Real-time remote temperature control of concrete samples during construction of the shaft's liner of a potash mine

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Abstract

The large potash resources of northern Saskatchewan (Canada) in the western sedimentary basin are usually extracted through conventional mining methods. The potash deposits of this region are typically located at depths between 900 and 1000 m. The construction and sustained operation of these mines is challenging due to flooding risks as the potash beds are located beneath water-bearing formations. Since the 1960s, more than 5 shafts have been flooded and currently-operated shafts are all closely monitored. The Blairmore formation, a sand-shale-clay-siltstone layer, at a depth of 500 m is commonly the largest obstacle. For the shaft-sinking project at BHP's Jansen mine, the unique construction method of the waterproof liner requires custom-formulated high-strength concrete to ensure long-term structural integrity. In order to obtain the most accurate maturity curves, concrete samples should to be cured and tested in real-time at exactly the temperatures they are subjected to during liner construction. A new method was developed to monitor concrete temperatures in real-time, relay the readings to the surface over a LoRa radio link where the readings are used. The LoRa gateway distributes the readings to several programmable logic controllers (PLC) as setpoints for curing baths. Each batch of samples has to undergo controlled cure for a schedule of at least one month. The system scales in order to accommodate up 24 sections at once in each of the two shafts. In addition to the mechanical tests conducted on the samples, a custom-built visualization tool computes the maturity curves for each section and handles numerous alarm types to ensure that temperatures rise at a specific rate, that it never exceeds specific thresholds, that there are no significant temperature gradients and that sections behave accordingly to the models. This new method is applicable for linear structures such as tunnels and bridges.

Keywords: Liner construction, potash mining, telemetry, internet of things

1. Introduction

Saskatchewan (Canada) is home to the world's most productive potash production operations where mines have been extracting ore for decades. The construction and sustained operations of these mines face a number of unique challenges, not the least of which is that the ore is located approximately 900 m below ground level. This difficulty is compounded by the shafts crossing the Blairmore group, a late-cretaceous water-rich formation located at approximately 500 m from the surface. This layer is a consistent flooding risk to operations for all mines in this region. Since the 1960s, more than 5 shafts have been flooded and currently-operated shafts are all closely monitored.

The construction of a new mine in the area, the Jansen mine, is a challenging project that was tackled with innovative methods. Shaft sinking was done by artificially freezing the ground and excavating it using a shaft boring roadheader (SBR), which also provided support for construction of the primary liner. The SBR included an arm designed to install tubbing at the Blairmore formation to limit risks of water ingress during shaft sinking. Thousands of geotechnical instruments and hundreds of data loggers during both shaft sinkings and primary liner constructions were commissioned. Instruments include multi-point borehole extensometers, piezometers, pressure cells and thermistors. The construction of the final liners was undertaken after the SBR reached the target elevation in 2018. Their design addressed the risks posed by the Blairmore formation. A welded steel outer liner ensures waterproofing of the shafts on their entire length, including through the Blairmore formation. Structural integrity is provided by a 3 to 10 m thick layer of poured high-strength non-reinforced concrete. Due to it being poured concrete as opposed to more commonly-used shotcrete, construction had to start at the bottom and new sections had to be continuously poured on top of freshly poured sections, in 6 m increments. A strict quality assurance protocol was put in place to test each batch and each pour of concrete. In the first months, it was critical to check that the concrete behaved and matured as designed. Standard pours of high-strength concrete are not usually done on top of each-other so using standard schedules of 24 of 48 days to achieve a known strength would not be a concern. In this case however, waiting 24 days after each pour to start a new one would have led to the liners requiring over ten years to build. Real-time temperature matching and testing lets workers move on to the next section as soon as the target strength is reached. Speeding up this process by having the most accurate knowledge of concrete strength was therefore critical to the success of the operation.

The system introduced in this project offers real-time matching of temperature between the poured concrete in the mine shafts and sample cylinders at the surface. Quality assurance team studied the samples to measure early-age strength as a safety measure and as a way to calibrate the early-age maturity curve. It has been reported that real-time matching is at least as good (Sofi et al. 2012, Soutsos et al. 2016) as standard maturity monitoring for early age strength. Moreover, there are disagreement on the exact model to apply for early-age estimation of concrete strength that were being investigated at the time the system described here was being developed, using an independently designed real-time matching method (Soutsos et al 2018).

The system leverages Internet of things (IoT) best practices to control the temperatures of concrete sample cylinders in real-time. It integrates embedded thermistors, a LoRa-enabled data logger, a Modbus/TCP server and programmable logic controllers (PLC). This paper goes over the design framework, results and future developments of this system. Embedded instruments with radio-enabled loggers will form the backbone of instrumentation programs in the mining industry, leading to faster and more responsive monitoring programs. The basic framework is shown to be expandable and adaptable for other situations where remote data collection is overlooked.

2 System design

The concrete match system monitors the temperature data in real-time during the curing of each pour and relays it to the surface. An automated system retrieves temperatures and uses them as setpoints for real-time curing baths. In each one, up to 24 concrete cylinders (poured in 4X8 capped plastic moulds) are placed in a tank within one hour of the pour, and break tests (as per CSA A23.1) are conducted at increasing intervals following a log pattern. The samples are therefore subjected to conditions that mirror exactly that of the pours, as opposed to more commonly used methods that set the concrete cylinders at a steady temperature. The final implementation had to comply to the following requirements: read and transmit temperature data to a collection point potentially located hundreds of meters above the data loggers, have the loggers be battery-powered so that no cabling would be required, perform at least one temperature reading every 30 minutes, control temperatures of the cure boxes within 2 °C of the shaft concrete temperature at all times, distribute real-time alarms on temperature values and temperature differentials within the structure, and offer real-time maturity calculations based on the temperature readings. Figure 1 shows an overview of the main components and their interconnections.

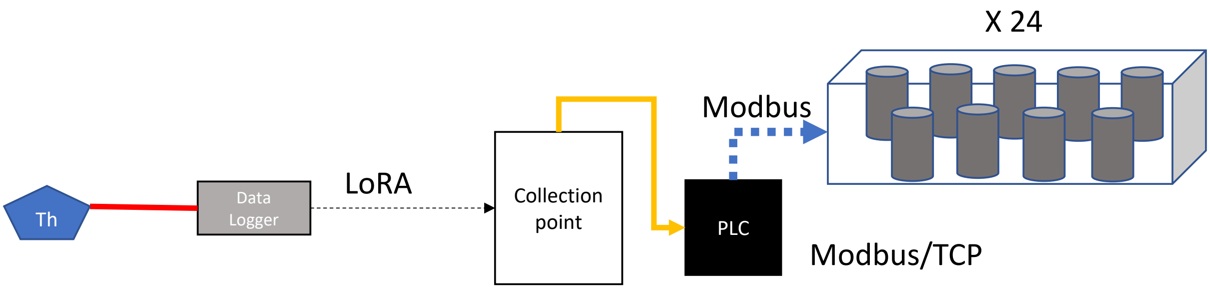

Figure 1: Schematics of the main components of the concrete curing system deployed at the Jansen mine.

2.1 Sensors

The thermistors (Geokon) (Th on Figure 1) are installed at three locations for each pour, 10 cm from the inner wall (Th-1), at the centre (Th-3), at 10 cm from the outer wall (Th-1) and in the air (Air temp). The thermistors are attached to a piece of rebar or fiberglass which was held by a support welded to the steel form (Figure 2).

The thermistors are attached to custom-built military connectors that protrude out of a plate in an opening in the steel form (Figure 2). The process required that connectors be added at the end of the thermistor wires for easy disconnection and reconnection as the logger had to be temporarily removed at the time of removing the forms. Th-3 is used as the reference of for sample control due to its position at the centre of mass of the concrete pour. Th-1 and Th-2 are used to track radial temperature differentials with respect to the centre.

Three main types of temperature sensors are available on the market: platinum resistance thermometers (RTD), thermocouples and thermistors. RTD measure the change in resistance of a platinum circuit close to 100 Ω, thermistors measure the change in resistance of a semiconductor in the 1 to 10 000 kΩ range over its temperature range and thermocouples measure the change in mV of a bi-metallic junction. Thermistors have a more limited temperature range than other options, but temperatures were expected to never climb above 80 °C. They offer better sensitivity than RTDs as a 1 °C change leads to a change of tens of Ω as opposed to 0.3 Ω for an RTD. Of the three main technologies, thermistors are the least subject to errors caused by parasitic resistances. An improperly built connector might add hundreds of mΩ to the measured resistance of the sensor: this translates to a 1 to 2 °C error on resistance when reading an RTD. Thermistors, with resistances of several kΩ are largely shielded against such effects. Thermocouple are versatile and can be built to length on-site but with a few key limitations: they are best-suited to measure large changes in temperature, high temperatures, and connecting them to connectors runs the risk of inducing errors due to cold-junction effects. In addition to these considerations, thermistor strings had already been established to be reliable in the mine's harsh conditions as they had been used during the shaft sinking projects.

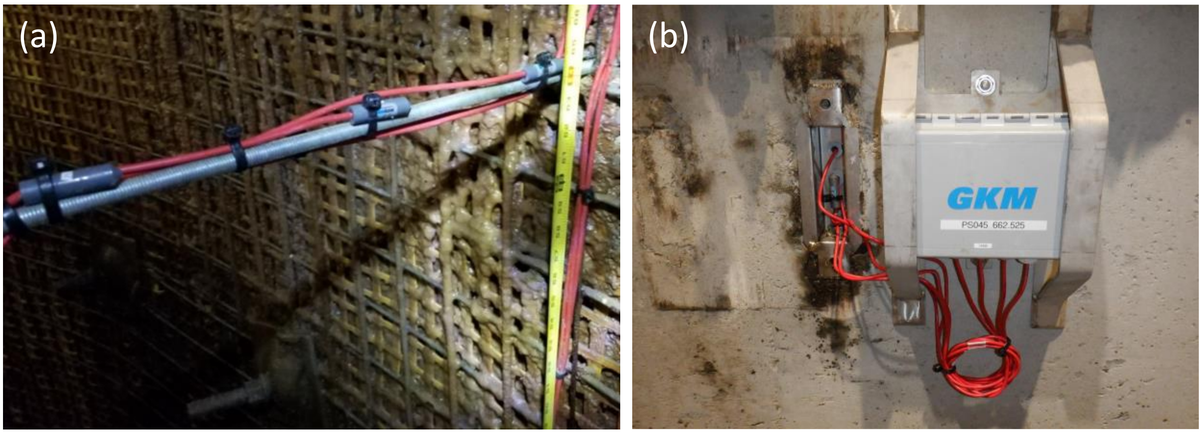

Figure 2: (a) Thermistors attached to their support before the concrete pour. (b) Embedment plate for the thermistors and data logger.

2.2 Data Loggers

Off-the-shelf products for remote monitoring of concrete temperatures usually rely on fully embedded in the concrete (sensor, battery and transmitter) and use a Bluetooth transmitter (Giatec 2022). The main advantage of this method is that instruments cables don't have to be run out of the concrete structure. Instrument cables can, in some cases, create preferential paths for water or create localized weak points. Bluetooth has a shorter range in open air (<100 m for Bluetooth 5). Compounding this, the steel form would have blocked Bluetooth transmission before its removal.

The selected data logger technology had to meet several requirements: Compatibility with thermistors, battery-powered, long battery life so that no intervention would be needed for throughout the project, reading and wireless data transmission every 5 minutes and a collection point that would be accessible for PLCs and other automation processes. The selected technology uses modified LoRa-based data loggers (Worldsensing, Figure 3). LoRa is a low-power long-range radio technology developed for IoT applications (Develal *et al.* 2018). LoRa is a proprietary radio protocol developed by the LoRa alliance since 2015. Its uses are comparable to other technologies such as ZigBee or Meshnet, which are also found in IoT applications. While LoRa has a lower bandwidth and doesn't easily allow for two-way communications compared to the latter two, it benefits from having a range of 10 to 15 km as opposed to 100 m. The 100 m standard range for ZigBee and Meshnet would have precluded collecting data remotely from the top of shaft.

The data loggers had to be repackaged in order to fit them with connectors that would allow for easy removal and reinstallation after removing the forms, as well as to protect them from the corrosive environment of a potash mine. As mentioned previously, the addition of connectors was necessary to facilitate the removal and reinstallation of the data loggers. The antenna is contained inside the plastic enclosure to prevent it from corroding. The thermistor measuring the air temperature is seen embedded in a cable gland at the bottom right corner of the enclosure. In total, approximately 150 data loggers were commissioned in each shaft.

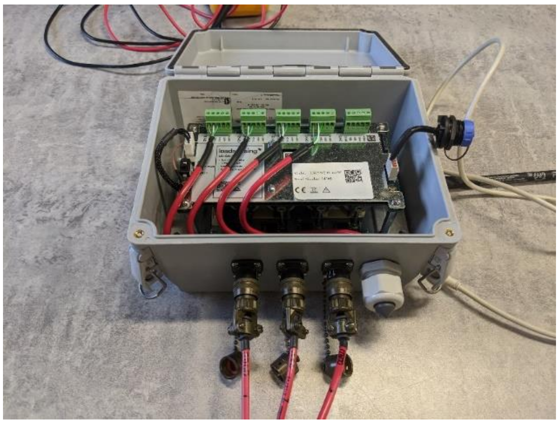

Figure 3 Data logger assembly

2.3 Collection point

The collection point (also known as the gateway) acts as the receiver for readings. In this implementation of LoRa, the loggers are "standalone" devices. They have their own internal clock, turn on a schedule and broadcast their readings, all without receiving any instructions from the collection point. This star configuration differs from other implementations that might have bi-directional communications or even mesh capabilities. This passive star network ensures a high level of reliability, so long as the receiver is within range and the line of sight is unobstructed between the emitter and the receiver.

Each shaft had three collection points installed on the work platform. The antennas were located underneath the platform to facilitate data collection as the platform was moved up at every step during liner construction. In each shaft, one gateway retrieved data for dataloggers that were selected for live matching, while the other gateway retrieves data from all other data loggers. On average, only one out of four pours were used for live matching. The third gateway was a redundancy ready to go should any of the two primary gateways fail.

The collection point also acts as the distribution point for other services and systems. Temperature data is collected from its Modbus/TCP server. Modbus is a protocol that has been in use in automation for decades (Drury 2010). While it is being supplanted by newer protocols such as MQTT in IoT, it is still used in automation for its simplicity and robustness. The collection point also generates .csv files (comma separated values) that are pushed vie FTP (file transfer protocol) to a server where data is hosted for online visualization and management.

2.4 Control system

The PLC (Siemens) system is programmed to take readings from individual gateways and use them as setpoints. It handles basic error control to account for cases where a temperature sensor might have failed or if communications between the collection points and the PLC to maintain a known setpoints on the samples until the situation is addressed. Furthermore, a human-machine-interface (HMI, Figure 4) was commissioned for workers to see at a glance temperature (from the concrete pours and curing boxes), setpoints, error status as well as manually select which temperature sensor is used to control which set of samples.

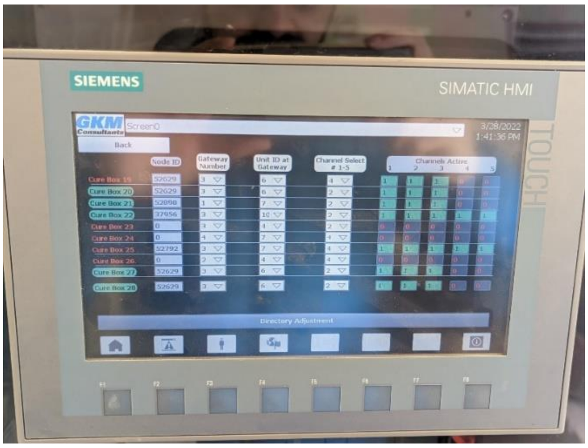

Figure 4: HMI displaying connection and error status

2.5 Cure boxes

The cure boxes (Teledyne), were modified to add a temperature controller that can be addressed remotely (i.e., by the PLC). A typical concrete curing system leaves the samples in moist air or be submerged in water, heating them to keep them at a constant temperature of 23 °C (ASTM C31). The system deployed at this mine goes beyond the standards by keeping the cylinder temperatures within 2 °C of the poured concrete at all times. In this specific instance, cooling is required in addition to heating as the large number of samples in each cure box increase the temperature of each tank's water too fast by shedding heat in the first few hours. Figure 5 shows how the sample temperature (green curve) tracked in real-time with the Th-3 (center yellow curve). The solid blue curve shows the air temperature measure outside the concrete pour. The spikes and dips are due to activity in the shaft. The air temperature curve shows that temporary changes in air temperature after the pour has a negligible effect on concrete temperatures.

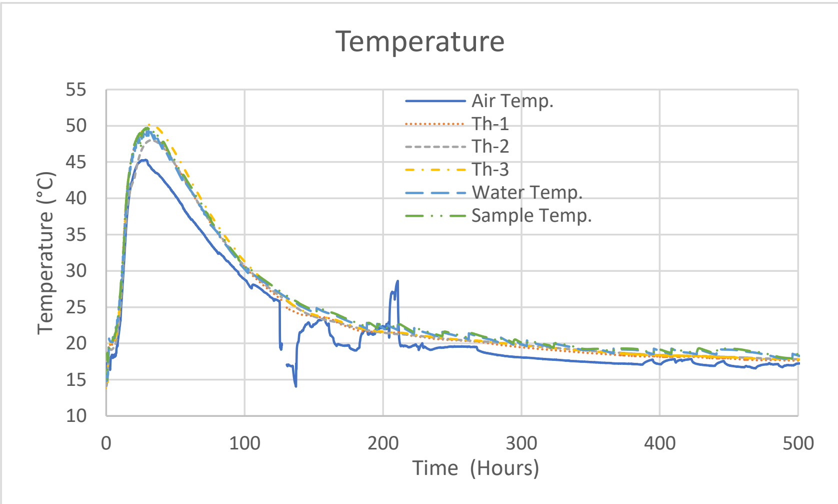

Figure 5: Example of temperature tracking between the concrete pour and the sample cylinder temperatures

2.6 Online visualization platform

The online visualization system was used to distribute data to conduct QA on the system. Alerts were configured to be triggered should any sensor stop reporting readings, if temperature gradients within a concrete form exceeded 10°C between the edge and the centre of the structure or if temperatures reached 60 °C. Excessive temperature gradients can lead to stress gradients, weakening structural concrete (American Concrete Institute 2016).

For security and reliability purposes, the collection point itself is not reachable over the internet. Control of the cylinder's temperatures being the most critical component of the system, it is self-contained to the local network of the mine. The data used by the online platform is pushed by the collection point to a secure server and all incoming connections are blocked by a firewall. Should the internet connection be compromised, graphing and alerts would have been lost, but the samples would have cured adequately.

3. Framework

The steps of the discussed process in this paper can be abstracted into a framework as shown in figure 6. For instance, based on mining method, geotechnical structures, ground stress condition and patterns and stability of the underground structure, the construction of deep mines can induce uncertainties in the long-term stability of the structure. Closely monitoring of ground behaviour, pillars deformation as well as ground water condition around mine site provides clearer picture of the mine stability and deformation for engineers and decision makers. In addition, monitoring temperature, pressure and pore pressure in backfills help engineers to monitor and analyse the efficiency of backfilling in stopes.

The critical step that is rarely taken in the underground mining is the remote collection of data from embedded sensors. Addressing this single link opens up new options for monitoring and automation of field instruments. Each of the steps of the concrete monitoring system can be expanded or modified for other types of projects. In mining operations, including in potash mines, monitoring backfilling is recurring challenge (Fliß 2011, Thompson 2015). Embedded instruments such as pressure cells, piezometers and temperature sensors give critical information on the curing process inside the backfilled chambers. However, retrieving the data and putting it to use in real-time are not commonly done. The data could be transferred from a local logger to a remote collection point hundreds of m away and then to the control room for engineers to make informed decisions. In this case, very little automation would be required (see the process as shown in figure 6).

The automation of the curing boxes could be altered while retaining the rest of the framework. Dewatering is often required to protect the workers and assets of mines. Piezometers are routinely used for this application, but data collection is usually wired. By decoupling local data collection and automation using a radio-enabled logger, it is possible to control pumping remotely, as well as take advantage of IoT methods, such as storing live data into a historian.

The system was expanded into a structural health monitoring system at the Jansen mine. Embedded instruments, such as concrete strain gauges and strain gauges welded to the steel liner, are read and re-transmitted to a collection point based on the same technology. This solution is more cost-effective than running cables all the way to ground-level and allows for remote data collection during construction of stages at higher elevation. In this case, the automation part was not required and a different set of online tools are used.

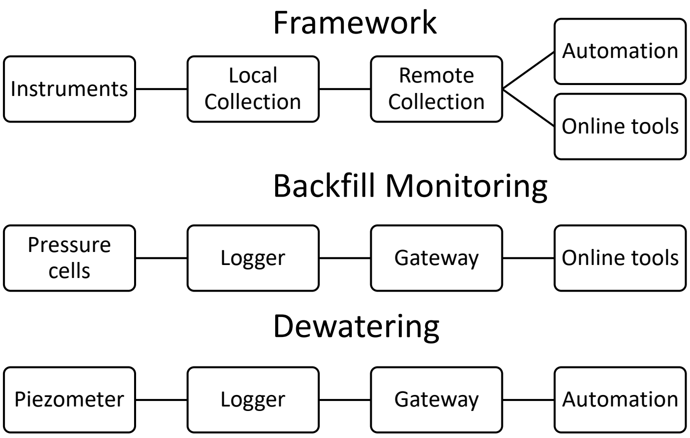

Figure 6: Framework for automated remote collection and control

4. Conclusions

The challenges associated with the liner construction of BHP's Jansen mine required the development of a novel concrete cure matching system. Liner construction required high quality cylinders in order to measure the concrete maturity and strength as the liners were built from the bottom up. The system combines off-the-shelf parts in a fully automated system that provides high-quality concrete cylinders required for safe and fast construction. The approach described in this paper can be used as is for other types of projects with difficult access, such as tunneling, bridge construction or deep excavations. In all of these cases, samples could be prepared in safe locations to have the best possible information on the concrete structure. It is possible, for future projects, that the entire system be deployed over the internet, meaning that that the online platform, the poured concrete and the control system for the curing boxes to be in separate locations.

The framework posed during the design of this system rests on the remote data collection offered by technologies created for IoT in manufacturing and other industries. The topic introduced in this paper should be use as the starting point for digital transformation projects in mining and geotechnical monitoring.

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