed further to determine their severance level and repairability. Records of defects and corrective actions are documented and filed with the pre-shipping inspection report.

(2) Transportation stage

Transportation of PC elements includes 1) moving PC elements from cast to yard, 2) loading on trucks/trailers, 3) transporting to the project site, and 4) unloading for on-site storage (see Fig. 4). As-built data of PC elements from the previous stage is needed to facilitate planning work such as selection of handling/transportation equipment, utilization of lifting devices, and route planning. The needed transition data includes concrete dimensions, compressive strength, types of embedded lifting inserts, etc. [4]. Before transportation to the site, the transportation manager from the manufacturer drafts the delivery ticket and coordinates the planning work with the shipping firm.

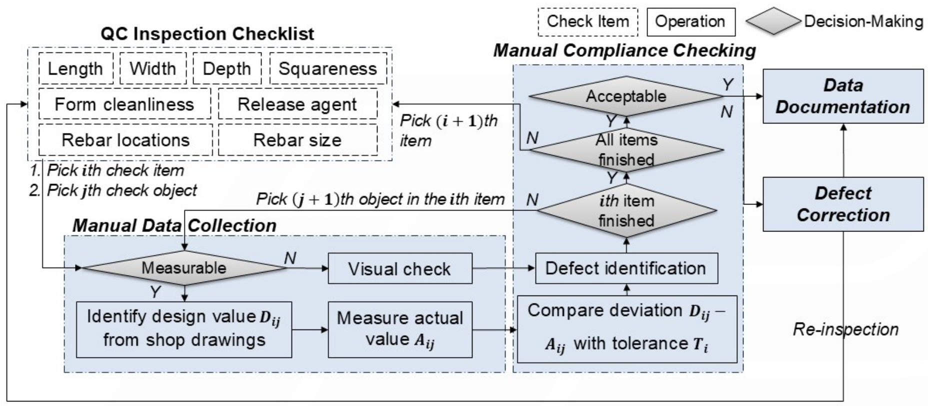

Fig. 3. Workflow of pre-pour and post-pour inspections for single PC element.

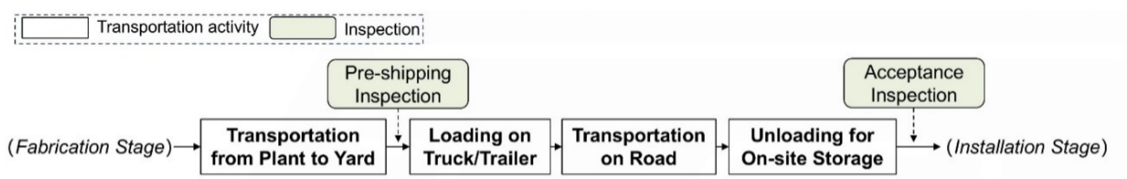

Fig. 4. QM procedure in the transportation of PC elements.

Pre-shipping inspection and acceptance inspection are conducted by the manufacturer and contractor respectively for quality control. Pre-shipping inspection ensures that the products conform to design specifications and are properly marked for identification. Based on visual checks and measurement, the inspection verifies that 1) the elements meet project specifications, plans, and contract documents, 2) the elements are properly marked in post-pour inspections, and 3) all necessary repairs have been completed. Once the transported products arrive, acceptance inspection is performed by checking their identification and condition (e.g., cracking and spalling).

(3) Installation stage

Installation of PC elements involves surveying and site preparation, installation through handling and connection, and finishing and open traffic (see Fig. 5). The transition data from previous stages includes the layout of assembled PCS, lifting instructions, identification of individual PC elements, and their storage locations. The data supports the jobsite handling in the aspects of equipment selection and sequencing of handled elements.

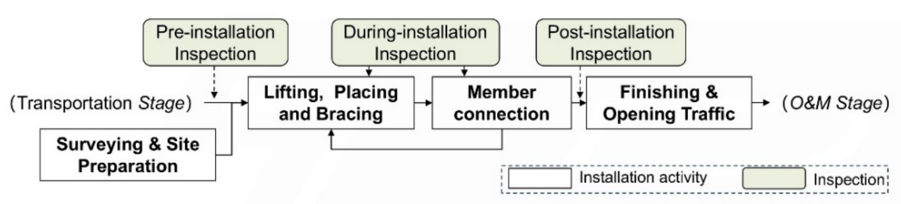

Fig. 5. QM procedure in the installation of PC elements.

During the installation stage, pre-installation, during-installation, and post-installation inspections are conducted to ensure the assembled system's quality. Pre-installation inspection examines the availability of required equipment and preparation of work areas. During-installation inspection checks the placement of PC elements such as base grade for PC pavement slab placement, and the connection of neighboring PC elements such as dowel/tie bar slot grouting involved in connecting PC pavement slabs. Post-installation inspection verifies that the PC elements are installed as required and checks their structural integrity. Tools such as standard surveying equipment (e.g., total station) and a carpenter's level are used to measure the grade of support surfaces and verticality of erected elements. In addition, visual checks are commonly used for inspecting the compliance of installation with requirements [5,6].

(4) Operation and maintenance stage

The main QC activity in O&M stage is inspections by DOT agencies, to check deficiencies of PCS and associated components and record them in terms of location, number, and severity. Visual checks and tape measurements are widely used to identify and measure defects such as cracks, spalls, delamination, and disjointed members. Advanced inspection techniques can be adopted to reduce manual efforts and improve efficiency, including drone inspection, ground penetrating radar, sonic and ultrasonic testing, computed tomography, and infrared thermography [6,7].

2.1.2 State-of-the-art BIM practice of PCS QM

BIM has been explored as a data hub for managing the QC information and enabling automated quality assessment of PC elements during the precast manufacturing stage. Specifically, BIM is used to document inspection results (e.g., actual dimensional measurements, dimensional deviations, acceptance of PC elements) to facilitate reporting [8–10]. The information is represented as attributes/properties of PC element objects using object-oriented modeling. Industry Foundation Class (IFC), an open standard for digitally describing the built environment, was extended by existing studies to store the QC data generated during QC processes.

As an open data format, IFC offers interoperability between various BIM software and effective exchanges of precast element data (e.g., geometry, material) among project participants [8]. A few researchers proposed extending the IFC schema with new entities or property sets to store the attribute data of quality inspections. Kim et al. (2015) designed an IFC-based entity relationship model, adding new entities like *IfcSpalling* with attributes such as *IfcCount*, *IfcArea*, *IfcVolume*, and *IfcDirection* to describe spalling defects [8]. However, the addition of new entities into IFC requires a long-time verification process to be applied in the existing BIM software. Besides, the extension could make IFC that has been already extensive and complex unmanageable [11]. To minimize these negative extension effects, a few studies created new property sets to extend IFC for describing precast QC data without changing the fundamental structure of IFC schema. Kim et al. (2016) created a customized property set called QualityAssessment to store dimensional inspection results [9]. Xu et al. (2020) further enhanced the property set customization by specifying associated property values and property value types [10].

2.1.3 BIM-based digital twin system for PCS QM

This project proposes a BIM-based dynamic QC framework that enables continuous data sharing of quality-related data/information/knowledge across project lifecycle stages (see Fig. 6). As an example, Fig. 7 demonstrates the evolution of the BIM-based digital twin within the manufacturing stage. Using object-oriented modeling (OOM), BIM represents precast concrete system components and their relationships into interconnected classes and associated attributes. The OOM feature enables BIM to be expandable by adding additional attributes for new data, creating "live" digital twins (DT) through increasing detail levels of BIM. The resulting DT allows seamless data sharing with subsequent lifecycle stages such as transportation.

Coupled with sensing technologies and computational algorithms, QC digital twins can automate labor-intensive inspections and enhance working efficiency. Fig. 8 demonstrates the workflow of automated inspection for one single PC element enabled by combining BIM and sensing technologies. The workflow is divided into four modules: automated data collection, automated compliance checking, data documentation, and defect corrections. LiDAR, ground penetrating radar, and cameras can be used to scan precast elements and gather geometrical data. Actual measurement values are estimated from preprocessed data using AI algorithms. Then, automated compliance checking assesses the quality conformance of the inspected PC element by determining if deviations exceed allowed tolerances. The deviations are derived by comparing the actual measurement values with design values. Throughout the workflow, BIM serves as a central data hub, providing inputs for compliance checking and storing records of quality compliance and corrections to address deviations for each PC element. Conventional manual QC data collection can be easily integrated into the workflow when automation is not applicable. As the manufacturing process progresses, BIM that starts with the design information, evolves with the accumulation of QC data collected during each subsequent manufacturing stage. The resulting BIM digital twin is expected to facilitate 1) PC element quality monitoring, 2) efficient tracing of quality issues and data-driven QC decision-making, and 3) collaboration among production managers, engineers, QC technicians, and suppliers through a centralized platform.

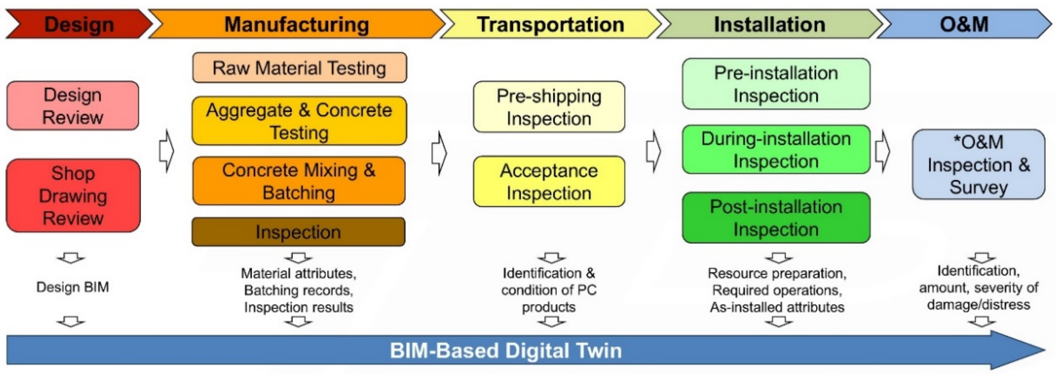

Fig. 6. BIM-based overall framework for PCS QM throughout all lifecycle stages.

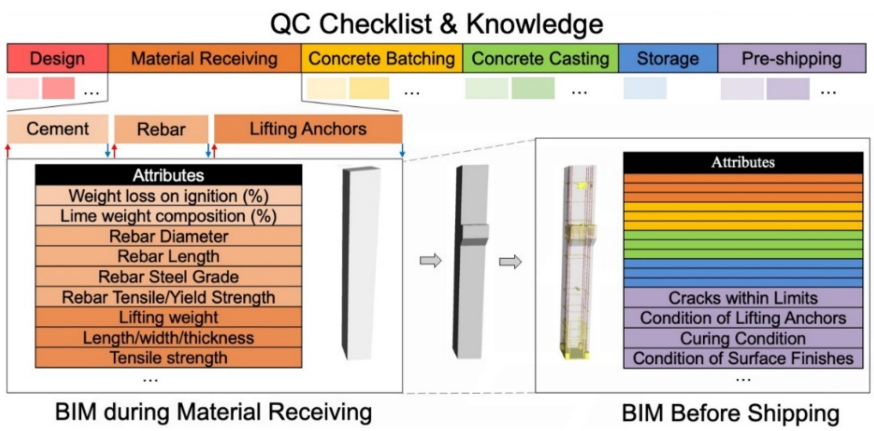

Fig. 7. Evolution of BIM-based digital twin during manufacturing stage (the arrows represent the interactions between QC activities and BIM).

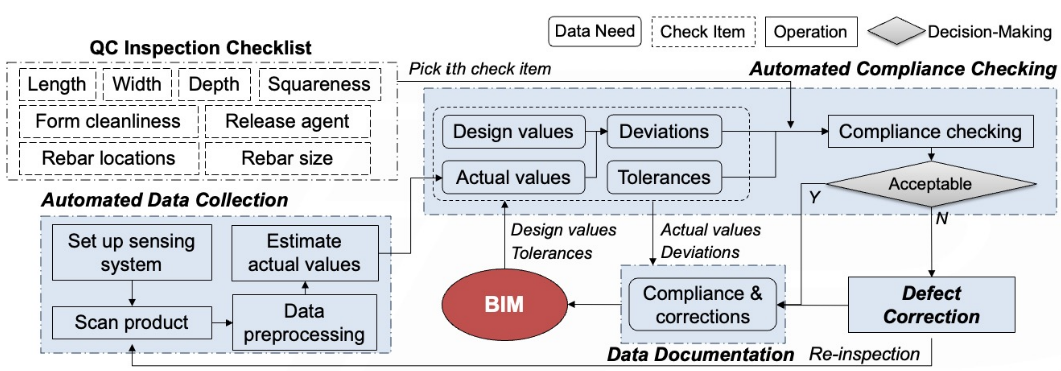

Fig. 8. Workflow of automated inspection for single PC element enabled by coupling BIM and sensing technologies.

2.2 Design of expandable BIM approach

Task 2 aims to design an expandable BIM approach to meet the data and information needs of lifecycle PCS QM. This task includes 1) identification of data needs in precast manufacturing, transportation, installation, and operation and maintenance, 2) design of templates for expandable BIM, using IFC as the open standard, and 3) implementation to accommodate data needs in precast manufacturing and generate data to meet the transporting and installation needs.

2.2.1 Identification of data needs

The current practice of PCS QM leverages inspection checklists and testing reports to document quality-related data. In this project, the research team collected quality related data needs from checklists developed by the National Precast Concrete Association [12]. Appendices A-1 to A-4 illustrate the quality-related data items for MSE wall systems.

2.2.2 Design of templates for expandable BIM

IFC is leveraged to design BIM templates that can store the quality data of elements across their lifecycles. Extension of IFC entities is necessary to incorporate important QC concepts that are not covered in the current IFC specification [13]. The extension is performed by creating customized property sets to represent quality-related properties and provide storage space for QC data [10].

A task-centered data structure is developed for the template to model QC activities and their associated QC data needs (see Fig. 9). The add-ons are highlighted in bold in the figure. The substructure of testing/batching (*IfcTask*) covers QC activities such as raw material testing, aggregate testing, concrete testing, and concrete batching. The substructure of inspection tasks models the inspections of PC elements (e.g., *IfcWall*, *IfcBeam*, *IfcSlab*). These entities contain original design information such as concrete dimensions and layout of embedment. Each inspection task is provided with tolerances (*Pset_Tolerances*) as quality requirements. The inspected PC element is recorded with the inspection results, including the inspection measurements (*Pset_ActualValues*), deviations (*Pset_Deviations*), compliance results (*Pset_Compliance*), and corrective actions (*Pset_Corrections*). The two substructures are implicitly linked with the PC product entities in the inspection substructure through shared attributes (see green dash lines in Fig. 9). This design allows the quality of a PC product to be traced all the way back to its origin, including batch history and material sources.

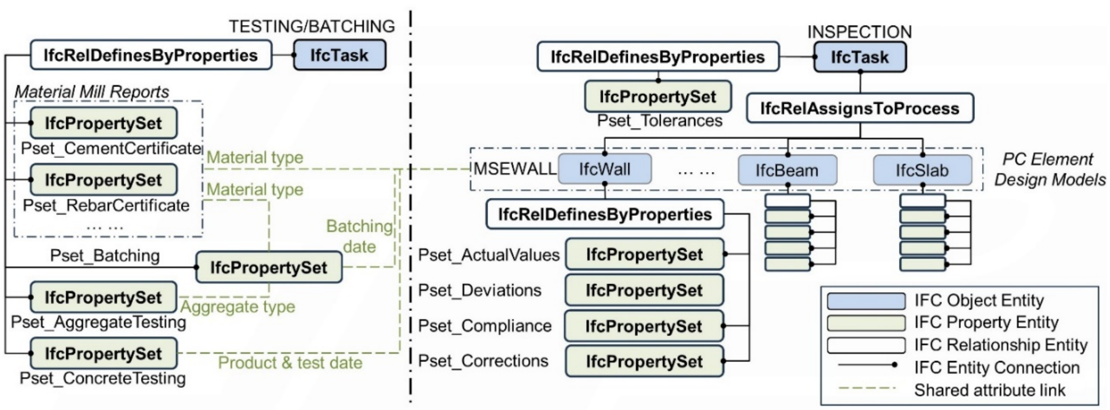

Fig. 9. Task-centered IFC data structure for description of QC activities and associated data needs. Entities in bold are the add-ons to IFC design models for creating the IFC QC template.

To define the individual properties (i.e., quality attributes) within property sets, each property name, property value, and property value type must be specified. As illustrated by the inherent structure of property entities (Fig. 10), a property set is a container that holds different types of properties. Each property has its own value and value type. In this project, the properties critical to QC activities are identified, and the corresponding IFC property values and value types are selected (see Fig. 10). Table

1 presents representative QC properties in each property set along with their selected values and value types.

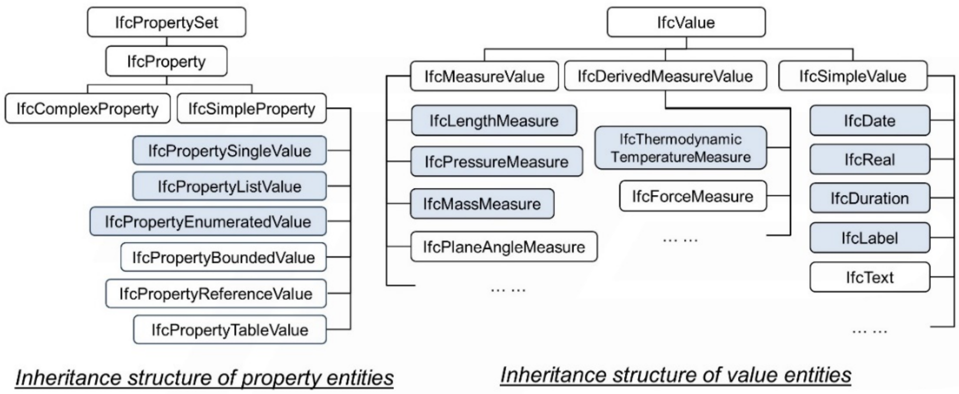

Fig. 10. Inheritance structures of property entities and value entities. The entities selected for representing QC attributes are highlighted in blue.

Table 1 Definition of representative properties for quality of MSE wall panels.

Property Set	Property Name	Property Value	Property Value Type
Pset_CementCertificate	Chemical items/Air content of mortar/Autoclave expansion (%)	IfcPropertySingleValue	IfcReal
	Time of setting		IfcDuration
Pset_AggregateTesting	Sieve size	IfcPropertyListValue	IfcLengthMeasure
	Weight retained		IfcMassMeasure
	Weight retained (%)/Weight passed (%)		IfcReal
Pset_ConcreteTesting	Slump/Slump flow	IfcPropertySingleValue	IfcLengthMeasure
	Ambient/Concrete temperature		IfcThermodynamicTemperatureMeasure
	Cylinder number	IfcPropertyListValue	IfcLabel
	Curing age		IfcDuration
	Load		IfcMassMeasure
	Comprehensive strength		IfcPressureMeasure
Pset_Batching	Batching date	IfcPropertySingleValue	IfcDate
	Weight of cement/aggregate/air entrainment/water reducer		IfcMassMeasure
	Type of cement/aggregate/air entrainment/water reducer		IfcLabel
	Fine/Coarse aggregate moisture (%)		IfcReal
Pset_ActualValues/Pset_Deviations	Length/Width/Thickness/Squareness	IfcPropertySingleValue	IfcLengthMeasure
	Spacing of rebars/tie strips	IfcPropertyListValue	
Pset_Tolerances	Dimensions/Thickness/ Squareness/Rebar spacing/ Tie strip spacing	IfcPropertySingleValue	IfcLengthMeasure
Pset_Compliance	Square/ Dimensions/ Rebar spacing/Tie strip	IfcPropertyEnumeratedValue	IfcLabel

Pset_Corrections	Defect type/ Defect severity/ After-repair compliance	IfcPropertyEnumerated Value	IfcLabel
	Corrective action	IfcPropertySingleValue	

2.2.3 Implementation of expandable BIM

Autodesk Revit and IfcOpenShell are used to create the base IFC design models and add customized quality attributes for generating the templates, respectively. Fig. 11 shows the base models of the MSE wall panel, bridge deck panel, bridge beam, and pavement slab. Synthetic data is generated to simulate the quality data collected in precast manufacturing and test if the designed templates can meet the data representation needs. Fig. 12 presents the BIM-IFC template for MSE wall panels as an example.

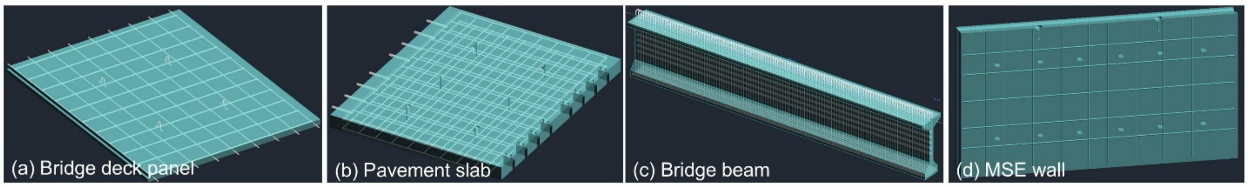

Fig. 11. Base design models

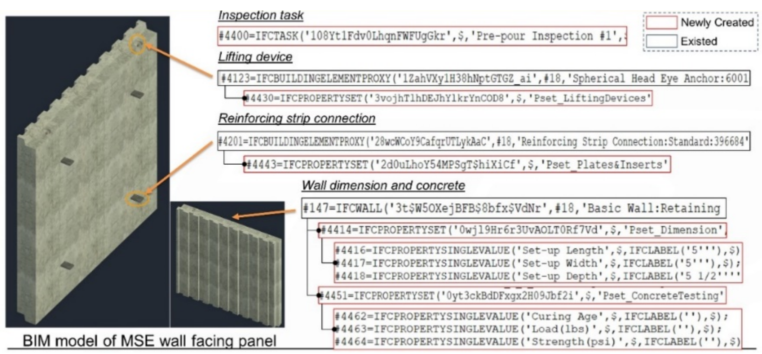

Fig. 11. BIM template of MSE wall panels.

2.3 Panel Discussion

A panel discussion was conducted at 2024 Purdue Road School to share project findings and to engage with/learn from experienced researchers and practitioners in the field of precast concrete in transportation projects. Four keynote speakers, namely: Tommy Nantung (Research Manager) and Andrew Pangallo (Construction Digital Lead Engineer) from INDOT, Jeff Brechbill (President and part owner) from First Group Engineering, and John Lendrum (President) from Norwalk Concrete Walk Concrete Industries provided presentations on 1) the growth of PCS, 2) common types of structure, 3) common challenges, 4) specific perspectives on QM, 5) Stakeholders and involved parties, and 6) Inspection, identification, and correction of defects (Fig. 13). A Q&A session followed the presentations to exchange ideas regarding QC concerns of PCS. The key takeaways from the presentations are as follows. First, current in-plant and on-site inspections rely primarily on subjective observations. Second, most damages to PC elements are caused by improper shipping and handling due to limited resources on site (e.g., lifting equipment) and undertrained contractors. Third, training and workforce development are required to enhance field workers' understanding of quality issues and their impact on the constructed/manufactured product. Fourth, constructability is still a challenge due to factors like

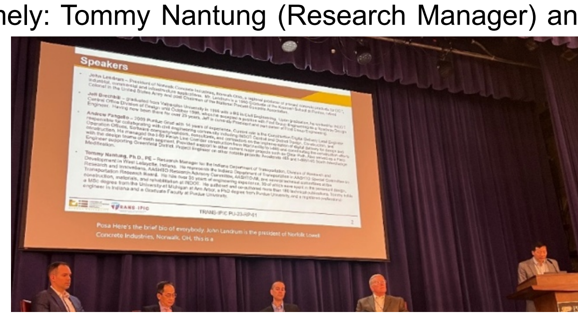

Fig. 12. Panel discussion at Purdue Road School 2024

site conditions (e.g., limited space) and workforce skills, even though PC products are precisely manufactured at the plant.

2.4 Validation of designed BIM framework

To validate the newly designed BIM framework, a case study of the prefabrication of MSE retaining wall panels was conducted to 1) provide an overview of in-plant QC practice and 2) demonstrate the viability of the proposed framework. MSE wall systems are commonly used composite structures for retaining the soil. The wall facing panels, which are key system components, are manufactured in precast plants and typically consist of concrete, rebars, tie strips, and lifting inserts. The research team observed the QC processes of MSE wall panel manufacturing at an NPCA-certified regional precast manufacturer in the Midwest USA. Pre-pour and post-pour inspections are discussed as the representative QC activities in this case study due to their significance in assuring PC elements' quality.

2.4.1 Pre-pour and post-pour inspections

The inspection of an MSE wall panel is typically conducted by one or two QC technicians, depending on the panel size. Collaboration between two QC technicians improves not only inspection efficiency but also accuracy. Fig. 14 shows snapshots of inspectors performing measurements during pre-pour and post-pour inspections.

Fig. 14. Two QC technicians measure form dimensions in the pre-pour inspection (left) and one QC technician measures the location of a corner tie strip in the post-pour inspection (right).

During the site visit, the research team observed that the inspectors used inspection checklists to check each item one by one in order to inspect the MSE wall panel. Table 2 summarizes the checklist and associated check actions performed for pre-pour and post-pour inspections. The inspectors began by confirming the design values from shop drawings. Then they measured the corresponding objects using a tape measure and compared the measurements with the design values to assess deviations. During the measurement, a visual check was employed to expedite inspection time. For example, to check the location of all tie strips, the inspectors measured the locations of four corner tie strips and visually checked the alignment of the tie strip rows and columns. It took around 5 minutes to inspect one 9'-9 ¼''× 4'-10 ¼'' panel for the pre-pour inspection and 3 minutes to inspect one 9'-9 ¼'' × 5'-5 ¾'' panel for the post-pour inspection, respectively. Among the check items, inspections of the "Tie strips" and "Rebar spacing" items are more time-consuming than the inspection times of other items due to the larger number of objects to be measured and checked.

Table 2 Checklist and associated check actions for pre-pour and post-pour inspections.

Inspection	Check Item	Actions
Pre-pour inspection	Dimensions	Measure the length and width of the form once each.
	Squareness	Measure the length difference of two long edges of the form.
	Tie strips	1) Measure the spacing in one strip row one by one along the long direction. 2) Visually check if the tie strips are aligned along the short direction. 3) Measure the spacing of each strip row to the long edge three times (left, mid, right), respectively.
	Rebar Spacing	Measure the rebar spacing along the four edges.

Post-pour inspection	Dimensions	Measure the length and width of the concrete product on all four edges
	Tie strips	1) Visually check if the strips are twisted. 2) Measure the spacing of the two strip rows to the long edge two times (left, right). 3) Visually check the tie strips in the same row aligned. 4) Measure the spacing in a row one by one along the long direction. 5) Visually check if the tie strips are aligned in rows and columns.
	Edge details	Inspect concrete loss issues through visual checks and hand touch feeling.
	Surface condition	Lift the panel and check concrete loss issues on the face surface (the face with no tie strips).

Several differences were noted between the observed in-plant inspections and NPCA-recommended QC practice. The plant simplified the standard NPCA inspection checklist, excluding some inspection items to streamline the process. For example, "locations of lifting inserts" were not measured during pre-pour inspections, despite their importance for on-site installation. The exclusion is based on the use of templates, in this case steel forms, that have standard holes to hold the lifting inserts. The use of such templates minimizes location deviations. Meanwhile, some excluded inspection items such as "edge details" and "surface condition" (Table 2) were still checked by inspectors in practice but not covered in the plant-customized checklist (please refer to Fig. 16). This indicates an inconsistency between the inspection practice and specified inspection requirements in-plant, which may potentially increase the risk of missing certain items.

2.4.2 Demonstration of proposed framework

Fig. 15 shows the dimensional properties and associated design values of the MSE wall panel. Both real and synthetic data are leveraged to determine if the IFC template design can effectively document compliance results and actual measurements.

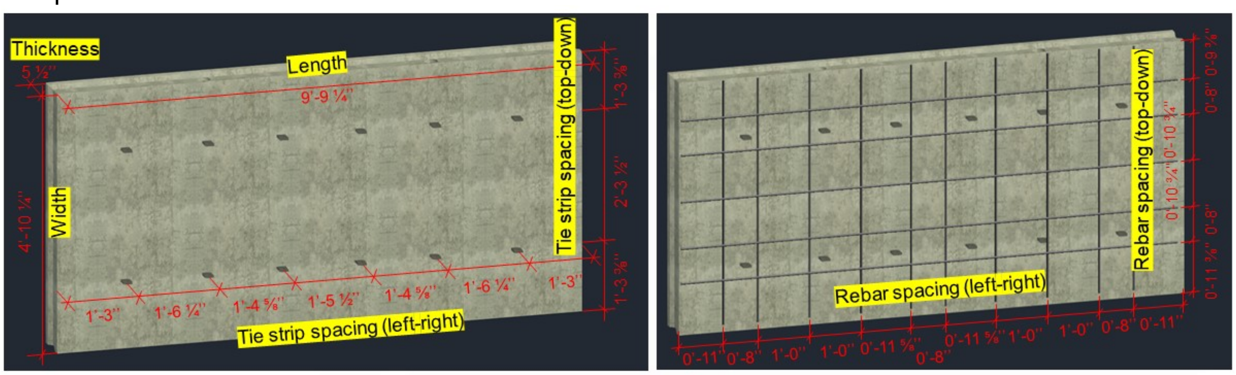

Fig. 15. BIM design model of MSE wall panel annotated with dimensional properties and property values.

(1) *Demonstration using real inspection data*

Current inspections document three types of information on paper inspection forms, including the information of PC element, inspection task, and check item. Fig. 16 shows the data documented on the inspection form and the information pieces are highlighted. On the form, each inspection task covers a set of wall panels, with each wall panel recorded with compliance results for a set of check items. The compliance results are represented by check marks to indicate the status of pass/fail.

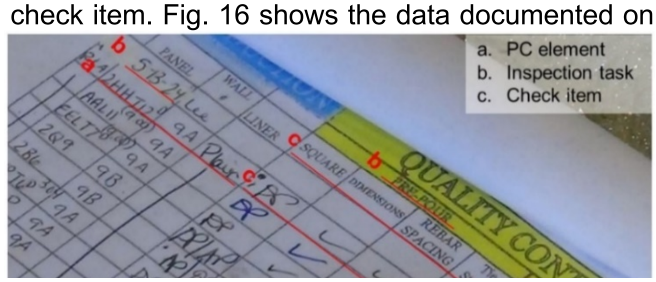

Fig. 16. QC Documentation using inspection forms.

The created IFC template mirrors the three types of information with corresponding IFC entities and attribute values. Fig. 17 illustrates 1) the relevant IFC entities from the IFC template STEP Physical File (SPF) and 2) the represented properties viewed in an IFC tool called usBIM browser1. Typically, IFC describes each entity in one line in the SPF with its line number, IFC entity class, and attribute values in the parentheses (as highlighted in blue). The location of the value in the parentheses informs the corresponding attribute. For instance, the first attribute of an IFC entity is usually Unique ID (GUID), followed by the entity name. In addition to these regular attributes, line numbers are used as references to establish connections between entities, while dollar signs indicate placeholders for empty attribute values. In this case, the tasks of pre-pour and post-pour inspections are timestamped with '2024-05-13' and panel '2HHT12' is assigned to the tasks for quality check. Check items are organized into two different instances of *IfcPropertySet* entities based on the inspection type. Each check item is modeled as an enumeration type property, storing the item name (e.g., Square) and compliance results (PASS/ FAIL). For the post-pour items that have not been checked, the default value NOTDEFINED is used as a placeholder for future data to populate. These data representations demonstrate that the template can structurally represent realistic quality attributes and store their data for precast quality inspections.

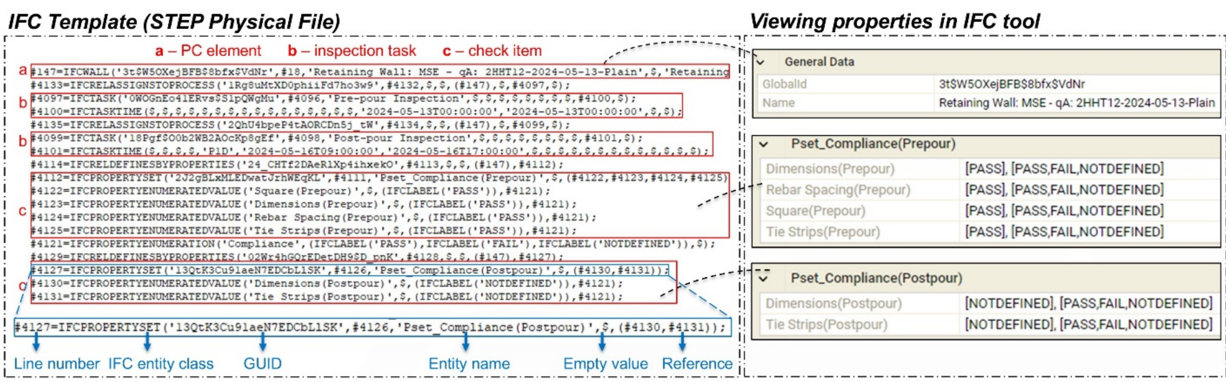

Fig.17. IFC template created using real inspection data (left) and QC properties visualized in the IFC tool (right). The red color highlights the relevant entities while the blue color explains the composition of a regular IFC entity.

(2) Demonstration using synthetic inspection data

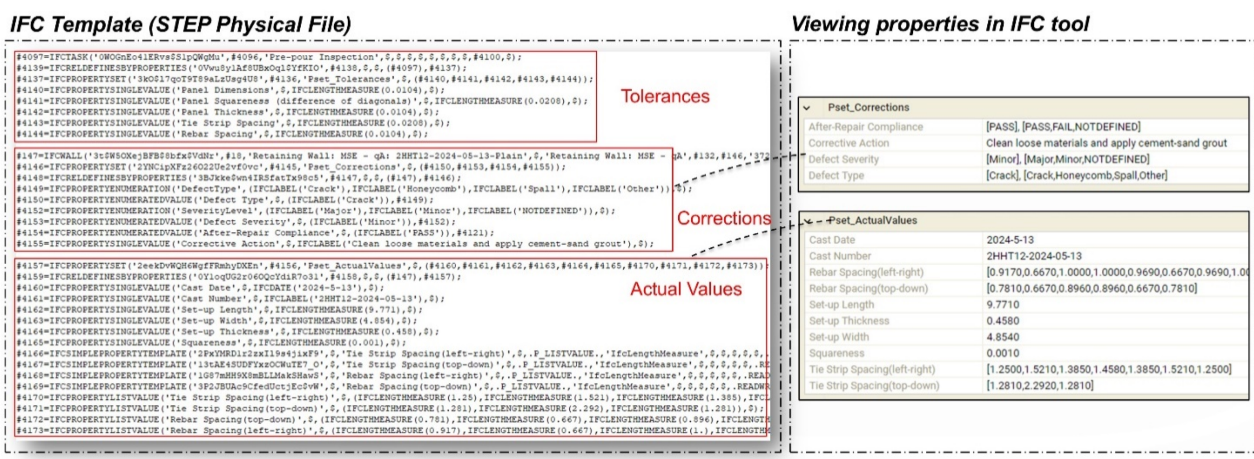

Fig. 18. IFC template created using synthetic inspection data (left) and QC properties visualized in the IFC tool (right).

Synthetic inspection data was used to verify the created IFC template can represent tolerances, actual values, and corrections. The data is synthesized based on ODOT SS840, the MSE wall panel's shop

[1] https://www.accasoftware.com/en/bim-viewer

drawings, and the NPCA manual. Fig. 18 displays the IFC entities describing tolerances, actual values, and corrections within the IFC template and their visualizations in the usBIM browser. The template creation follows the design of property metadata outlined in Table 1 in the aspects of property name, property value, and property value type. The demo confirms that the newly designed IFC template can effectively represent and store data related to tolerances, actual values, and corrections to support automated compliance checking and quality management.

3. Educational Outreach Activities

A course module on BIM for lifecycle quality management of precast concrete in infrastructure construction is being developed for CE 52200 Computer Applications in Construction. The first delivery will be in Spring 2025.

4. Workforce Development Activities

A panel discussion was held at Purdue Road School 2024. A presentation to Purdue Road School 2025 has been proposed to the organizers.

5. Technology Transfer Actions

A technology disclosure on the BIM-based templates for lifecycle quality management of precast concrete infrastructure will be filed.

6. Papers

Hong, Z., Hong, Y., Cai, H., Abraham, D.M., Zhang, J., Dunston, P.S. (2024). *BIM-based framework for in-plant quality control of precast concrete manufacturing – a case study*. [Manuscript submitted for publication].

7. Presentations

Hong, Z., Hong, Y., Cai, H., Abraham, D.M., Zhang, J., Dunston, P.S. (2024, Feb. 19). *Holistic Quality Management of Precast Concrete Construction for Transportation Infrastructure* [Webinar presentation]. TRANS-IPIC Monthly Research Webinar.

Hong, Z., Hong, Y., Cai, H., Abraham, D.M., Zhang, J., Dunston, P.S. (2024, Feb. 22). *Holistic Quality Management of Precast Concrete Construction for Transportation Infrastructure* [Poster presentation]. JTRP Poster Session. Indianapolis, IN, United States.

Hong, Z., Hong, Y., Cai, H., Abraham, D.M., Zhang, J., Dunston, P.S. (2024, Mar. 12). *Holistic Quality Management of Precast Concrete Construction for Transportation Infrastructure* [Poster presentation]. Purdue Road School 2024. West Lafayette, IN, United States.

Cai, H., Abraham, D.M., Zhang, J., Dunston, P.S., Hong, Z., Hong, Y. (2024, Mar. 12). *Holistic Quality Management of Precast Concrete Construction for Transportation Infrastructure* [Panel discussion]. Purdue Road School 2024. West Lafayette, IN, United States.

Hong, Z., Hong, Y., Cai, H., Abraham, D.M., Zhang, J., Dunston, P.S. (2024, April. 22). *Holistic Quality Management of Precast Concrete Construction for Transportation Infrastructure* [Keynote address]. TRANS-IPIC Annual Workshop 2024. Rosemont, IL, United States.

Hong, Y., Cai, H., Abraham, D.M. (2024, July 28). *Coupling Mobile Laser Scanning and BIM for Dimensional Quality Control of Precast Concrete Elements* [Poster presentation]. ASCE International Conference on Computing in Civil Engineering (i3CE 2024). Pittsburgh, PA, United States.

8. Other Events or Activities

Not applicable.

References

[1] L.P. Priddy, P.G. Bly, C.J. Jackson, G.W. Flintsch, Full-scale field testing of precast Portland cement concrete panel airfield pavement repairs, International Journal of Pavement Engineering 15 (2014) 840–853.

[2] D. Goulias, M. Scott, Effective implementation of ground penetrating radar (GPR) for condition assessment & monitoring of critical infrastructure components of bridges and highways., Maryland. State Highway Administration. Office of Policy & Research, 2015.

[3] National Precast Concrete Association (NPCA), NPCA QUALITY CONTROL MANUAL For Precast Concrete Plants, 2024.

[4] K. Brown, Calculations for Handling and Shipping Precast Concrete Deck Panels, Aspire - Concrete Bridge Technology (2019).

[5] Precast/Prestressed Concrete Institute (PCI), Bridge Design Manual (MNL 133 4th Edition), 2023.

[6] P. Smith, M.B. Snyder, Manual for Jointed Precast Concrete Pavement (3rd Edition), 2019.

[7] H. Parvardeh, Inspection of Bridge Components: An Introduction, (2022). https://www.assetintel.co/blogs/introduction-to-inspection-of-bridge-components (accessed November 24, 2024).

[8] M.K. Kim, J.C.P. Cheng, H. Sohn, C.C. Chang, A framework for dimensional and surface quality assessment of precast concrete elements using BIM and 3D laser scanning, Autom Constr 49 (2015) 225–238. https://doi.org/10.1016/j.autcon.2014.07.010.

[9] M.K. Kim, Q. Wang, J.W. Park, J.C.P. Cheng, H. Sohn, C.C. Chang, Automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM, Autom Constr 72 (2016) 102–114. https://doi.org/10.1016/j.autcon.2016.08.035.

[10] Z. Xu, R. Kang, R. Lu, 3D Reconstruction and Measurement of Surface Defects in Prefabricated Elements Using Point Clouds, Journal of Computing in Civil Engineering 34 (2020) 1–17. https://doi.org/10.1061/(asce)cp.1943-5487.0000920.

[11] P. Hüthwohl, I. Brilakis, A. Borrmann, R. Sacks, Integrating RC Bridge Defect Information into BIM Models, Journal of Computing in Civil Engineering 32 (2018). https://doi.org/10.1061/(asce)cp.1943-5487.0000744.

[12] National Precast Concrete Association. https://precast.org/. Accessed on Nov. 26, 2026, (n.d.).

[13] buildingSMART International, IFC 4.3.2.0 (IFC4X3_ADD2) Official Documentation, (2024). https://standards.buildingsmart.org/IFC/RELEASE/IFC4_3/ (accessed October 21, 2024).

[14] US Department of Transportation Federal Highway Administration, JOINTED PRECAST CONCRETE PAVEMENT PANEL FABRICATION AND INSTALLATION CHECKLISTS, 2019.

[15] P.J. Becker, Mechanically Stabilized Earth Wall Construction Inspection Manual, 2024.

[16] W.Y. Mergia, Retaining Wall Inspection and Common Problems, 2023.

Appendix

A-1: Quality data items required for MSE walls in manufacturing stage

1	**MSE Wall Manufacturing: Raw Material Testing (Cement as example)**
1.1	SiO2 (%)
1.2	Al2O3 (%)
1.3	Fe2O3 (%)
1.4	CaO (%)
1.5	Loss on Ignition (%)
1.6	Air Content of Mortar (%)
1.7	Blaine Fineness (m2/kg)
1.8	Compressive Strength (MPa)
2	**MSE Wall Manufacturing: Aggregate Testing**
2.1	Job Number
2.2	Job Name
2.3	Testing Date
2.4	Technician
2.5	Inspector
2.6	Sieve Size
2.7	Weight Retained
2.8	% Retained
2.9	% Passing
2.10	ASTM C 33% Passing
2.11	ASTM C 33 size 67 % Pass
2.12	ASTM C33 size 8 % Pass
3	**MSE Wall Manufacturing: Concrete Testing**
3.1	Product
3.2	Job Number
3.3	Job Name
3.4	Testing Date
3.5	QC Supervisor
3.6	Inspector
3.7	Slump or Slump Flow & VSI
3.8	Air %
3.9	Ambient Temperature
3.10	Concrete Temperature
3.11	Mix Design No.
3.12	Cylinder No.
3.13	Strength Test Date
3.14	Time Made
3.15	Time of Strength Test
3.16	Curing Age
3.17	Load (lbs)
3.18	Strength (psi)
3.19	Required Strength (psi)
4	**MSE Wall Manufacturing: Batching Records**
4.1	Mix Design
4.2	Batching Date
4.3	Batching Time
4.4	Quantity
4.5	Batching Operator
4.6	Project/Job
4.7	Cement Weight (lbs)

4.8	Cement Type
4.9	SCM (lbs)
4.10	Water (gal/lbs)
4.11	Fine Aggregate Weight (lbs)
4.12	Fine Aggregate Type
4.13	Coarse Aggregate Weight (lbs)
4.14	Coarse Aggregate Type
4.15	Air Entrainment Weight (ozs)
4.16	Air Entrainment Type
4.17	Water Reducer Weight (ozs)
4.18	Water Reducer Type
4.19	Other Weight
4.20	Other Type
4.21	Fine Aggregate Moisture (%)
4.22	Coarse Aggregate Moisture (%)
4.23	w/cm Ratio
5	**MSE Wall Manufacturing: Pre-pour Inspection Checklist**
5.1	Product
5.2	Job Number
5.3	Casting Date
5.4	Casting Number
5.5	Inspection Date
5.6	QC Supervisor
5.7	Inspector
5.8	Form Condition
5.9	Form Cleanliness
5.10	Form Joints
5.11	Release Agent/Retarder
5.12	Design Length (ft/in)
5.13	Set-Up Length (ft/in)
5.14	Design Width (ft/in)
5.15	Set-Up Width (ft/in)
5.16	Design Depth (ft/in)
5.17	Set-Up Depth (ft/in)
5.18	Squareness
5.19	End and Edge Details
5.20	Location of Lifting Devices
5.21	Lifting Devices
5.22	Tie Strips
5.23	Reinforcing Steel -Design v Actual
5.24	Size of Reinforcing Design v Actual
5.25	Spacing of Reinforcing Design v Actual
5.26	Corrosion
5.27	Reinforcement Cleanliness
5.28	Top Finish (wet)
6	**MSE Wall Manufacturing: Post-pour Inspection Checklist**
6.1	Product
6.2	Job Number
6.3	Casting Date
6.4	Casting Number
6.5	Inspection Date
6.6	QC Supervisor
6.7	Inspector

6.8	Mark Number
6.9	Top Finish
6.10	Bottom Finish
6.11	Surface Texture
6.12	As Cast Length (ft/in)
6.13	As Cast Width (ft/in)
6.14	As Cast Depth (ft/in)
6.15	Squareness
6.16	Stripping Strength
6.17	Cracks
6.18	Spalls
6.19	Honeycomb / Grout Leak
6.20	Tie Strips
6.21	Lifting Devices

Source: [3]

A-2: Quality data items required for MSE walls in transportation stage

1	**MSE Wall Transportation: Pre-shipping Inspection Checklist**
1.1	Conformance to project specifications and contract
1.2	Proper post-pour markings
1.3	Correct repairs
2	**MSE Wall Transportation: Acceptance Inspection Checklist**
2.1	Panel identification
2.2	Panel condition (cracking, spalling)
2.3	Condition of lifting inserts and strip connection devices

Source: [3,14]

A-3: Quality data items required for MSE walls in installation stage

1	**MSE Wall Installation: Procurement Checklist**
1.1	The Contractor has selected a pre-approved MSE wall system from INDOT's qualified products list (QPL) of approved retaining wall systems
1.2	The Contractor has submitted project specific MSE wall shop drawings and design calculations that satisfy ISS 105.02 and ISS 731.04
1.3	INDOT Engineers, including INDOT Division of Geotechnical Engineering, have provided written notice approving MSE wall submittals
2	**MSE Wall Installation: Storage Checklist**
2.1	Pre-cast components (facing panels and copings) have been properly stored onsite in accordance with INDOT specifications and MSE wall system vendor recommendations
2.2	Soil reinforcements have been properly stored onsite in accordance with INDOT specifications and MSE wall system vendor recommendations
2.3	Fasteners, bearing pads, and geotextile joint covering materials have been properly stored onsite in accordance MSE wall system vendor recommendations
3	**MSE Wall Installation: Foundation Preparation Checklist**
3.1	Excavation operations are being conducted in accordance with ISS 201.03 and ISS 731.04
3.2	Excavation operations abide by State and local safety requirements
3.3	Excavations requiring support systems have been properly shored or braced
3.4	Water has been appropriately removed from excavations
3.5	Excavation operations do not endanger stability of the future MSE wall
3.6	Foundation soils deemed unsuitable by the Engineer have been removed and replaced with B Borrow
3.7	Replacing B Borrow has been compacted to at least 95% maximum dry density based on DCP blow count criteria in ISS 203.23
3.8	The foundation has been compacted in accordance with ISS 203
3.9	The width of the foundation equals or exceeds the length of prescribed soil reinforcement units
3.10	The foundation has been graded as detailed in the road/bridge plans
3.11	The foundation has been graded with a 1 in per 1 foot downward slope toward the back of the reinforced zone
3.12	That the portion of foundation below the leveling pad is level graded
3.13	The contractor has proofrolled the MSE wall foundation using an appropriately sized on-highway dump truck in accordance with ISS 203.26
3.14	Locations failing proofrolling have been appropriated remediated as directed by the Engineer
3.15	DCP tests of the foundation advanced to 30 in. deep yield blow count measurements equal to or greater than 5 blows per 6 in.
3.16	Foundation soils where DCP tests yielded failing blow count measurements have been removed and replaced with compacted B Borrow
3.17	DCP measured factored bearing resistances meet or exceed the factored bearing resistance detailed on the shop drawings Borrow
4	**MSE Wall Installation: Leveling Pad Placement Checklist**
4.1	Soil underneath the leveling pad has been compacted in accordance with ISS 203
4.2	The Engineer has approved the prepared foundation elevations along the length of the leveling pad
4.3	The leveling pad has been cast using unreinforced concrete as detailed on the shop drawings
4.4	The leveling pad has cured in accordance with ISS 702.22 for at least 12 hours
4.5	Leveling pad top elevations meet tolerances recommended by the MSE wall system vendor
4.6	Leveling pad step-ups (i.e., where leveling pad elevation changes) have been constructed in accordance with recommendations from the MSE wall system vendor
5	**MSE Wall Installation: Placement of the Initial Panel Course Checklist**
5.1	MSE wall pre-cast components (facing panels and copings) have been cast with lifting connections set into their upper edges

5.2	Panels are being lifted and transported from onsite storage in accordance with recommendations from the MSE wall system vendor
5.3	Procedures for placing panels on the leveling pad are not causing undue damage to the panels
5.4	Panels placed on the leveling pad are in alignment with the wall layout line detailed on the shop drawings
5.5	Panels placed on the leveling pad are horizontally level determined using a 4-ft level
5.6	Panels place on the leveling pad that require shimming have been shimmed in accordance with guidelines from the MSE wall system vendor
5.7	Panels place on the leveling pad have been battered toward the back of the MSE wall in accordance with recommendations from the MSE wall system vendor
5.8	Where needed, temporary wooden wedges have been used to maintain the batter for panels placed on the leveling pad
5.9	The Contractor is monitoring panel movement during construction and adjusting the degree of panel battering accordingly
5.10	Panels within the initial panel course have been braced following guidelines from the MSE wall system vendor
5.11	Panels have been placed with ¾ in. wide vertical joints separating them per INDOT standard specifications
5.12	Appropriate joint spacers using materials consistent with MSE wall shop drawings have been used
5.13	Adjacent panels within the initial course have been clamped together following recommendations from the MSE wall system vendor
5.14	Panels have been placed within a ¾ in. in 10 ft horizontal alignment tolerance
5.15	Any panels deemed to be out-of-tolerance have been properly adjusted following recommendations from the MSE wall system vendor
5.16	Panel joints (both horizontal and vertical) have been covered with MSE wall system vendor supplied geotextile fabric and adhesive
5.17	Geotextile fabric has been affixed to the backside of wall panels as detailed in the shop drawings
5.18	Structure backfill backfilling operations are neither damaging nor disturbing pre-cast facing panels
5.19	Pre-cast facing panels that are damaged or misaligned during backfilling are either corrected or removed and replaced, as directed by the Engineer
5.20	Appropriate compaction equipment is being used to compact the structure backfill, i.e., full-sized rollers are not compacting within 3 ft of the pre- cast facing panels
5.21	Loose lifts of structure backfill do not exceed 8 in. thick where full-sized vibratory rollers will be used for compaction operations
5.22	Loose lifts of structure backfill do not exceed 5 in. thick where lightweight compactors (e.g., vibratory plate compactors) will be used for compaction operations
5.23	Compaction operations using full-sized vibratory rollers consist of four passes in vibratory mode followed by one pass in static mode
5.24	Compaction operations using lightweight compactors consist of no less than 5 passes
5.25	Either DCP testing (ISS 203.23) or sand-cone testing (ISS 203.24) has been selected for structure backfill compaction acceptance
5.26	DCP blow counts on the compacted structure backfill meet or exceed minimum criteria per ISS 203.23
5.27	Compacted structure backfill dry densities meet or exceed 95% relative compaction
5.28	Structure backfill displacements and rutting are repaired before placing subsequent lifts
5.29	Structure backfill placement follows recommendations from the MSE wall system vendor
5.30	Unobstructed soil reinforcements are placed normal (perpendicular) to the MSE wall facing
5.31	Soil reinforcements are placed around vertical and horizontal obstructions in accordance with the submitted MSE wall shop drawings, i.e., skewed

5.32	Skewed soil reinforcements are not skewed more than 15°
5.33	Soil reinforcements have not been cut or altered unless approved by the Engineer
5.34	The approved amount of additional soil reinforcements has been provided to compensate for Engineer approved cut or altered soil reinforcements
5.35	Cut or altered soil reinforcements have been covered with a galvanized paint or coal tar
5.36	Soil reinforcement have been connected to pre-cast facing panels as detailed in the MSE wall shop drawings
5.37	Soil reinforcements have not been damaged during backfilling operations
5.38	Structure backfill over soil reinforcements has been placed and compacted in accordance with ISS 731.11
6	**MSE Wall Installation: Placement of Subsequent Panel Courses Checklist**
6.1	Bearing pads have been placed at each horizontal panel joint in accordance with the MSE wall shop drawings
6.2	Subsequent panel courses are placed following recommendations from the MSE wall system vendor
6.3	Locations for different pre-cast panel types (size and texture) are in accordance with MSE wall shop drawings
6.4	Subsequent panel courses and soil reinforcements have been placed and backfilled in accordance with items 5.8 to 5.38 of this checklist
6.5	Before concluding work for the day, the Contractor has graded the structure backfill away from the MSE wall facing
7	**MSE Wall Installation: Internal drain, wall embedment, removing wooden wedges Checklist**
7.1	The internal drainage system is constructed as detailed on the road/bridge plans and in accordance with INDOT standard specifications
7.2	Only qualified materials (e.g., geotextiles) have been used for internal drainage system pipe and geotextiles
7.3	The wall embedment has been placed in accordance with the road/bridge plans and with guidelines from the MSE wall system vendor
7.4	Wooden wedges used for maintaining panel batter are being removed following guidelines from the MSE wall system vendor
8	**MSE Wall Installation: Checking Panel Alignments and Joint Spacing Checklist**
8.1	The Contractor is regularly checking and recording panel alignments— plumb, vertical, and horizontal—and joint spacings
8.2	Panel alignments (plumb, vertical alignment, and horizontal alignment) do not exceed the tolerances specified in ISS 731.09
9	**MSE Wall Installation: Final Panel Course and Coping Checklist**
9.1	The tops of panels constituting the final panel course are flat and level prior to placing coping
9.2	Pre-cast coping sections are placed atop the final course of panels where appropriate
9.3	Cast-in-place coping is placed atop the final course of panels where pre- cast coping cannot be accommodated

Source: [15]

A-4: Quality data items required for MSE walls in O&M stage

1	**MSE Wall O&M: Maintenance Inspection Checklist**
1.1	Drainage issues
1.1.1	Stains on wall panels
1.1.2	Open joints/cracks on the roadway surface
1.1.3	Open longitudinal joint on the roadway surface
1.1.4	Presence or absence of drainage provisions
1.1.5	Washed out backfill material
1.1.6	Washed out backfill material adjacent to the wall or riprap
1.1.7	Washed out backfill material through longitudinal joints at abutments
1.1.8	Voids
1.2	Loss of backfill
1.2.1	Mounds of backfill material at the panel joints
1.3	Disjointed panels
1.3.1	Wider panel joints provide clue
1.3.2	Filter fabric could be seen from the joint opening
1.3.3	Mounds of backfill material
1.3.4	Lack of connection between wall panels and reinforcement
1.3.5	Lack of adequate friction due to backfill washout
1.4	Pavement distress
1.4.1	Parallel cracks with settlement (flexible pavements)
1.4.2	Longitudinal joint separation
1.4.3	Joint cracks could get bigger and bigger over time
1.5	Traffic rails
1.5.1	Misalignment of railing

Source: [16]