

Research Article

Digital Transformation of Concrete Quality Management: A Systematic Review of Advances and Challenges

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Abstract

Concrete quality management is essential for ensuring the structural safety, durability, and long-term performance of concrete structures. Traditionally, quality assurance (QA) and quality control (QC) of concrete rely on periodic inspections, laboratory testing, and manual documentation. However, these conventional methods often provide delayed feedback and limited insight into in-situ concrete behaviour, particularly for time-sensitive parameters such as compressive strength development and early-age plastic shrinkage cracking. This study aims to examine how Information and Communication Technologies (ICTs) are transforming concrete quality monitoring and management by synthesising existing research on QA/QC practices, assessing technological contributions to monitoring compressive strength and plastic shrinkage, and identifying barriers to ICT adoption in practice. A mixed-methods systematic literature review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency and methodological rigour. A structured search strategy was applied across major scientific databases, guided by predefined inclusion and exclusion criteria. From an initial pool of 2,426 studies retrieved from multiple academic databases, successive filtering based on publication year (2014-2025), subject area, and thematic relevance to concrete quality management reduced the number of eligible studies to 425. Following title, abstract, and full-text screening, 69 articles met the inclusion criteria and were analysed using both bibliometric and content analysis methods to identify key research trends, themes, and developments in concrete quality management. Findings show that IoT-based sensing systems, when integrated with Building Information Modelling (BIM) and Digital Twin (DT) platforms, significantly improve the capacity for real-time monitoring of temperature, humidity, and curing conditions, thereby improving the management of early-age strength development and reducing the risk of cracking. These technologies strengthen QA and QC processes through proactive quality management, early detection of adverse conditions, and enhanced decision-making during construction. Despite these benefits, adoption remains limited due to data reliability issues, system interoperability challenges, skill gaps, organisational readiness, and the absence of standardised regulatory frameworks. The study recommends further validation of ICT tools under real construction conditions, development of standardised sensor calibration and data integration frameworks, and capacity-building initiatives to support broader implementation of ICT-enabled concrete quality monitoring systems.

Keywords

Compressive Strength, Plastic Shrinkage, Building Information Modelling, Concrete Quality Management, Digital Twin, Quality Assurance, Quality Control

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1. Introduction

Concrete quality management plays a critical role in ensuring structural safety, durability, and long-term performance of constructed concrete structures [1]. It traditionally revolves around quality assurance (QA) and quality control (QC) processes, where QA focuses on preventive measures such as material selection, mix design, and production planning, while QC emphasises inspection, testing, and verification during and after construction [2, 3]. Conventional QA/QC practices in concrete construction rely heavily on periodic inspections, laboratory-based testing, and manual documentation, which often provide delayed feedback and limited visibility into in-situ concrete behaviour [4]. These limitations are particularly pronounced for time-sensitive quality parameters such as compressive strength development and early-age plastic shrinkage cracking, where delayed detection restricts timely intervention and increases the risk of defects and long-term performance loss [1-4].

Recent advances in Information and Communication Technologies (ICT) have begun to transform concrete quality management by addressing several shortcomings of traditional QA/QC approaches [4]. ICT-enabled systems support a shift from reactive, inspection-based practices toward continuous, data-driven monitoring frameworks capable of capturing concrete behaviour in real time [4, 5]. The integration of Internet of Things (IoT) sensing technologies with Building Information Modelling (BIM) and DT platforms enables real-time tracking of key parameters such as concrete temperature, humidity, curing conditions, and early-age strength development [4, 5]. These capabilities enhance QA/QC functions by providing early warnings of unfavourable conditions, supporting informed decision-making during construction, and reducing quality-related risks associated with insufficient strength gain or plastic shrinkage cracking [6-8].

Beyond standalone sensing applications, emerging ICT-enabled concrete quality management systems increasingly combine sensor-based data acquisition with predictive analytics and model-driven digital platforms [4-8]. IoT-based monitoring supports automated estimation of compressive strength development and environmental exposure effects, reducing reliance on labour-intensive manual testing and subjective site assessments traditionally associated with QA/QC activities [4, 5]. When these data streams are integrated into BIM and DT environments, they enable dynamic visualisation of concrete quality parameters, facilitate remote assessment by project stakeholders, and strengthen the linkage between QA planning assumptions and QC performance verification throughout the concrete lifecycle [8, 9].

Despite these technological advancements, the adoption of ICT-based solutions for concrete quality management remains uneven and largely experimental [6]. Existing studies frequently focus on isolated tools, specific technologies, or laboratory-scale validation, with limited synthesis of how QA processes, QC activities, and ICT-enabled monitoring systems interact to support comprehensive concrete quality management

in real construction contexts [10-12]. Furthermore, adoption is constrained by persistent challenges, including data reliability under site conditions, system integration and interoperability limitations, skill and organisational readiness gaps, and the absence of clear regulatory and standardisation frameworks [6, 10-12].

Consequently, there is a need for a systematic and structured synthesis of existing research that examines concrete quality management through the combined lenses of QA, QC, ICT-enabled monitoring and management, and adoption barriers. Such synthesis is essential to clarify the contribution of emerging digital tools to monitoring and management of concrete quality parameters such as compressive strength development and early-age plastic shrinkage cracking, and to guide future development of reliable, scalable, and practice-oriented concrete quality management systems.

1.1. Research Significance

This systematic review provides a structured and integrated synthesis of concrete QA/QC as well as recent advances in ICT-enabled concrete quality management, with particular emphasis on compressive strength development and early-age plastic shrinkage cracking. The review clarifies how sensor-based monitoring, BIM integration, and DT frameworks support and enhance both QA and QC functions across the concrete lifecycle, from production planning to post-placement performance assessment. In addition, the review consolidates fragmented evidence on technical, organisational, and regulatory barriers that constrain the practical implementation of ICT-enabled quality management systems under real construction conditions. The findings offer a merged knowledge base for researchers, practitioners, and policymakers, supporting informed decision-making and guiding future research, system development, and industry adoption of data-driven concrete quality management approaches.

1.2. Research Objectives and Questions

This study evaluates ICT-based tools for monitoring concrete compressive strength and early-age plastic shrinkage cracking, identifies barriers to their adoption, and outlines future research directions for ICT-enabled concrete quality monitoring systems. Based on this aim, the following research objectives were formulated:

- 1) To examine existing quality assurance and quality control practices in concrete construction across the concrete lifecycle.
- 2) To synthesise how ICT-enabled approaches support quality assurance and quality control processes related to compressive strength development and early-age cracking across the concrete lifecycle.
- 3) To critically analyse the technological, organisational,

and regulatory barriers limiting the adoption of ICT-based solutions for monitoring compressive strength and early-age plastic shrinkage cracking.

- 4) To propose future research directions for advancing ICT-enabled concrete quality monitoring systems across the concrete lifecycle.

To address the objectives of this systematic review and to synthesise existing evidence, the following research questions are formulated:

- 1) What quality assurance and quality control practices are currently employed to manage overall concrete quality across different stages of the construction lifecycle?
- 2) How do ICT-enabled approaches contribute to quality assurance and quality control of concrete with respect to strength development and early-age cracking prevention?
- 3) What barriers hinder the adoption and effective implementation of ICT-based solutions for monitoring compressive strength and early-age plastic shrinkage cracking in concrete quality management?
- 4) What future research directions can advance the integration of ICT-enabled systems for concrete quality monitoring across the concrete lifecycle?

2. Materials and Methods

This study adopts a systematic literature review methodology guided by the Preferred Reporting Items for Systematic

Reviews and Meta-Analyses (PRISMA) framework to ensure transparency, completeness, and methodological rigor. PRISMA is a reporting guideline developed to improve the clarity and reliability of systematic reviews and meta-analyses by clearly explaining why a review was conducted, how it was carried out, and what findings were obtained [13]. Originally introduced in 2009 and subsequently updated, PRISMA provides a structured approach that enables readers to assess the validity and reproducibility of the review process [13].

A mixed-methods approach was employed, combining quantitative bibliometric analysis with qualitative content analysis to identify research trends, technological developments, and adoption barriers. The review considers studies published between 2014 and 2025, a period during which digital technologies began to gain significant traction in construction and concrete quality management research. Figure 1 illustrates the distribution of the retrieved articles from 2014 to 2025.

Although the study used the PRISMA framework, the review protocol was not registered in any formal review registry. However, the review objectives, inclusion and exclusion criteria, and analysis procedures were predefined and consistently followed throughout the study to ensure methodological rigor and transparency. The detailed methodological steps followed in this systematic review are presented in the subsequent sections.

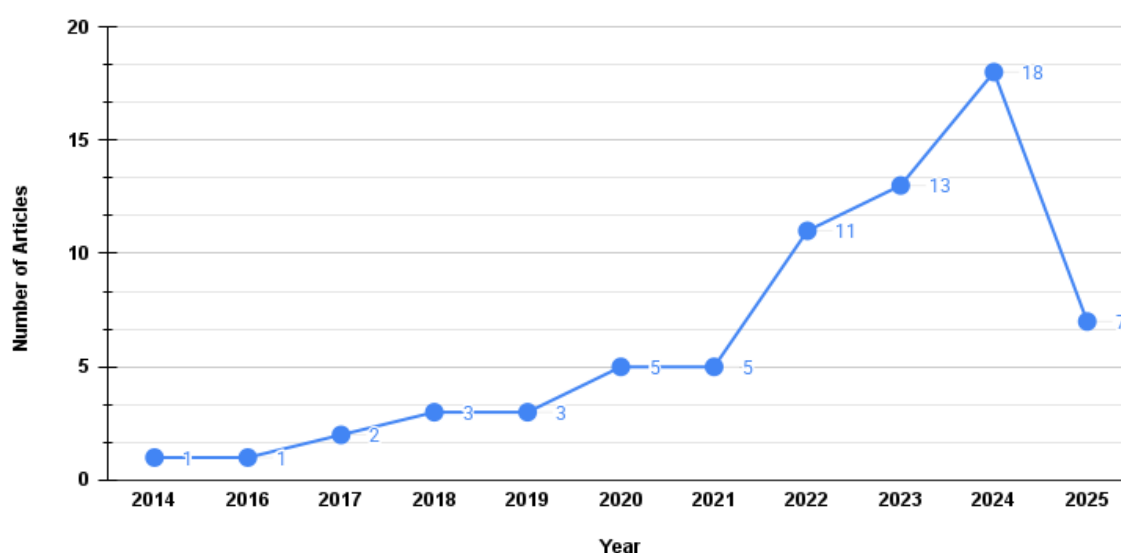


Figure 1. Distribution of retrieved articles from 2014 to 2025.

Data Sources and Search Strategy

The selection of relevant literature is a critical step in any systematic review, as it directly influences the quality, reliability, and validity of the findings [14, 15]. Accordingly, this study adopted a structured and reproducible literature search strategy in line with the PRISMA framework, which comprises three main stages: literature retrieval, literature filtering,

and literature classification [9].

A comprehensive literature search was conducted using leading scientific databases and publishers commonly adopted in engineering and construction research, including MDPI, Springer Link, ASCE Library, Science Direct, and Taylor & Francis and many others as presented in Figure 2.

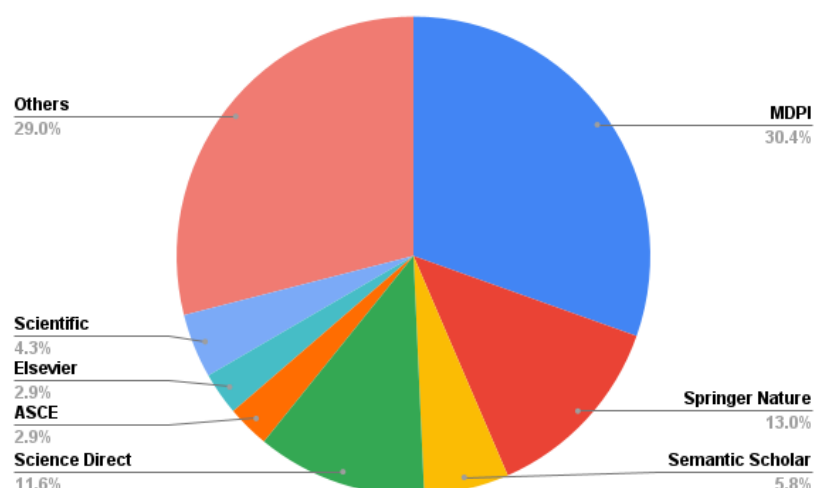


Figure 2. Distribution of Search Databases/publishers.

These databases and publishers were selected to ensure broad coverage of peer-reviewed journal articles and conference proceedings relevant to concrete quality management and digital transformation in construction. To provide more

clarity on the sources of the reviewed literature, Table 1 summarises the number of articles retrieved from each individual journal.

Table 1. Distribution of Retrieved Articles by Journal Source.

Journal	Number of Retrieved Articles
10th Austroads Bridge Conference	1
Acta IMEKO	1
Advances in Civil Engineering	1
Advances in Geotechnics and Structural Engineering	1
AI in civil engineering	1
AIMS Materials Science	1
Ain Shams Engineering Journal,	1
American Journal of Science, Engineering and Technology	1
Applied Sciences	2
Arabian Journal for Science and Engineering	1
Automation in Construction	1
Buildings	6
Case Studies in Construction Materials	1
Cement and Concrete Composites	1
Civil Eng	1
Concrete international	1
Construction and Building Materials	3
CUNY Academic works.	1
Developments in the Built Environment	1
Digital Twin	1

Journal	Number of Retrieved Articles
Discover Civil Engineering	1
Engineering Sciences	1
Eurasian Physical Technical Journal	1
Heliyon.	1
Innovative infrastructure solutions	1
International Journal of Concrete Structures and Materials	1
International Journal of Engineering Research in Africa	1
International Journal of Technical & Scientific Research Engineering	1
Journal of building pathology and rehabilitation	1
Journal of Civil Engineering and Management	1
Journal of Construction Engineering	1
Journal of Engineering and Applied Science	1
Journal of Information Technology in Construction	1
Journal of infrastructure systems	1
Journal of King Saud University - Engineering Sciences	1
Materials	4
Materials and Structures	1
Materials Sciences and Applications	1
Nigerian Journal of Engineering	1
Nordic Concrete Research	1
Open Journal of Civil Engineering	1
Others	3
Proceedings in civil engineering	1
Sensors	5
SSRN Electronic Journal.	1
Structural Health Monitoring	1
Sustainability	3
The Fifteenth International Conference on Construction in the 21st Century	1
UNIZIK Journal of Engineering and Applied Sciences	1
World Journal of Advanced Engineering Technology and Sciences	1

Step 1: Literature Retrieval

In the first stage, relevant studies were retrieved using a structured and reproducible search strategy applied to the title, abstract, and keyword fields of selected academic databases. The search strategy was developed using Boolean operators ('AND', 'OR') to ensure comprehensive coverage of the research domain while maintaining relevance.

The search strings included the following terms:

- 1) "concrete quality management" OR "concrete quality

control" OR "concrete quality assurance"

- 2) "Building Information Modelling" OR BIM OR "Internet of Things" OR IoT OR "machine learning" OR "artificial intelligence" OR "digital twin"
- 3) "ICT adoption in concrete quality management" OR "technology adoption" OR "barriers" OR "challenges"
- 4) "construction industry" OR "concrete quality management"

The search strategy was applied across multiple academic

databases, including MDPI, Springer, ScienceDirect, Taylor & Francis, and American Society of Civil Engineers journals. The initial search retrieved approximately 2,426 publications. To improve relevance and consistency, the studies were subsequently filtered according to publication year, subject area, and thematic relevance.

Firstly, the retrieved studies were limited to publications between 2014 and 2025, reducing the number of articles from 2,426 to 1,800. The selected time period was chosen to capture recent developments in digital construction technologies and their application to concrete quality management. Secondly, subject area filtering was applied to retain studies within civil engineering, construction management, and material science disciplines. This process further reduced the retrieved studies to 1,400 publications. A further thematic filtering stage was then conducted focusing specifically on studies related to concrete quality management and ICT-enabled quality assurance systems, reducing the database to 425 studies for detailed

screening.

Step 2: Literature Filtering

The second stage involved a systematic screening and filtering process in which duplicate records were removed and titles and abstracts were reviewed to assess relevance. Studies that did not directly address concrete quality management or the application of ICT-based solutions in construction quality management were excluded. A more detailed examination of abstracts and conclusions was subsequently conducted to identify studies explicitly focusing on technological advancements, implementation strategies, barriers, and challenges associated with digital concrete quality management systems. Following the screening and eligibility assessment process, 69 studies were retained for full-text review, systematic review synthesis, and bibliometric quantitative analysis. Figure 3 illustrates the PRISMA flow diagram adopted for the study selection and screening process.

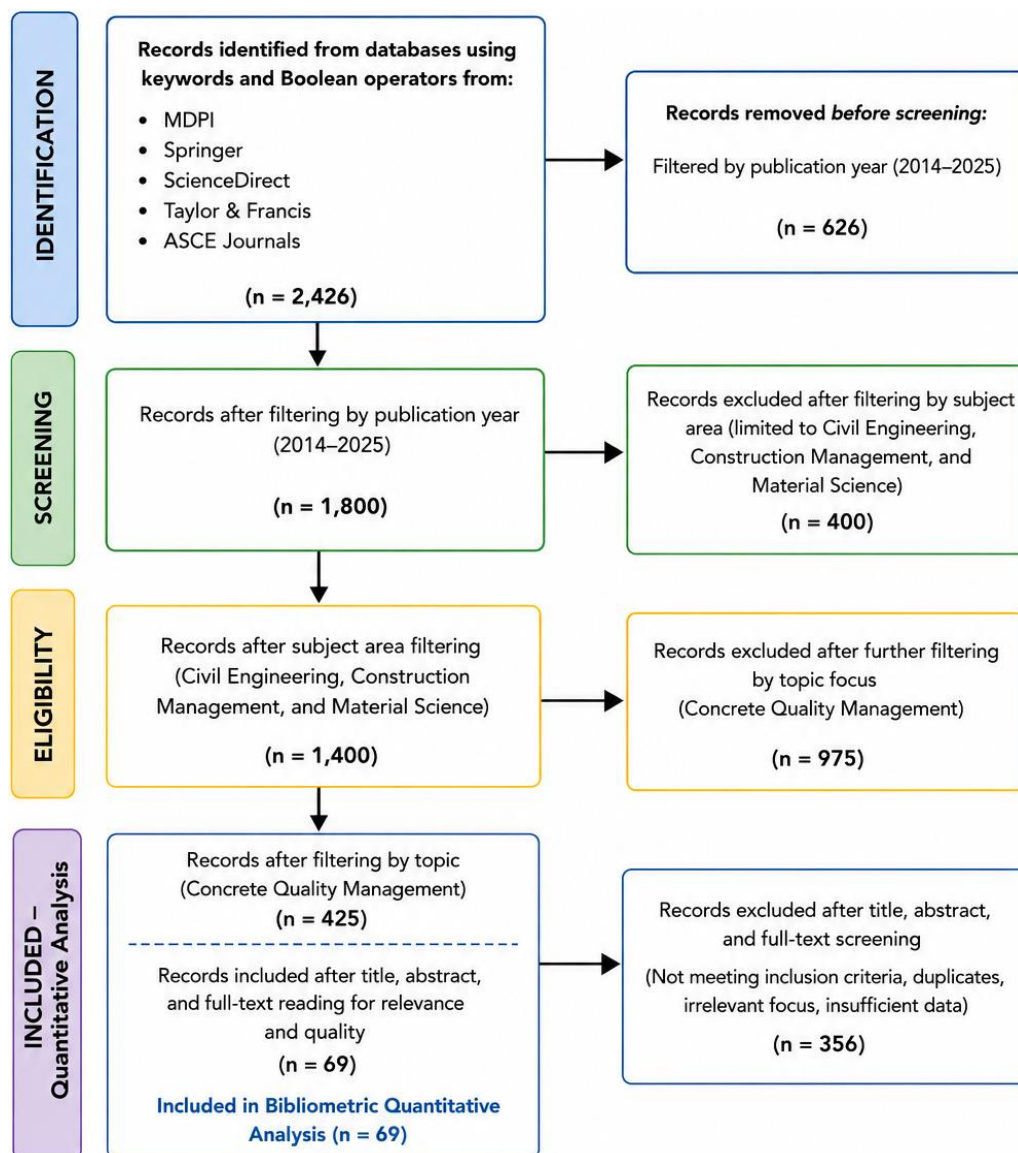


Figure 3. PRISMA flow diagram for bibliometric quantitative analysis.

Step 3: Literature Classification

In the final stage, the selected studies were systematically classified based on their thematic focus. The literature was categorised into three main domains:

- 1) concrete quality assurance and control practices in construction,
- 2) advances in concrete quality management enabled by ICTs, and
- 3) challenges and barriers to ICT adoption in concrete quality management.

Further classification was carried out according to the specific technologies investigated, including BIM, IoT, machine learning, artificial intelligence, and DT technologies. This classification enabled a structured synthesis of the existing body of knowledge and informed the subsequent analysis and discussion of research trends and gaps.

2.1. Assessment of Bias and Study Quality

To minimise bias and ensure the reliability of the review findings, predefined inclusion and exclusion criteria were consistently applied throughout the screening process.

Publication bias was reduced through the use of multiple academic databases, including MDPI, Springer, ScienceDirect, Taylor & Francis, and American Society of Civil Engineers journals. Studies were further assessed based on relevance, methodological clarity, and contribution to concrete quality management and digital construction technologies.

2.2. Inclusion and Exclusion Criteria

To ensure relevance and consistency, explicit inclusion and exclusion criteria were applied during the screening process. Studies were included if they:

- 1) Focused on concrete quality management, quality control, or quality assurance;
- 2) Explored barriers to ICT adoption in concrete quality management;
- 3) Investigated the use of digital technologies such as IoT sensors, BIM, machine learning, data analytics, or digital twins;
- 4) Were published in peer-reviewed journals or conference proceedings;
- 5) Were written in English;
- 6) Fell within the 2014 - 2025 publication period.

Studies were excluded if they:

- 1) Addressed digital technologies unrelated to concrete or construction quality management;
- 2) Examined ICT adoption in other construction-related

areas such as safety or estimation;

- 3) Were non-peer-reviewed sources, including editorials, or theses;
- 4) Belonged to disciplines unrelated to the built environment, such as medicine, chemistry, or the social sciences.

2.3. Data Extraction

Following the screening process, the eligible studies were subjected to a structured data extraction and content analysis procedure. The extracted data were systematically reviewed and synthesised to identify key themes, research trends, technological advancements, and challenges related to concrete quality management. This process enabled the integration of findings from the selected studies and provided the basis for the thematic discussion presented in this review.

3. Findings

3.1. Bibliometric Analysis

A total of 275 authors were identified across the 69 included studies and were analysed using VOSviewer to generate a co-authorship network. The resulting network revealed 20 distinct clusters, each comprising approximately 5 to 10 authors, indicating multiple research groupings within the field of concrete quality management. The clusters were largely centred on digital approaches to concrete quality assurance and control, while smaller clusters, comprising approximately 1 to 5 authors, also emerged. These more specialised groups focused on niche areas such as concrete material selection, production, transport, placement, and post-placement quality assurance and control. [Figure 4](#) presents the co-authorship network.

3.2. Concrete Quality Assurance and Quality Control

Concrete quality assurance (QA) refers to the planned and preventive measures implemented throughout material selection, batching, production, and placement processes to ensure that concrete achieves the required strength, durability, and performance standards [16-19]. To enhance clarity and synthesis, the findings on concrete quality assurance (QA) are summarised in [Table 2](#). The table presents QA stages, key focus areas, main contributions, and implications from the reviewed studies.

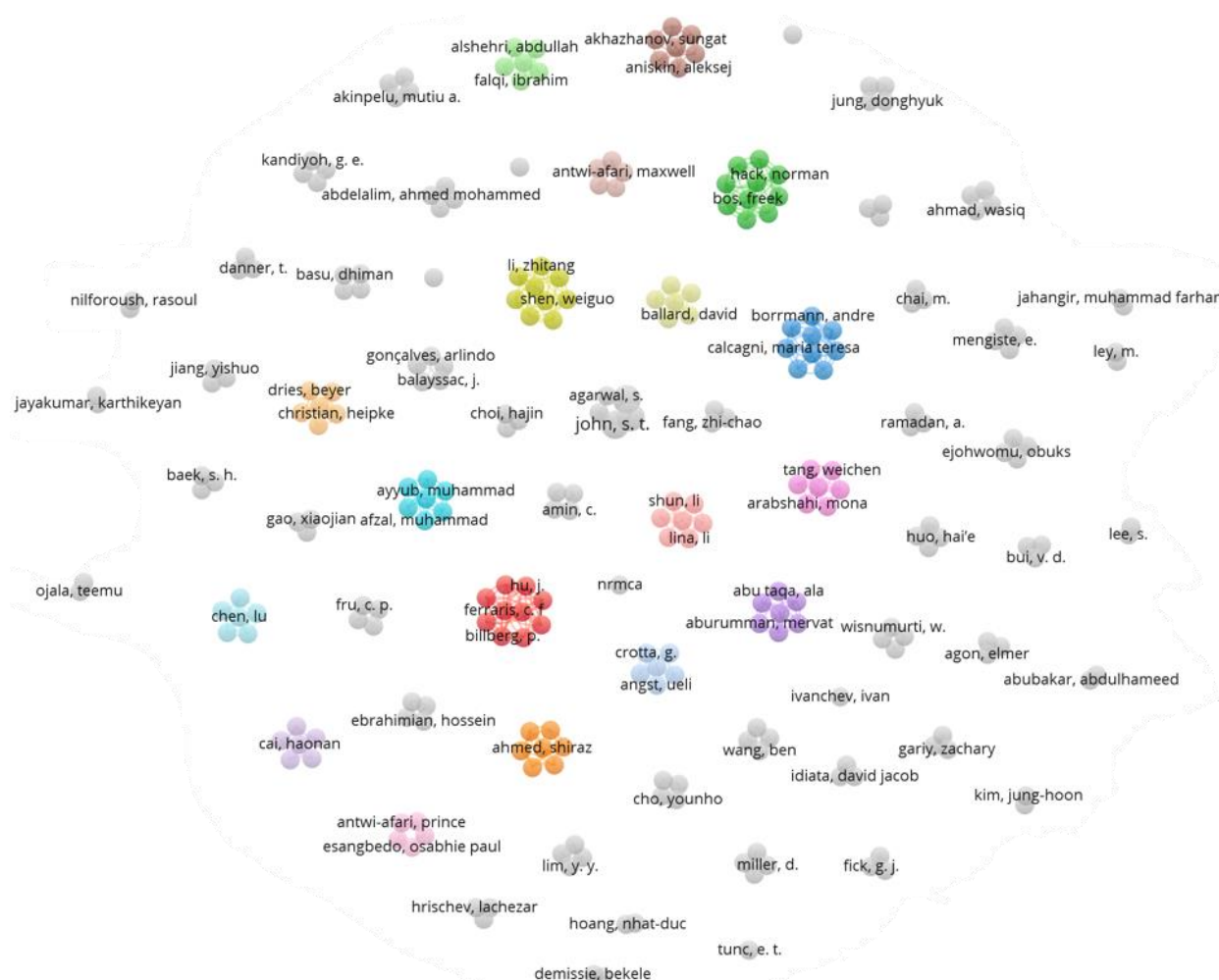


Figure 4. Network and clusters of co-authors of concrete quality management research.

Table 2. Concrete Quality Assurance (QA) Findings.

QA Stage	Key Focus Area	Key Author(s)	Main Findings	QA Implication
Selection of cementitious materials	Cement composition and strength development	[17, 20, 24]	Selection of cementitious materials improves compressive strength and reduces permeability by >50%	Material selection directly enhances durability.
Water quality verification	Mixing water properties	[18, 25, 26]	Hard/impure water reduces strength; pH, conductivity affect hydration of cement.	Water quality must be controlled as a QA input parameter.
Fine aggregates selection	Sand grading and impurities	[27-29]	Angularity and silt content significantly affect strength (up to 44% variation).	Strict aggregate quality control is essential in QA.
Chemical admixtures selection	Workability and durability enhancement.	[26, 30]	Admixtures improve strength but are highly sensitive to mix conditions.	Admixture selection must be context-specific.
Mix design verification	Trial mixes and calibration.	[31, 32]	Site-specific trial mixes reduce variability.	QA must include pre-production verification.
Production control	Water-cement ratio and batching accuracy.	[2, 33-35]	Real-time monitoring improves mix consistency.	QA must integrate digital monitoring tools.
Workmanship	Placement and compaction quality.	[36-38]	Poor vibration causes segregation and strength loss	Controlled workmanship is a key QA factor.

While quality assurance focuses on prevention, quality control (QC) in concrete construction encompasses systematic pre-placement, in-process, and post-placement inspections designed to ensure compliance with design, safety, and durability requirements [16]. QC involves sampling, testing, inspection, and corrective actions to maintain continuous oversight

of production and placement activities, supported by formal inspection procedures implemented by contractors [16, 21]. Table 3 presents the key QC stages, focus areas, methods, findings, and implications identified in the reviewed literature.

Table 3. Concrete Quality Control (QC) Findings.

QC Stage	Key Focus Area	Key Authors	Methods/Tools	Key Findings	QC Implication
Material testing	Pre-production verification	[16-18, 21-23, 32, 39, 40, 43]	Sieve analysis, testing of mixing water and admixtures, trial mixes.	Variability in supplier specifications necessitates routine material testing.	Mandatory pre-testing required.
Reinforcement & formwork inspection	Pre-placement inspection	[19, 41, 44]	3D Point Cloud Data Capturing	Automation improves accuracy	Digital inspection reduces human error.
Placement control	Vibration & compaction monitoring.	[42]	Field monitoring.	Poor vibration increases permeability.	QC must control vibration and compaction parameters.
Fresh concrete testing	Slump/workability	[52-56]	Slump test, stereovision systems.	Manual slump testing is inconsistent.	Automated slump monitoring improves reliability
Non-destructive testing (NDT)	Post-placement inspection	[45-51]	Ultrasonic, rebound hammer, thermography, Finite Element Analysis, Image processing	NDT makes early defect detection possible.	Post-placement QC uses non-destructive inspections to detect defects and verify concrete durability and performance.
Mechanical testing	Strength verification	[20, 57-61]	Compression, tensile, permeability tests	Mechanical testing verifies compressive, tensile, and flexural strength, while additional durability tests assess long-term concrete performance under aggressive conditions.	Mechanical testing verifies structural compliance and assesses the long-term durability performance of concrete.

Overall, while conventional QA and QC frameworks provide structured oversight of concrete quality, their effectiveness is often constrained by labour-intensive inspections, delayed feedback, and fragmented data across construction stages. These limitations have driven increasing interest in Information and Communication Technologies (ICT) as a means of enhancing real-time monitoring, integration, and decision-making in concrete quality management.

3.3. Emerging Technologies for Concrete Quality Management

Advancements in emerging digital technologies have the potential to equip engineers and other project stakeholders with tools to enhance quality in the construction industry [6]. These emerging technologies can help address issues in the construction quality inspection process such as intelligent

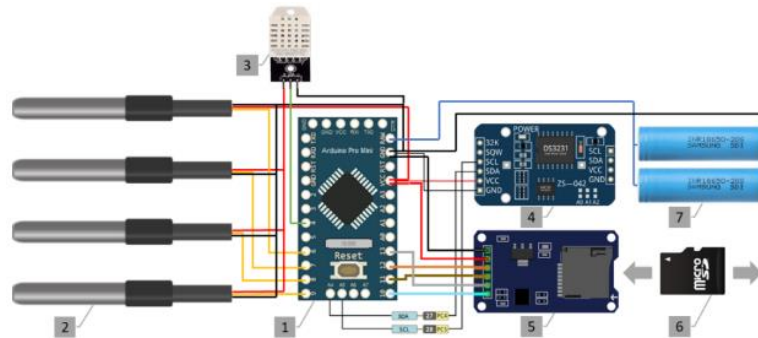
component positioning, data replication as well as inadequate feedback during rework and maintenance [7]. BIM, powered by IoT-based data, represents a significant advancement in the application of ICT technologies for real-time monitoring and management of concrete quality [8]. By integrating IoT-based data with BIM, the development of a DT allows stakeholders to remotely access early-age concrete strength parameters [8]. This continuous connectivity between various components and the internet enables an IoT system to automate real-time monitoring of factors like concrete internal temperature, aiding in the estimation of early-age strength gain [5].

Additionally, for speedy and accurate real-time monitoring of plastic shrinkage cracking, an IoT-backed system can be used to remotely monitor the process, reducing the need for extensive human resources and manual effort [4].

A couple of systems have been proposed by various researchers around the world with the capability to provide real-

time monitoring of both early age strength and plastic shrinkage cracking. Utepov et al. [69] developed a Multi Sensory Device (MSD) that monitored concrete curing conditions such as curing temperature, ambient temperature and relative humidity. The system consisted of an Arduino Pro Mini micro-controller (1), four waterproof DS18B20 temperature sensors

(2), a DHT11 ambient temperature and humidity module (3), a DS3231 real-time clock module (4), a micro-SD card module (5) with a card (6), and two 3.7V INR18650-20S Li-ion batteries connected in parallel (7), as shown in Figure 5.

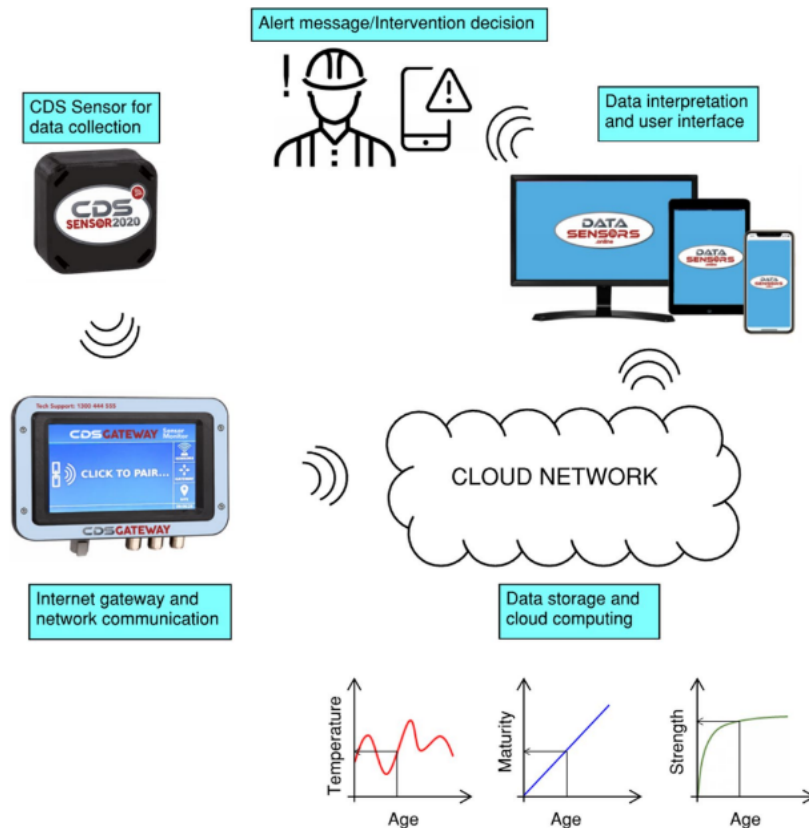


Source: [69]

Figure 5. Architecture of proposed MSD.

The system developed by Utepov et al. [69] monitored curing temperature, ambient temperature, and relative humidity, with the data stored on a micro SD card for later retrieval. To assess the influence of these parameters, manual calculations

were performed and the results were compared with traditional cube strength tests. The variation between the estimated values and the actual crushing test results from the control experiment was minimal.

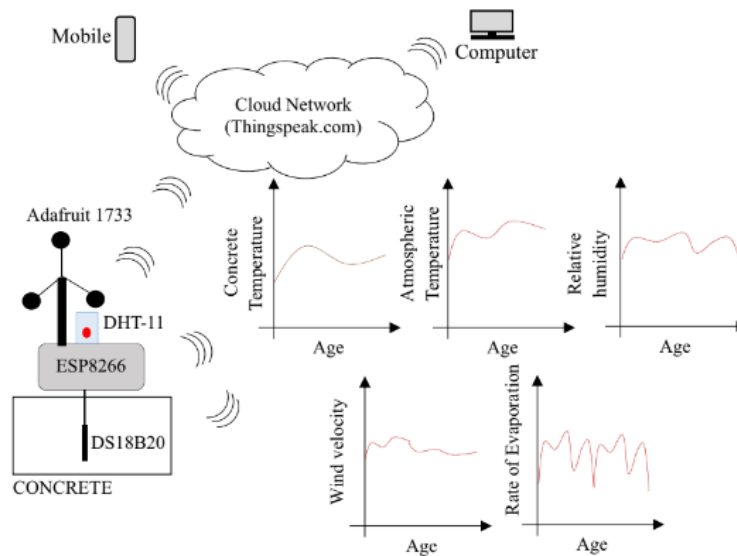


Source: [5].

Figure 6. IoT framework of the developed real-time monitoring system.

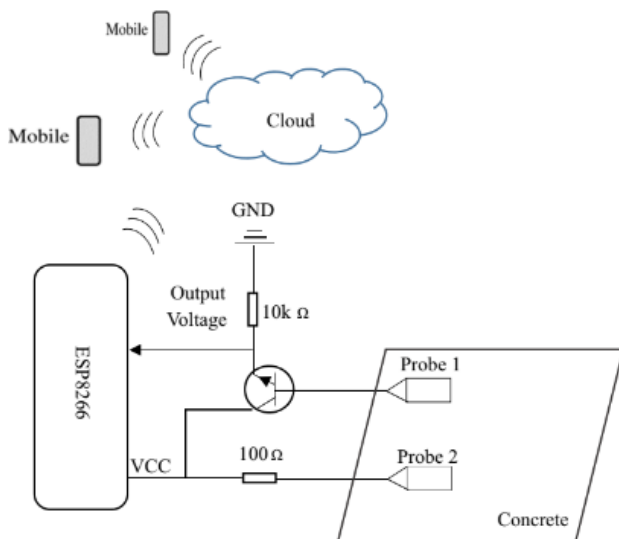
Miller et al [5] further advanced the approach and introduced an IoT-based system shown in Figure 6. The system was designed to automate the real-time monitoring of concrete's short-term strength development. The system featured a gateway, sensors, and a LoRa antenna. It was tested in the lab by calibrating strength-age relationships for three different concrete mixes. These maturity relationships were incorporated into the system to accurately estimate early-stage compressive strength. The system effectively predicted compressive strength and transmitted data to a cloud-based portal for remote access.

Plastic shrinkage cracking, a significant early-age defect in concrete, can now be predicted through IoT-enabled systems that monitor environmental and material conditions. John et al [4] introduced two complementary systems for monitoring fresh concrete: one predicting evaporation rates and the other detecting real-time bleed water presence. System 1 predicted evaporation rates by measuring atmospheric temperature, concrete temperature, relative humidity, and wind velocity, while System 2 detected bleed water on the concrete surface in real time. Schematic representations of both systems are shown in Figures 7 and 8 respectively.



Source: [4].

Figure 7. Schematic representation of proposed System 1.



Source: [4].

Figure 8. Schematic representation of proposed System 2.

Both systems monitored plastic shrinkage from pouring until the final set. Data from the sensors were processed by an ESP8266 Wi-Fi microcontroller and sent to the cloud via a Transmission Control Protocol (TCP)/ Internet Protocol (IP) connection. ThingSpeak.com was used as the cloud platform, with data analysed using MATLAB tools integrated into ThingSpeak.

While Utepov et al. [69] laid the groundwork for real-time monitoring by focusing on environmental conditions, Miller et al. [5] advanced this by integrating cloud-based IoT solutions for compressive strength prediction. Similarly, John et al. [4] introduced crucial advancements in predicting plastic shrinkage cracking, which remains a challenge in concrete quality management. These systems collectively represent the future of automated, data-driven concrete monitoring.

BIM powered by IoT-based data serves as an innovative advancement in the application of ICT technologies for real-time monitoring and management of concrete quality. Integrating IoT-based data with BIM enables the development of a DT, allowing project stakeholders to remotely access early-age concrete strength parameters and track real-time compressive

strength data, which supports informed decision-making throughout the construction cycle [8]. While BIM offers technologies, processes, and data schemas to represent building components and systems, DT complements this by integrating real-time data from cyber-physical systems, allowing for live asset monitoring and improved decision-making [9].

The integration of BIM and DT technologies has become a focal point for researchers aiming to enhance concrete quality management in recent years. A very notable example of this BIM-DT integration for real time monitoring and management of concrete quality is provided by Iqbal et al. [8], who introduced a novel framework for real-time monitoring of concrete strength using IoT technology. The framework is structured into four main tiers: the sensing layer, network layer, server layer, and application layer. The sensing layer captures crucial data related to concrete core temperature, ambient temperature, and humidity, which are key for estimating concrete strength. This data is transmitted via the network layer to the server layer, where it is stored in a Google Firebase database in JSON format. A Windows-based application retrieved the data from the server, calculated the concrete strength, and exported it to a local file, which is integrated with the BIM application Navisworks. This allowed for the real-time display of strength parameters for each structural component. Automation ensured that new data was continuously updated and displayed in Navisworks. The framework

used both wired and wireless networks to ensure efficient communication between components. The server layer processed the data, while the application layer used ASTM standards to calculate concrete strength.

According to Iqbal et al. [8] once data was imported into the BIM model via the local Excel file, Navisworks' "Appearance Profiler" visualised the concrete's compressive strength by colour-coding objects based on strength values. This process aided in tracking concrete strength progression and automated scheduling when sufficient strength was achieved. Additionally, Iqbal et al. [8] highlighted that Navisworks' Data-Tools feature connected sensor data with Revit models, transforming the system into a DT. This integration allowed for near real-time 3D visualisation of concrete compressive strength, enhancing decision-making during construction.

3.4. Barriers to ICT Adoption in Concrete Quality Management

Despite the potential of ICT to enhance concrete quality management, its adoption remains limited globally, particularly due to technical, organizational, and contextual barriers. A summary of these barriers is presented in Table 4, with further discussion provided in the subsequent sections.

Table 4. Summary of Barriers to ICT Adoption in Concrete Quality Management.

Barrier Category	Key Barriers	Authors
Digital Data Collection & Processing	Limited field validation, unreliable sensor data in real conditions, environmental interference, high computational demands, and challenges in real-time data fusion and prediction.	[4, 6, 10, 58, 62, 70, 72].
System Integration & Information Flow	Fragmented systems, poor interoperability, inconsistent sensor protocols, weak feedback loops, limited cloud integration into workflows, and data security/cost constraints.	[4, 6, 10, 63, 64, 67, 72].
Skill & Organisational Readiness	Limited digital skills, low technical readiness, reliance on manual methods, and insufficient ability to interpret real-time IoT data.	[4, 6, 68, 71, 72].
Policy & Regulatory Gaps	Lack of standards, certification systems, governance frameworks, and construction codes for ICT and IoT adoption in construction.	[10-12, 65, 66].
Overall Barrier	ICT adoption remains limited due to combined technical, organisational, and regulatory constraints, preventing large-scale and industry - wide adoption.	[4, 6, 10-12, 58, 62, 63, 64, 65, 66, 68, 67, 70, 72]

4. Discussion

The findings of this systematic review indicate a clear paradigm shift in concrete quality management, driven by the increasing integration of ICT-based solutions. Traditional con-

crete quality management, encompassing both quality assurance (QA) and quality control (QC) practices, has historically relied on periodic, labour-intensive inspections, post-construction testing, and manual documentation [4, 5, 10-12, 73]. These approaches often result in delayed feedback and limited ability to prevent early-age defects, reducing the effectiveness of QA/QC processes [73]. The reviewed studies collectively establish that ICT-enabled systems fundamentally change this

approach by enabling continuous, real-time, and data-driven monitoring that supports both QA and QC, particularly during the critical early-age curing phase of concrete.

A consistent theme across the literature is the central role of IoT-based sensing technologies as the foundation of digital concrete quality management. Studies [4, 5, 24] illustrate how embedded and surface-mounted sensors enable continuous tracking of temperature, humidity, evaporation rate, and bleeding behaviour-parameters that are difficult to monitor reliably using conventional QA/QC methods. However, as noted by John et al [24] and Guray [74], IoT and other digital technologies continue to be developed and applied in construction and concrete quality management in a fragmented and isolated manner, without a unified or integrated approach. Over time, this fragmentation has reduced the overall aggregated impact and effectiveness of digitalisation in concrete quality management [4, 6, 10, 63, 67, 72].

Nonetheless, compared to traditional cube testing or visual inspection, these digital systems provide earlier and more granular insight into strength development and defect formation, allowing proactive interventions that strengthen both QA planning and QC verification. This confirms earlier assertions by Haist et al. [25] that real-time monitoring aids in proactive management of concrete defects and is essential for overcoming the limitations of conventional QA/QC inspections, provided that the monitoring systems are properly calibrated and rigorously validated.

Beyond standalone sensing, the review highlights a progressive evolution toward integrated digital ecosystems, where IoT data are combined with BIM and DT platforms to enhance QA/QC processes. While early systems focused primarily on data acquisition and local storage, more recent frameworks, such as those proposed by Iqbal et al. [8], demonstrate how sensor data can be embedded within BIM environments to create dynamic and visually intuitive representations of concrete quality status. However, similar to the challenges faced by IoT systems, BIM-DT integration continues to be developed in isolation, with multiple independent frameworks emerging without a unified approach. This fragmentation has slowed the pace of innovation, as research and development efforts remain dispersed across clustered and disconnected systems [74].

The use of colour-coded strength visualisation in BIM models exemplifies how ICT can support faster decision-making, automated QA checks, and improved QC verification, enhancing communication among project stakeholders. This integration represents a significant advancement over isolated monitoring tools and aligns with Afzal et al. [9], who argue that DTs bridge the gap between cyber-physical systems and construction management processes, enabling QA and QC to operate in near real-time.

Another important finding is the expanding scope of ICT applications in concrete quality management. While early research predominantly focused on compressive strength estimation, recent studies have increasingly expanded toward

broader QA/QC concerns, including early-age defects such as plastic shrinkage cracking, which is often the first concrete defect and has the potential to drastically compromise the structural integrity of concrete. The systems developed by John et al. [4] suggest that combining environmental sensing with surface condition monitoring enables prediction of shrinkage risk before visible cracking occurs, strengthening QC procedures. This shift from strength-centred monitoring to holistic quality assessment reflects growing recognition that concrete quality is multi-dimensional, and that robust QA/QC must integrate material, environmental, and operational factors.

Despite these technological advances, persistent barriers that limit practical adoption, particularly in real-world construction environments. Many systems reviewed remain at laboratory or pilot scale, with limited validation under variable site conditions. Environmental climate, sensor durability, inconsistent curing practices, and unreliable power or connectivity continue to affect data accuracy and system reliability, constraining effective QA/QC implementation [10, 72]. Overall, this indicates that although ICT-based monitoring systems are technically viable and increasingly sophisticated, their effectiveness in QA/QC is still highly dependent on successful large-scale field deployment, system robustness, and integration within real construction site conditions.

System integration and information flow emerge as another major constraint for QA/QC. Although BIM and cloud platforms enable data visualisation, seamless integration with conventional QA/QC procedures, inspection schedules, and decision-making hierarchies is often lacking. Fragmented data pipelines, privately owned platforms, and absence of real-time feedback loops limit the operational value of digital systems in supporting continuous QA/QC verification [6, 63]. This fragmentation partially explains why ICT adoption in concrete quality management remains slow, particularly in comparison to other construction domains such as scheduling or cost control.

Organisational readiness and skills gaps further constrain QA/QC-focused ICT adoption. Resistance to change, reliance on experience-based judgement, and limited training opportunities further reduce the perceived value of ICT-enabled QA/QC systems. This aligns with Souza et al. [75], who identified cultural adaptation, inadequate skills development, and organisational challenges as key barriers affecting the successful implementation of Industry 4.0 technologies in the construction sector. Several studies indicate that construction personnel often lack the technical expertise required to interpret sensor data and integrate digital insights into daily quality assurance and control workflows [8, 72]. In this regard, regulatory bodies within the construction sectors, academic institutions, and private research facilities have a critical role to play in closing these skills gaps through training, research collaboration, and professional development initiatives that support the smooth adoption and integration of ICT into day-to-

day workflows. Ultimately, technological innovation alone is insufficient, and successful implementation therefore requires parallel investment in workforce development and organisational change management. Finally, the review highlights significant policy and regulatory shortcomings that hinder large-scale QA/QC integration and adoption. The absence of standardised guidelines, certification procedures, and code recognition for ICT-based monitoring systems, particularly in developing contexts, limits industry confidence and commercial uptake [10, 65]. This finding is consistent with Kumar et al [76], who highlighted that without regulatory recognition and formal integration into construction standards, ICT-based tools are likely to remain supplementary solutions rather than becoming embedded components of established quality assurance and quality control frameworks.

Overall, ICT has strong potential to transform concrete quality management from reactive inspection to proactive, predictive, and integrated QA/QC. However, realising this potential requires addressing technical robustness, system integration, workforce readiness, and regulatory support simultaneously. The findings suggest that future research should prioritise field-scale validation, interoperable system architectures, and alignment with construction standards to facilitate meaningful industry adoption of ICT-enabled QA/QC systems.

5. Conclusions and Future Research Directions

This systematic review demonstrates that Information and Communication Technologies (ICT) are progressively transforming concrete quality management, enabling continuous, data-driven monitoring and control of key quality parameters. The findings indicate that IoT-based sensing systems, when integrated with BIM and DT platforms, enhance real-time data acquisition, visualization, and decision-making, addressing limitations inherent in traditional manual inspection and laboratory-based QA/QC methods. These digital systems support proactive quality assurance and quality control throughout the concrete lifecycle, moving construction practice from reactive correction towards predictive management.

Despite these advancements, the practical adoption of ICT-enabled concrete quality management remains limited. Persistent challenges include data reliability under field conditions, fragmented system integration, workforce skills gaps, organisational readiness, and insufficient policy and regulatory support. These constraints highlight that technological innovation alone is insufficient to ensure effective QA/QC implementation.

Future research should therefore prioritise the validation of ICT-based concrete quality management systems under real-world construction conditions, emphasizing long-term field deployment beyond laboratory experiments. Emphasis

is needed on developing standardized sensor calibration, reliable data fusion methods, and scalable integration frameworks linking IoT, BIM, and DT environments. In addition, simplified, cost-effective solutions should be explored for resource-constrained contexts, alongside initiatives to strengthen workforce capabilities, organisational change management, and regulatory and certification frameworks. Collectively, these directions are essential to advance ICT-enabled concrete quality management from experimental applications toward routine, reliable QA/QC practice in construction.

Abbreviations

ASTM	American Society for Testing and Materials
BIM	Building Information Modeling
ICT	Information and Communication Technology
IoT	Internet of Things
JSON	JavaScript Object Notation
MSD	Multi-sensory Devices
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QA	Quality Assurance
QC	Quality Control
TCP	Transmission Control Protocol

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Author Contributions

Arthur Siwlanji Bweupe: Conceptualization, Data curation, Formal Analysis, Methodology, Project administration, Resources, Visualization, Writing – original draft

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Data Availability Statement

The data supporting the findings of this study are contained within the articles reviewed and reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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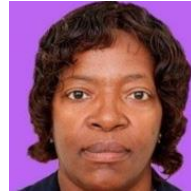
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Biography



Arthur Siwlanji Bweupe is a Civil/Structural Engineer and PhD candidate in Construction Management at the University of Zambia, where he also obtained his Master of Engineering (MEng) in Construction Management in 2024. He earned his Bachelor of Engineering (BEng) in Civil Engineering from Belgorod State Technological University named after V.G. Shukhov, Russia, in 2018. He currently serves as Civil Engineer – Quality Control, heading the Quality Control Department for a civil engineering contractor operating in the mining

sector across the Katanga region, in the Democratic Republic of Congo. His research explores real-time digital monitoring of concrete quality, focusing on compressive strength and plastic shrinkage cracking. It addresses challenges in ICT adoption, applies machine learning for predictive analysis, and evaluates the impact of these technologies on quality management.



Balimu Mwiya is a Senior Lecturer in the School of Engineering at the University of Zambia where she obtained her Doctor of Philosophy (PhD) and Master of Engineering (MEng) in Construction Management. She is also a holder of the Bachelor of Science (BSc) in Building from the Copperbelt

University. She also holds an Associate Degree in Software Engineering from the University of Advancing Computer Technology, Tempe, Arizona, USA. Dr. Mwiya is a Registered Quantity Surveyor and a member of the Surveyors Institute of Zambia, as well as a Registered Engineer and a Fellow of the Engineering Institution of Zambia. Her research interests span construction operations and productivity, cost engineering, and technology integration in construction.



Bennie Hamunzala is a Lecturer at Mulungushi University, Zambia, and a holder of a Doctor of Philosophy (PhD) in Civil Engineering from Hokkaido University, Japan, where his research focused on developing methods to estimate the construction years of road bridges using remote sensing techniques to support infrastructure management and deterioration assessment.

He earned his Master of Science (MSc) in Civil and Architectural Engineering from KTH Royal Institute of Technology, Sweden, specializing in Structural and Bridge Engineering, and a Bachelor of Engineering (BEng) in Civil and Environmental Engineering from the University of Zambia. Dr. Hamunzala's research interests include infrastructure design and management, structural and bridge engineering, sustainable construction solutions, and the application of advanced technologies such as remote sensing for infrastructure assessment and decision-making.

Research Field

Arthur Siwlanji Bweupe: Concrete Technology, Concrete Quality, Construction Quality, Building Information Modelling, Information Communication Technology in Construction, Construction Engineering

Balimu Mwiya: Cost Engineering, Building Science, Construction Operations and Productivity, Building Information Modelling, Quality Management

Bennie Hamunzala: Bridge Engineering, Structural Engineering, Construction Engineering, Concrete Structures, Infrastructure design and management