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IoT-Based Quality Control Technology for Concrete Pavement Construction

Fei Huang [1], Jianguo Zhang [1], Guangli Zhou [1], Shengshu Liu [1], Hang Gao [1], Sili Li [2] *, Minyi Fu [2]

[1] China Road & Bridge Corporation. Beijing, 100011, China

[2] Research Institute of Highway Ministry of Transport. Beijing, 100088, China

Abstract: Concrete quality control is a crucial part of concrete construction. It affects not only the workability of fresh concrete and the mechanical performance of concrete structures but also the long-term durability of concrete components. Therefore, choosing effective concrete quality control methods helps improve the construction quality of concrete projects. This paper designs and improves a mixer for the online observation of cement mortar quality. It also introduces an experimental twin-shaft concrete mixer that can monitor torque, power, and rotational speed data in real-time, providing a basis for online quality control. Furthermore, leveraging Internet of Things (IoT) technology, this study developed an online monitoring system for concrete construction quality and a corresponding data acquisition and transmission system. This establishes a multi-level, networked, and intelligent concrete construction quality control system. The research findings offer technical support for enhancing the quality, durability, and long-term service safety of cement concrete structures.

Keywords: concrete; construction quality control; Bingham model; IoT; monitoring system; data system

1. Introduction

Cement concrete is a primary material in road construction, and while widely used, it frequently faces issues related to quality and durability[1]. Both domestically and internationally, concrete structures have experienced numerous problems with safety and durability during their service life. For example, in 1998, the United States spent an astonishing $155 billion on concrete bridge repairs, four times the initial construction cost, with another $95 billion allocated for other concrete structure repairs. In the UK, over a third of concrete structures built in marine and chloride-rich environments required rebuilding or strengthening due to steel reinforcement corrosion and concrete spalling. Clearly, the quality of concrete directly impacts a structure's operational safety and its long-term maintenance costs. Therefore, effective concrete quality control during the construction phase is paramount[2].

Currently, in the construction phase, the quality of concrete pouring and curing is primarily ensured through standardized worker operations, adherence to the "three-inspection" system, and enhanced on-site supervision. The main experimental method for testing concrete performance involves preparing a certain number of concrete test blocks during pouring, curing them under standard conditions for a specific period, and then conducting relevant mechanical and durability tests. While this evaluation method does control concrete quality to some extent, it's essentially a post-hoc control measure with significant lag and limitations[3]. By the time the pre-cast concrete test blocks have been cured for a certain period, the concrete structure poured on-site has already hardened. If, at this point, the concrete's performance is found to be below design requirements, it will inevitably compromise the structure's safety and lead to economic losses. Furthermore, the molding and curing conditions of the pre-cast test blocks differ from those of the actual construction process, meaning their long-term performance may not fully represent the actual development of concrete material properties in the field[4]. Additionally, in the context of major transportation infrastructure development, particularly as projects move into more complex mountainous and watery environments, quality and safety risks are increasing. The mismatch between quality control

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capabilities and construction scale is becoming prominent. There is an urgent need to address the shortcomings of current concrete quality control methods by adopting advanced scientific and technological solutions to implement process-based quality control for concrete structures, focusing on the concrete materials themselves.

Given these challenges, this paper leverages Internet of Things (IoT) technology to research intelligent monitoring and network information technologies for road construction quality control processes. We've developed an online monitoring system for concrete construction quality along with a data acquisition and transmission system. This allows for process quality control at every stage of construction, providing real-time feedback and establishing a multi-layered, networked, and intelligent highway construction quality control system. This system enables real-time monitoring, data acquisition, and analysis of both production and construction phases. The findings of this research provide crucial technical support for enhancing the quality, durability, and long-term service safety of cement concrete structures.

2. Technology and Equipment

In the 1970s, based on extensive experimental work, G.H. Tattersall in the UK observed that at low shear rates, cement paste exhibits Bingham plastic properties[6]. This means the cement paste behaves as an elastic solid until the applied external force reaches its yield value. Once the external force exceeds the yield value, the shear rate becomes directly proportional to the difference between the shear stress and the yield stress, as illustrated in Figure 1[7].

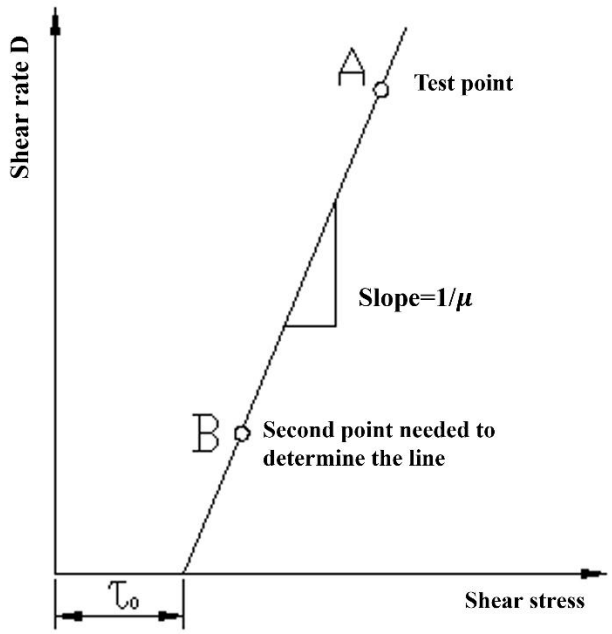


Figure 1 Bingham Model Schematic Diagram

2.1 Quality Control Technology for Cement Mortar

Building upon the Bingham model, and to better study the workability of cement mortar, this paper designed a torque-speed-power test instrument, as shown in Figure 4.2 (presumably Figure 2 in the provided text). In the diagram, ① is the blade adjustment screw rod, ② is the variable-speed motor, ③ is the torque sensor, ④ is the mixing blade, ⑤ is the mixing pot, ⑥ is the mixing pot lifting frame, and ⑦ is the blade lifting slide. The adjustment screw rod ① moves the blade up and down within a 30cm range, ensuring normal mixing and removal from the mixing pot. To guarantee mixing uniformity, the distance between the blade and the bottom of the mixing pot is typically controlled within 4mm±2mm, and the distance from the blade to the edge of the mixing pot is set to 3mm. The variable-speed motor ② adjusts the blade speed, with an adjustable range between 0 r/min and 1400 r/min. The torque sensor ③ measures the blade's mixing torque, with a range of

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0.1N·m to 100N·m. The mixing blade ④ is similar to the discontinued spiral impeller of the American Tattersall MKII device. Based on commonly used blade design principles domestically and internationally, this paper designed each layer of blades to have three pieces, evenly distributed on the mixing shaft at a 45° inclination angle. The mixing pot ⑤ has a diameter of 260mm and a height of 300mm, with a fixing device at the bottom to ensure the centerlines of the mixing pot and the mixing shaft are aligned. The lifting frame ⑥ moves the mixing pot up and down within a 30cm range, facilitating installation and removal of the mixing pot. The blade lifting slide ⑦ fixes the blade, torque sensor, and variable-speed motor to a flat plate, ensuring smooth vertical movement of the blade. Figure 3 shows the physical view of this test instrument, Figure 4 shows its side view, and Figure 5 shows the data acquisition software. This software connects to a computer via an RS232/485 interface, acquiring data every second, thus achieving real-time collection of torque, speed, and power.

During the experiment, the torque and speed values can be measured by the tester. The specific steps are: adjust the lifting slide ⑦, fix the lifting frame ⑥, so that the mixing pot is fixed in a certain position. Then, adjust the screw rod ① to ensure the distance between the blade and the bottom of the mixing pot is within the appropriate range. Add each material sequentially (water, cement, sand, admixture) into the mixing pot ⑤. Adjust the variable-speed motor ② to set the mixing speed to the desired gear. Start the automatic recording function of the data acquisition software, and use the torque sensor ③ to measure the torque and speed of the mortar mixing blade ④ at a certain speed. When using this mortar mixer, attention should be paid to the following aspects: ① Avoid mixing at excessively high or low speeds, and choose a moderate speed; ② During the feeding process, rotate at a low speed initially, and after all materials are added and there are no dry materials, then mix at a high speed. This ensures that all materials are fully involved in mixing, guaranteeing the uniformity of the cement mortar; ③ After all materials are added, the paste adhering to the pot wall should be promptly cleaned.

The flowability is tested according to the cement mortar flowability determination method in the "Test Procedure for Cement and Cement Concrete in Highway Engineering" (JTG E30-2005). Correspondingly, the relationships between torque and speed, and torque and flowability can be established, thereby providing online monitoring basis for cement mortar quality control[8].

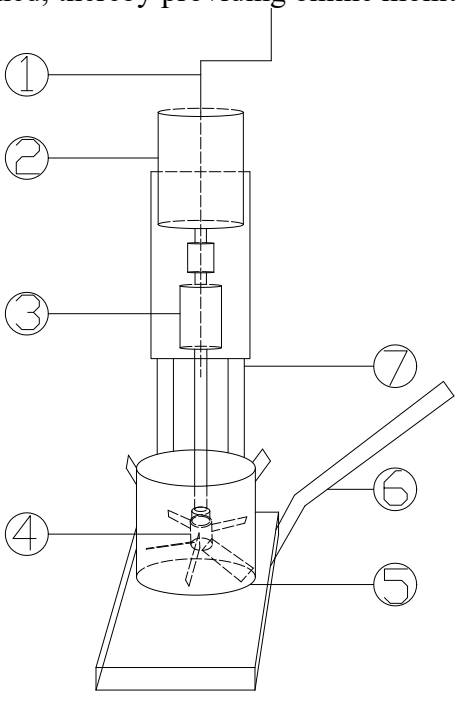


Figure 2 Cement Mortar Mixer Structure Diagram


Figure 3 Physical Diagram of Cement Mortar Mixer

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Figure 4 Side View of Cement Mortar Mixer

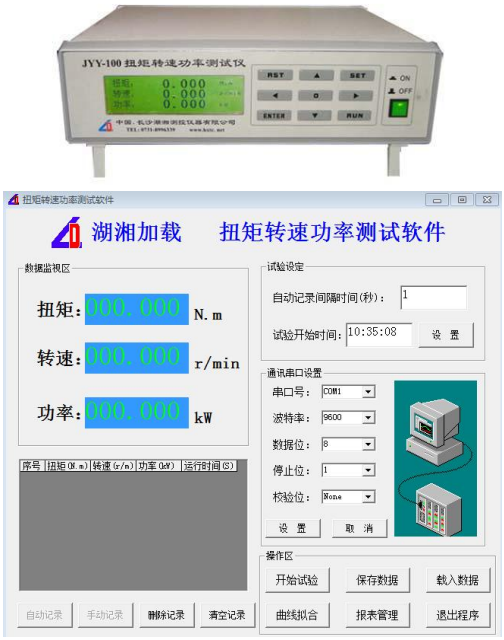


Figure 5 Cement Mortar Test Instrument and Data Acquisition Software

2.2 Quality Control Technology for Fresh Cement Concrete

Building upon the Bingham model, and to better study the workability of fresh cement concrete and achieve its online quality monitoring, while also better simulating the twin-shaft structure characteristics of large-scale concrete batching plants, this paper designed an experimental twin-shaft concrete mixer, as shown in Figure 6. In the diagram, ① is the electric motor, ② is the torque-power-speed sensor, ③ is the reducer, ④ is the electrical control box, ⑤ is the transmission box, ⑥ is the frame, ⑦ is the mixing tank, commonly referred to as the mixing pot, ⑧ is the mixing blades, ⑨ is the fixing device, and ⑩ is the discharge device.

The electric motor ① operates at a voltage of 380V, frequency of 50HZ, and mixing power of 3.0KW. The mixer's speed can be adjusted via the motor and the frequency converter within the electrical control box ④, with a speed range of 0 r/min to 60 r/min. During experiments, the rheological properties of fresh cement concrete can be observed at different speeds. The torque-power-speed sensor ② measures torque, power, and speed during the mixing process, with a torque range of 0.1 N·m to 300 N·m and an accuracy of 0.1%. The reducer ③ serves two main purposes: firstly, to control the motor speed, keeping the mixing speed within an appropriate range; secondly, to change the direction of power transmission, converting the motor's longitudinal transmission to transverse transmission, thereby driving the transverse mixing shafts to rotate. The main components of the electrical control box ④ are the frequency converter and the power controller. The frequency converter is used to control the motor speed, with a variable frequency from 0HZ to 50HZ. The power controller controls the power switch and provides overcurrent protection to prevent adverse effects on the motor caused by excessive current due to jamming or other reasons during mixing. The transmission box ⑤ distributes the motor's power evenly across the two mixing shafts and further reduces the motor's speed with a reduction ratio of 10:6, providing better control over the mixing speed. The frame ⑥ is the supporting part of the entire equipment, welded from channel steel and steel plates, possessing sufficient strength and rigidity to support the entire equipment. The mixing tank ⑦ is the core part for material storage and mixing, with a maximum capacity of 80 liters. The mixing blades ⑧ are spirally distributed on the mixing shafts at a 45° angle. During twin-shaft mixing, they achieve three-dimensional helical mixing (front-back, left-right, and up-down), simulating the relevant structure of mixing blades in large concrete

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batching plants. The fixing device ⑨ is used to secure the mixing tank during mixing, preventing it from rotating with the mixing shafts and ensuring the normal progress of the mixing process. The discharge device ⑩ rotates the tank, allowing the mixed material to be smoothly poured out and facilitating the cleaning of debris inside the mixing tank. Figure 7 shows the physical front view of this twin-shaft mixer, Figure 8 shows its back view, and Figure 9 shows the internal structure diagram of the twin-shaft mixer's mixing tank.

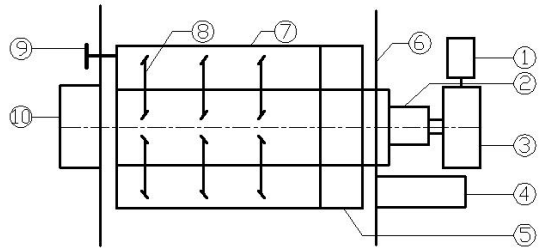


Figure 6 Structure Diagram of Cement Concrete Twin-Shaft Mixer



Figure 7 Physical Front View of Cement Concrete Twin-Shaft Mixer



Figure 8 Physical Rear View of Cement Concrete Twin-Shaft Mixer



Figure 9 Internal Structure Diagram of Cement Concrete Twin-Shaft Mixer Mixing Tank

During the experiment, values for torque, speed, and power can be measured using the data acquisition device. According to the "Test Procedure for Cement and Cement Concrete in Highway Engineering," the slump of cement concrete is determined using a standard slump cone, and the cubic compressive strength is tested using a 300-ton press of model AC-300DE. This yields values for slump and compressive strength. Consequently, relationships can be established between torque and speed, torque and slump, power and speed, and power and slump. Additionally, the influence of different speeds and mixing times on the strength of cement concrete can be observed, thereby providing an online monitoring basis for the quality control of fresh cement concrete[9].

3. System Construction

In the construction of cement concrete pavements, large-scale concrete batching plants are widely applied in actual engineering projects. Controlling the construction process is a crucial step in ensuring the quality of highway engineering. Among these, the concrete mix production stage is the most fundamental step in guaranteeing structure quality. To improve the quality level of highways and ensure the durability of roads and structures, online monitoring of concrete batching plants is a relatively effective method[10].

3.1 Concrete Batching Plant Online Monitoring System

This paper, based on IoT technology, constructed a concrete batching plant online monitoring system, achieving intelligent, remote, and real-time control over the entire production and construction process of distributed concrete batching plants. This system is built using a Browser/Server (B/S) model, relying on the internet to achieve real-time interconnection between the headquarters and various section project departments[11]. The establishment of this system

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enables monitoring of key construction process information, such as batching plant basic information, mixer information, material warehousing information, and real-time production data, providing fundamental information support for concrete construction quality control. The specific implementation plan for the system is as follows:

(1) System Architecture

The concrete batching plant online monitoring system developed in this study adopts a B/S (Browser/Server) architecture. B/S is a network structure model that has evolved with the rise of web technology, using web browsers as the primary client application software. The server runs web application services, and clients directly log into the system using a browser, allowing for convenient data querying and simple maintenance[12].

(2) Network Structure Requirements

The headquarters' local area network (LAN) connects to the internet via routers and firewalls, establishing an interconnected network with each section project department. The headquarters' internet access bandwidth is 20 Mbps, while section project departments can use fiber optic or ADSL for internet access, with bandwidths ranging from 6 Mbps to 10 Mbps[13][14]. For this purpose, a network topology diagram was established, which illustrates the network structure composed of network node devices and communication media, as shown in Figure 10.

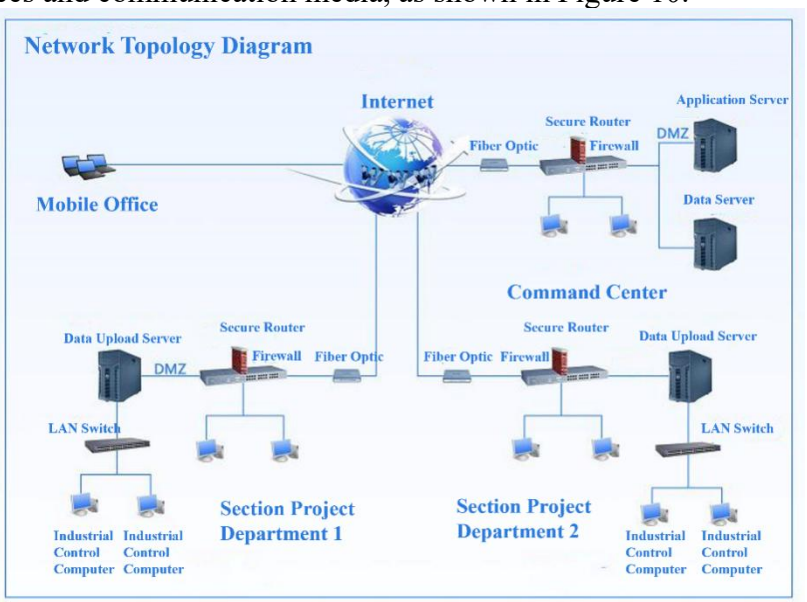


Figure 10: Network Topology Diagram

(3) Basic Functions of the System

To meet the need for monitoring and managing various batching plants, the system must collect basic information from each plant for online management[15].

a. Batching Plant Basic Information: This section includes the batching plant number (a unique number assigned by the headquarters, including section information code), batching plant name, address, person in charge's name, phone number, mobile phone number, fax, number of production lines, status parameters, and remarks.

b. Mixer Information: This section includes the batching plant number, production line number, production line equipment manufacturer's name, maximum capacity of the mixer, current set capacity of the mixer, mixer status, and remarks.

c. Material Warehousing Information (Material name must be combined with material specifications): This section includes the batching plant number, production line number, warehousing order number, warehousing time, material name, quantity, warehousing location (silo name), and remarks. Each batching plant needs to upload daily material warehousing data promptly; the upload can be performed once the warehousing operation is completed. Based on the uploaded warehousing data, the system can query the current day's and current month's material warehousing

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data for each plant and compare it with the current month's material consumption data to verify material usage.

d. Silo Name Information: This section includes the batching plant number, production line number, number of silos, aggregate, powder material, water, admixture, and remarks. Silo names are used to identify both metering hoppers and material inventory locations. Each batching plant needs to upload its existing silo types and names. If the information remains unchanged, a single upload is sufficient.

e. Real-time Production Monitoring Data: This section includes batching plant number, production line number, number of silos, aggregate target value, aggregate weighed value, powder material target value, powder material weighed value, water target value, water weighed value, admixture target value, admixture weighed value, batching plant number, production line number, number of silos, unit name, project name, mix ratio number, construction location, pouring method, vehicle number, operator, total quantity for this batch, cumulative number of batches, cumulative weight, slump, water content, temperature, mixing time, target total weighed value, actual total weighed value, current, power, and torque. When batching plants are in production, they should promptly upload production record data. Uploaded data needs to be marked to avoid duplicate uploads. Production record data can be uploaded every 60 seconds. Based on the uploaded production record data, the system can organize and generate various reports: detailed production per batch, detailed production per vehicle, and production summary reports, for querying and verifying production status and checking production process requirements, thereby achieving the goal of production monitoring. Real-time production monitoring of the concrete batching plant is shown in Figure 11.



(a) Concrete Batching Plant Control Room (b) Production Monitoring Interface

Figure 11: Real-time Production Monitoring Interface of Concrete Batching Plant

3.2 Concrete Batching Plant Data Acquisition and Transmission System

This paper, based on "Cloud Computing + IoT" technology, constructed a concrete batching plant data acquisition and transmission system, aiming to ensure high-quality and efficient collection and transmission of critical production data. The establishment of this system is an effective measure for controlling highway engineering quality. By collecting real-time monitoring data, engineering quality can be controlled online, especially through the collection of current, power, and torque data[16]-[18]. This allows for real-time feedback adjustment of concrete based on observed changes, realizing dynamic analysis of real-time indicators and deviation warning functions, thus ensuring concrete quality[19]. The specific implementation plan for the system is as follows:

(1) Data Acquisition System

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The data acquisition system is part of the intelligent and remote monitoring system for road construction quality control, applying the concepts of "cloud computing + IoT." It integrates data acquisition modules to real-time collect critical parameters from highway cement concrete batching plants, such as cement usage, water usage, aggregate dosages for each grade, and mixing time. The data is then wirelessly transmitted to a cloud server. This system offers advantages such as quick installation, simple operation, and portability. It enables real-time automatic data reading, eliminating the need for additional manual assistance or maintenance. This makes it possible for owners, supervisors, contractors, and quality supervision departments at all levels to understand the performance of cement concrete materials and the operational status of batching plants in real-time without leaving their offices. The data acquisition system on a concrete batching plant is shown in Figure 12.

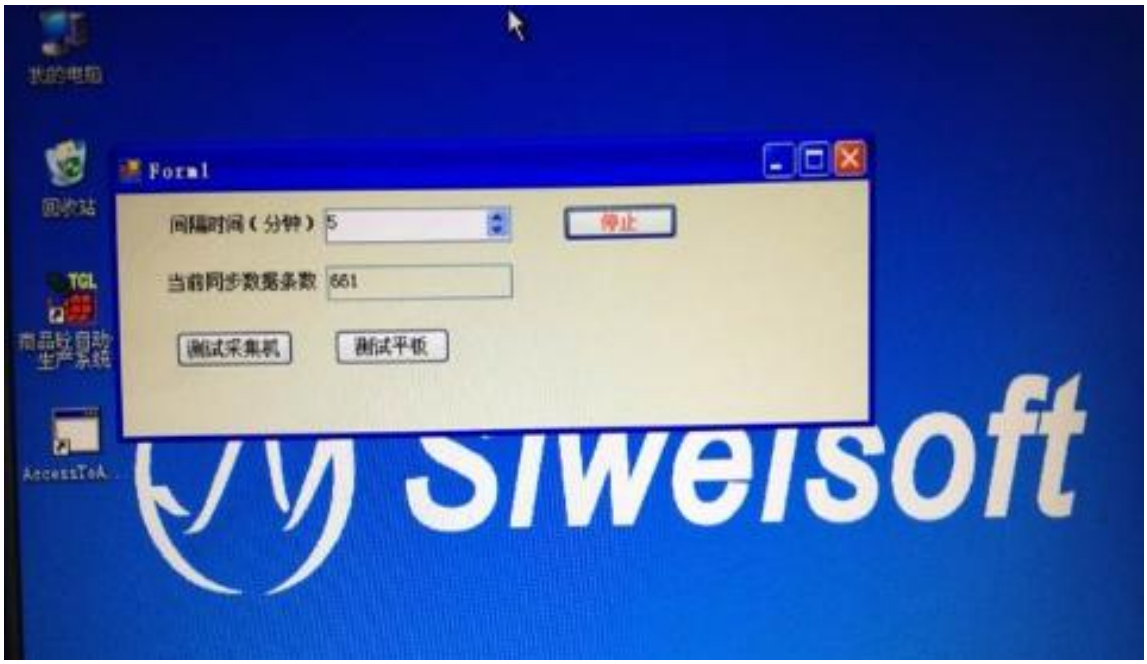


Figure 12 Concrete Batching Plant Data Acquisition Terminal Interface

The data acquisition device uses a GPRS module and connects to external modules for communication via a 485 interface (if not present, a USB to 485 module is required). Before sending data, the acquisition device must establish a connection with the receiving host. By sending the character "a" through the 485 port and awaiting the "a" character reply from the receiving host, the connection is established. After this, collected data is packed and sent to the 485 port, ensuring that the total number of bytes in a data packet (including two-byte checksum) does not exceed 512 bytes. If a single packet cannot send all data, subsequent packets are sent. The connection establishment character only needs to be sent once before the connection is established; once established, data can be sent directly without further sending the "a" character. Data packets use CRC checksum with a generation polynomial of $x^{16}+x^{12}+x^5+1$. The communication baud rate is set to: 9600 baud, 1 stop bit, no parity. While establishing the acquisition device, storage functionality is added to the GPRS module to prevent data loss.

(2) Data Transmission

The data transmission process includes two parts: uploading data from the batching plant to a designated cloud server, and port data transmission[20]. Each batching plant is equipped with a data acquisition and upload system, as well as a data transmission port, to allow for relevant data extraction at any time. The data transmission system in a concrete batching plant is shown in Figure 13.

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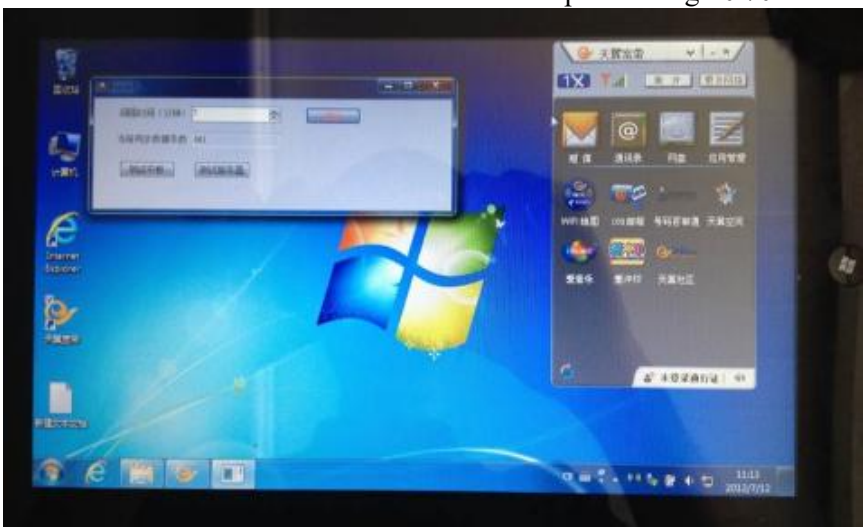


Figure 13 Concrete Batching Plant Data Transmission Terminal Interface

All data types uniformly adopt the Microsoft Excel workbook (.xls) format. The data directory is shown in Table 1.

Table 1: Concrete Batching Plant Data Collection Directory

Weight Unit: Kg															
Batching Plant ID			Production Line ID					Number of Silos							
Unit Name			Project Name					Mix Ratio ID							
Production Time			Construction Location					Pouring Method							
Vehicle Number			Operator					Total for Current Batch							
Cumulative Batches			Cumulative Weight					Slump (mm)							
Material Name	Aggregate 1	Aggregate 2	Aggregate 3	Aggregate 4	…	Cement 1	Cement 2	…	Powder 1	Powder 2	…	Admixture 1	Admixture 2	…	Water
Target Value															
Weighed Value															
Error															
Water Content (%)															
Temperature (°C)															
Mixing Time (s)			Target Total Weighed Value					Actual Total Weighed Value							
Current (A)			Power (W)					Torque (N.m)							

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4. Conclusion

(1) This study designed a mixer for online observation of cement mortar quality. It features blades inclined at a 45° angle to the horizontal, making it suitable for observing the mixing process of cement mortar under shear stress. Compared to conventional cement mortar mixers, it includes a speed adjustment device and online data acquisition and storage equipment, enabling real-time monitoring of torque, power, and speed data.

(2) An experimental twin-shaft concrete mixer was designed to simulate the mixing equipment of batching plants. It utilizes multiple individual mixing blades spirally distributed on two mixing shafts, ensuring thorough, three-dimensional mixing of materials (up-down, left-right, front-back) during concrete mixing, thereby improving concrete uniformity. Compared to common cement concrete mixers, it adds a speed adjustment device and online data acquisition and storage equipment, enabling real-time monitoring of torque, power, and speed data.

(3) A detailed implementation plan for a concrete batching plant online monitoring system was developed. It describes the system's Browser/Server (B/S) architecture, network structure requirements, and basic functions. The B/S structure allows clients to directly log into the system via a browser, offering convenient data querying and simple maintenance. Furthermore, the headquarters can collect batching plant information through various network access points, including mixer information, basic batching plant information, real-time production monitoring data, silo name information, material warehousing information, and more, to achieve real-time monitoring.

(4) A concrete batching plant data acquisition and transmission system device was designed. It describes the working principle of the data acquisition and transmission device, which uses a GPRS module for data collection and transmission. Data is uniformly formatted as Excel spreadsheets, and the data collection directory includes information about the batching plant and its auxiliary equipment. Data transmission involves two parts: uploading data from the batching plant to a designated cloud server, and port data transmission. Based on the establishment of the relevant monitoring systems, online monitoring of batching plants has been achieved.

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