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Internet of Things (IoT) for digital concrete quality control (DCQC): A conceptual framework

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Abstract. Concreting is generally a manual, labour intensive and time-consuming process, putting additional burden on constrained resources. Current practices of concreting are wasteful, non-sustainable and end products usually lack proper quality conformance. This paper, as the first outcome of an ongoing research project, proposes concrete as an area ripe for being disrupted by new technological developments and the wave of automation. It puts forward arguments to show that The Internet of Things (IoT), as an emerging concept, has the potential to revolutionize concreting operations, resulting in substantial time savings, confidence in its durability and enhanced quality conformance. A conceptual framework for a digital concrete quality control (DCQC) drawing upon IoT is outlined; DCQC facilitates automated lifecycle monitoring of concrete, controlled by real-time monitoring of parameters like surface humidity, temperature variance, moisture content, vibration level, and crack occurrence and propagation of concrete members through embedded sensors. Drawing upon an analytical approach, discussions provide evidence for the advantages of adopting DCQC. The proposed system is of particular appeal for practitioners, as a workable solution for reducing water, energy consumption and required man-hours for concreting procedures, as well as, providing an interface for access to real-time data, site progress monitoring, benchmarking, and predictive analytics purposes.

Keywords: Concrete structure, Industrial Internet, Industry 4.0, sensors, digitization

Introduction

Cutting edge technology like bricklaying robots (FastBrick Robotics), automated OH & S reporting (SmartSite), asset management (AutoDesk Fusion Connect), drone technology for aerial survey and monitoring, embedded technology in building components providing intelligent structural elements (Smart Products) will change the "way of work" across the construction industry. Of these, the application of Internet-of-Things (IoT) can provide solutions for many such issues. It is predicted that IoT will have a monetary impact of saving, up to 22-29% of the total costs in construction, translated to $75-96 billion in annual benefits (Ramasundara *et al.* 2018). IoT will ensure high-speed reporting, and hence reducing the cost of communication, will ensure better process control and optimization. Moreover, the considerable amount of data collected makes possible real-time monitoring and analysis at the micro-level, leading to better decision making, accountability and transparency of stakeholders.

Of various construction activities, concrete works are of paramount importance **(**Jarkas 2011**)**. Approximately 25 billion tons of concrete is produced annually. The construction industry produces around 1200 MT of construction and demolition waste, a significant proportion of which is concrete waste (Klee 2009). Poor performance of concrete structures has also received serious attention due to: (1) significant failure events like the infamous Opal Tower incident in Sydney; (2) large amount of waste (Korkmaz *et al.* 2019); (3) low productivity of concreting activities (Commission 2017); (4) insufficiency of concrete structures durability; (5) environmental disruption, among other issues associated with concreting activities and concrete structure. A brief description of the causes of each problem is presented below (Gardner *et al.* 2018).

The durability of concrete members is affected by many factors, e.g. materials, environment, construction, and design (Pan *et al.* 2017), of which temperature and humidity are critical parameters, controlled by the quality of curing procedures (Ha, su Jung & Cho 2014). Despite rapid technological advancements, curing of concrete on typical construction projects is still performed by labour-intensive processes like ponding, hosing, steam or saturated cover materials (Surahyo 2019). Some improvements have been made by using ultra-fine fog droplets or use of super-absorbent polymers and external plastic sheeting. None of these have gained widespread acceptance across the construction industry, due to high implementation costs and the need for upskilling the on-site workforce (Kewalramani 2014; Rattanadecho *et al.* 2016; Justs *et al.* 2015).

Moreover, transportation of concrete faces serious issues like the unauthorized addition of water by transit-mixer drivers to maintain workability and delay concrete setting time. Even the use of retarding agents sometimes are not fruitful due to unforeseen traffic jams or other logistical issues. This necessitates retesting of concrete once it reaches the site to ensure that the requisite characteristics of the concrete mix are maintained (Gao *et al.* 2019; Howes *et al.* 2019). This causes undue time delays during construction and sometimes essential quality checks are skipped to achieve the target deadline during peak concreting.

Manual curing causes early-age cracking and ugly water stains which significantly affect the durability and aesthetic appearance of the concrete members. If curing is automated and stable conditions for temperature and relative humidity can somehow be maintained, the durability and aesthetic appearance of the concrete members can be significantly improved (Bella *et al.* 2017; Ghourchian *et al.* 2018).

Concrete segregation due to improper placing techniques is also a common problem, which decreases the structural integrity of concrete structures. Especially, with the growing use of self-compacting concrete (SCC), monitoring of concrete viscosity level becomes an important issue to provide necessary information to contractors to determine the level of vibration allowable for such high-fluidity concrete (Safawi *et al.* 2004). On many occasions, an arbitrary rule of thumb of 28 days is taken, which may not be the actual time for concrete member to fully attain total hydration and gain full strength.

Early formwork removal, where concrete is not adequately hardened, can cause enormous material, labour and machinery loss and damage (Rockstroh 2018; Samouh, *et al.* 2015). There is an urgent need for a new methodology capable of monitoring the real-time strength of concrete as per the temperature and humidity, and providing the actual time when chemical curing is totally complete.

Structural health monitoring of large-scale infrastructure such as inverted T-bent caps, dams, and deck slabs of bridges, piers and abutments of bridges also present problems (Song *et al.* 2007). It is especially the case for bridge piers and abutments that are located underwater or underground. Traditional inspection methods like x-ray spectroscopy or C-Scan are expensive and sometimes ineffective for large-scale structures.

Despite the synergy between IoT and concrete activities, research into this area has remained in its infancy, where existing studies almost entirely have targeted specific use cases of IoT for concrete, overlooking the broad picture (Wei *et al.* 2018; Yang *et al.* 2018). As such, the potential of IoT for enhancing the concrete supply chain as a whole has been overlooked in the now-available literature. This study aims at addressing this gap. To this end, a conceptual framework for an automated concrete monitoring, placing and curing system (DCQC) is proposed which takes an integrated approach towards the solution of critical concreting issues through digitalization and using smart devices interconnected with one another> This arrangement can generate sufficient data to assist construction managers and personnel in key decision-making and significantly lowering material, labour and energy costs.

Research methods

The defined objectives of this paper are pursued through "explanation building," namely, conducting a theoretical review, as described in detail by (Paré *et al.* 2015). Theoretical review has as its objective making a contribution to the world of practice, while providing a conceptual framework to guide future research efforts. To this end, the theoretical review formulates required attempts to draw on existing conceptual and empirical studies to provide a context for identifying, describing, and transforming into a higher order of theoretical structure and various concepts, constructs or relationships." (Paré *et al.* 2015, p. 188). The theoretical review procedure is illustrated in Figure 1.

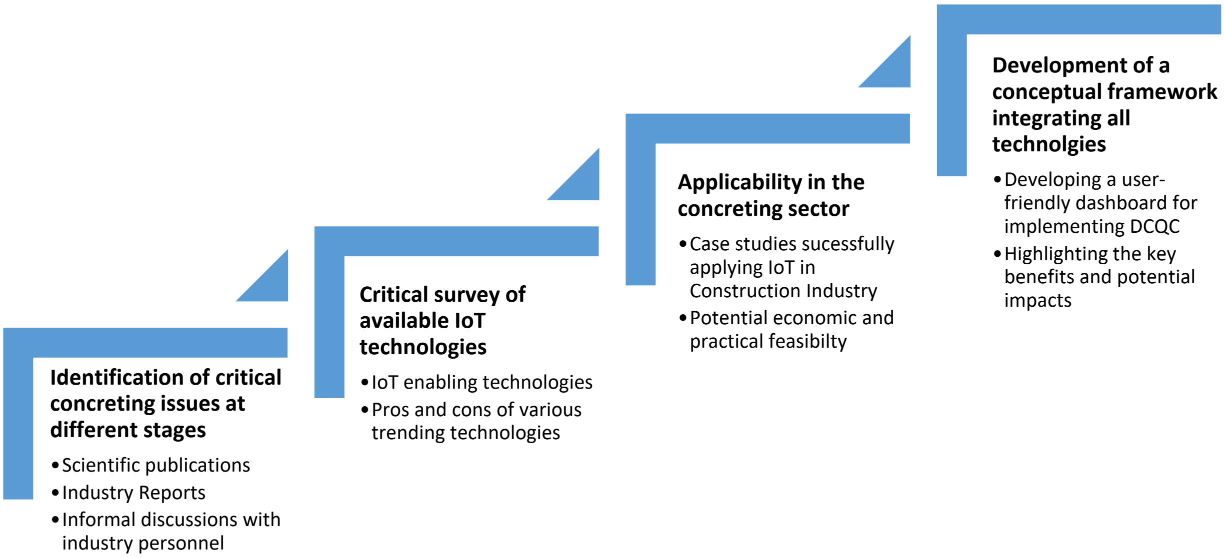

Fig.1 Research design

Initially, the critical problems currently facing the concrete industry is identified from recent scientific publications industry reports and informal discussions with industry personnel in this field from all over the world. Next, a survey of available IoT enabling technologies is performed – those utilized in other industries like mining or automobile engineering – to identify the possible merits and demerits of existing technologies. Next, the applicability of these technologies in the construction sector – by identifying successful case studies where IoT has proven useful – is explored, while also seeking to identify potential economic and practical feasibility of these IoT solutions. Finally, a conceptual framework is developed to outline the use of various components of IoT and develop a user-friendly interface to act as a tool for construction personnel, allowing them to monitor various parameters of concrete throughout its lifecycle in real-time, as well as, triggering alerts in case the acceptable thresholds are overrun.

Problems with current practices

A preliminary review of the literature concerning critical issues in concreting operations led to identifying significant problems with current concreting practices, as the items tabulated in Table 1. The issues have been categorized into different stages of concreting operations (both in-situ and pre-fabricated) to get an overview of the burning issues currently plaguing the concreting industry, throughout project delivery. The stages have been highlighted as concrete production at the batching plant or in-situ at the site, transportation through transit mixers, its placing using vibrators and formwork, curing of concrete, and post-construction structural health monitoring stages.

Table 1. Problems plaguing concreting activities

Sl.	Stage	Concrete problems	References
1	Production	Improper w/c ratio	(Juliafad *et al.* 2019)
		Quality control in real time	(Reiter *et al.* 2018)
		Material wastage	(Bassani *et al.* 2019; Sitnikov 2018)

2	Transportation	Unauthorized addition of water	(Juliafad *et al.* 2019)
		Climatic conditions	(Afzal & Khan 2018; Ghosh *et al.* 2018)
		Operator skill	(Afzal & Khan 2018; Ghosh *et al.* 2018)
		Traffic conditions	(Afzal & Khan 2018)
		Scheduling and routing issues	(Hasan *et al.* 2018; Kinable *et al.* 2014; Sheikh *et al.* 2016)
		Fleet management	(Ghosh *et al.* 2018; Niu *et al.* 2017)
3	Placing	Improper vibration imparted (over-compaction/under-compaction)	(Howes *et al.* 2019; Juliafad *et al.* 2019)
		Concrete segregation	(Gao *et al.* 2019)
		Formwork efficiency and sustainability	(Sitnikov 2018)
		Placement temperature	(Ouyang *et al.* 2019)
4	Curing	Non curing	(Juliafad *et al.* 2019)
		Early formwork removal	(Rockstroh 2018; Samouh *et al.* 2015)
		Plastic shrinkage	(Bella *et al.* 2017; Ghourchian *et al.* 2018)
		Thermal cracking	(Bella *et al.* 2017; Zhao *et al.* 2019)
		Early age cracking	(Khan *et al.* 2018; Safiuddin *et al.* 2018)
		Autogenous and drying shrinkage	(Gilbert *et al.* 2018)
5	Post Construction	Reinforcement and concrete corrosion	(Shi 2018; Zhou *et al.* 2018)
		Internal crack occurrence and propagation	(Cai *et al.* 2018; Dung 2019)

Application of IoT techniques in the construction sector

The Internet-of-Things (IoT) is a concept first coined around two decades back by Kevin Ashton in the context of supply chain management (Ashton 2009). It is defined as a network of physical objects with sensing and communication capabilities that enable data synthesis and processing through seamless access to domain-specific software and services. The various IoT enabling technologies are categorized into the application, middleware, networking and object domains which make up the four broad layers of the IoT umbrella (Čolaković & Hadžialić 2018). IoT has increasingly started to pervade the construction industry, and researchers are trying to harness its various potential benefits (Ghosh 2019).

Conceptual Framework - Digital Concrete Quality Control

Table 2 shows the sensors used in the DCQC system to monitor the different parameters of concrete and solve many of the problems outlined in Table 1. Fig.2 depicts an overview of the conceptual framework and a model of the proposed dashboard that would provide an integrated tool that would facilitate real-time lifecycle monitoring of concrete at all stages.

Table 2. Application of sensors and IoT principles for lifecycle concrete monitoring at all stages

Stage	Problem	Sensor Used	Description
Production	Quality control in real time, material wastage	Moisture Sensor	Moisture sensor is placed in the concrete - to monitor water content (to prevent excess addition of water during transportation), workability, and giving real-time data of the chemical characteristics of concrete.
Transportation	Unauthorized addition of water, climatic conditions	GPS, SmartRock2 Sensor, SONO-WZ water-cement analyser	Transit mixers optimized using GPS monitoring. Real-time monitoring of concrete w/c ratio through hydro-mix moisture sensor for fresh concrete or SONO-WZ water-cement analyser for fresh concrete would provide an effective practical solution to this problem (Tauqir 2018). Strength of concrete monitored through SmartRock2 sensor (Liu et al. 2017) during different stages of concrete life-cycle and effect of external factors on strength development analyzed for the same concrete mix.
Placing and Curing	Concrete segregation, improper vibration imparted (over-compaction/under-compaction), placement temperature, thermal and early age cracking, plastic shrinkage	Temperature and humidity sensors, viscosity sensors	Temperature and humidity sensors placed on the surface of the concrete at random locations to cover the entire surface. One temperature sensor attached to rebars to be embedded inside the concrete structure to monitor temperature difference between surface and core temperature of the concrete element. Water flow controlled by Programmable Logic Circuit to start spray when outside temperature is above 45 degrees Celsius or Relative Humidity is below 80 % (Yang et al., 2018). Viscosity sensors will monitor the real time workability of concrete ensure optimization of vibration imparted
Post Construction	Reinforcement and concrete corrosion, internal crack occurrence and propagation	Piezoceramic, piezoelectric sensors	Piezoelectric/piezoceramic (PZT) patches (made of lead zirconate titanate) are embedded, at pre-defined locations in the concrete structural element under study. The structural element is put in a test-frame set-up using hydraulic actuators for loading purposes. The sensor signal measured by a PZT sensor is decomposed into sub-signals by the wavelet packet algorithm. The damage index is calculated by comparing the energy vector of healthy state with the energy vector of the damaged state. The damage index gives real-time information regarding occurrence and propagation of cracks (Song *et al.* 2007).

All the sensors connected through LPWPAN (Low-Power Wide-Area Network, LoRa platform to for wide range connectivity (10 km radius). A suitable dashboard maybe developed for real-time monitoring the concrete placing, curing and rheological characteristics, giving critical alerts and suggesting predictive solutions whenever there is occurrence of critical cracks and greater stress produced in the concrete element (see Fig.2).

Fig.2 Proposed Framework and Dashboard for Digital Concrete Quality Control (DCQC) Monitoring

Discussion

Concreting operations constitute a crucial backbone for most construction activities (Jarkas 2011). However, the concrete industry suffers from serious issues like low productivity (Commission 2017**)** and quality conformance. The DCQC offers an innovative integrated system for real-time monitoring of concrete throughout its lifecycle and address the major issues outlined in Table 1.

Previous studies have tried to provide point solutions focussing on a single problem. This makes this study unique, as it proposes a methodology that addresses all current problems based on the capabilities provided by IoT. Though findings remain conceptual in nature, the study creates a ripe area for empirical research, namely, a direction for future research on the intersection of IoT and concrete activities by testing the practicality and operational aspects of implementing the proposed framework.

Key Benefits

- Greatly assist construction managers to monitor concrete throughout its lifecycle

- Reduce testing and retesting of concrete quality by managers and engineers (time savings)
- Reduce curing time and labour work hours
- Prevention of unwanted addition of external substances (water) during transportation, make transit mixer operators more accountable.
- Allow maintenance engineers to have real-time monitoring of structures both inside and outside without resorting to expensive methods x-ray spectroscopy for crack detection
- One – time capital cost easily compensated by reusability in large projects
- Ensures greater transparency between all stakeholders (contractor, client, worker, engineer)
- Saves valuable natural resource i.e. water and power (energy savings)

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