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Received 20 August 2022; Revised 15 November 2022; Accepted 19 November 2022; Published 15 December 2022

1. Introduction

In recent times, sensor technology has been an emerging interest with a significant role in monitoring civil infrastructures. The benefit of this exciting technology is the inexpensive use of sensors and sensor technology. Sensors integrated with an Arduino microcontroller board provide a significant role by providing early warnings in case of any environmental deterioration inside the constituent materials of the specimen and structure. The features and benefits of integrating sensors with Arduino microcontrollers were studied [1]. Portland cement, when it reacts with water, causes heat generation. Ordinary Portland cement, a widely used material in the construction industry, has evolved by adding pozzolanic materials [2, 3], admixtures, minerals, and superplasticizers, thus varying the early heat of hydration [4]. In OPC, tricalcium aluminate is mainly responsible for heat generation [5]. Various methodologies have been employed to evaluate the hydration reaction of cementitious materials, including calorimetric analysis of various mechanisms, such as heat evolved, stiffening, and hydration rates. The heat of hydration of cement was assessed using a calorimeter. Three types of OPC collected from different plants of north (COP-1), middle (COP-2),
Advances in Materials Science and Engineering

and south (COP-3) were tested. It was observed that the heat of hydration increased with the increase in waste water cement and curing temperature [6]. The isothermal calorimetry test was conducted for three days, measuring the heat of hydration of cement-containing slag and rapid hardening cement, concluding that the heat conduction calorimetry for determining the heat of hydration is more precise [7]. Rheological behavior was assessed using the conventional method of rheometric analysis. The conventional methods of rheology include rheometric analysis of cementitious mixes. The rheological properties of fresh cement pastes were investigated using a standard rheometer [8]. The rheological study analyzes various properties of viscous material. Amongst many properties exhibited by fresh cement, rheology has a major impact on thixotropic behavior of ordinary Portland cement. The microstructure of cement was analyzed. The thixotropic behavior of cement, the influence of addition of minerals, the effect of the mixing method, viscoelastic behavior, flow behavior, and the impact of addition of chemicals were the factors that affected rheological behavior. The elastic and viscous components of ordinary Portland cement pastes and blended (fly ash, silica fume, and slag) cement pastes were characterized using a dynamic shear rheometer (DSR) [9]. The decrease in plastic viscosity and yield stress was observed when cement was partially replaced with limestone. A direct correlation was observed between plastic viscosity and yield stress to the specific surface area [10]. The properties of cementitious pastes and their constituent materials also include water absorption capability, which directly affects compressive strength and durability. Fly ash and silica fume were added as a partial replacement material in ordinary Portland cement, and a sorptivity test was conducted. It was examined that the compressive strength of 28 day cubes increased for FA and SF and decreased for only FA-containing cubes [11]. The low-cost Arduino-based integrated sensor system can assess the mechanical properties of cement mortar [12]. Besides the conventional techniques of analyzing the heat of hydration, rheology, and sorptivity, several types of research were conducted to determine the hydration process and evaluate the temperature, including the mechanisms of analyzing the hydration rate. Various types of sensors (electrical devices for detecting certain types of signals, widely used as a technology for determining temperature, rheological behavior, and moisture content, etc., integrated with an Arduino microcontroller board) are used in this research for enhancing performance and monitoring cementitious mixes. The sensors SHT15 and SHT21S were embedded in a concrete structure for monitoring the humidity and temperature in an alkaline environment, enabling the low cost and real-time process. The alkaline environment was monitored for two months, emphasizing the monitoring at the early stage as well as the curing phase, validating an inexpensive approach, and minimizing structural health issues [13]. The long-term monitoring of large civil infrastructure and its constituent materials, including temperature, moisture state, reinforcement corrosion, and structural changes, was investigated using various sensors [14]. Long-term and real-time humidity and temperature monitoring were observed by implementing the radio frequency-integrated circuit (RFIC) and sensor technology [15]. An Arduino-based humidity and temperature sensor was built to monitor environmental parameters successfully, reducing cost and power consumption. Information was displayed on a liquid crystal display. The programmable USB port could be connected to a computer using a cable [16]. The system is based on a sensor network that monitors, collects, and processes the data of environmental parameters. The monitoring system is cost-effective and includes an XBee module, Raspberry Pi, Arduino Nano, and sensor nodes. The results and detailed design confirmed the effectiveness of the system [17].

Reviewing the literature, it is apparent that low-cost microcontroller sensors have been employed to predict the properties of cementitious mixes. Rheometers, calorimeters, and water tanks were used to measure rheological parameters, hydration mechanisms, and sorptivity. However, on-field measurement of the degree of hydration is unmanageable. Moreover, a calorimeter is expensive, and portability is also not possible. However, low-cost sensors are inexpensive for assessing the hydration, rheology, and moisture-absorbing properties of cement mixes. Moreover, real-time data transmission is also an important aspect of this research. This study intends to promote the use of integrated sensors with an Arduino microcontroller in substitution of conventional equipment.

There are three major aspects of the present research. First, the hydration mechanism was evaluated using a temperature sensor integrated with an Arduino MC. Second, rheological parameters such as apparent viscosity were predicted in terms of moisture and temperature data of cementitious mixes. Finally, using Arduino-integrated moisture sensors, sorptivity values of 28-day cured cement pastes were measured. SEM and EDX analyses were conducted. The sensor-based experimental setup was preferred for monitoring parameters and finding a solution to overcome or minimize the impact of internal physiochemical effects, i.e., humidity, temperature, and moisture condition. Thus, validated results were provided using sensor-based apparatus. However, certain limitations, i.e., calibration and signal transmission stability were considered.

2. Motivation for the Study

The key objective of this interdisciplinary study is the development of wireless sensing networks (WSNs) for monitoring parameters inside cementitious mixtures and the development of an integrative system to emphasize the applications of microcontrollers, sensors, and app development and to overcome or minimize risks in civil engineering structures. The proposed work is an explorative approach and one of the most significant possibilities for the safety of civil engineering structures.

The proposed network is an accessible way of incorporating an Arduino microcontroller device, sensors, a communication module, and an application installed to store data, and it has the ability to sense internal environmental changes and gather information detected using sensors. Data can be
acquired and transmitted through signal processing from the point inside the sample where sensors are inserted. WSN is useful when uninterrupted, and rapid monitoring is required in certain situations. The sensors integrated with the Arduino microcontroller help in a substantial reduction in cost as well as installation time. For the application of WSNs in civil engineering, a platform is given, enabling the accommodation of a number of sensors integrated with the Arduino microcontroller, reducing the cost, and sharing data through the network. To fulfill this requirement, a micro-SD card is a remote agent for storing data or wireless transmission through an Android application. The Arduino platform is used for programming and constructing electronics, which can receive data and send information to android apps and other devices [18–25]. Temperature is a significant factor during the curing stage of cementitious pastes, which directly affects hydration reactions. With the decrease in temperature, the process of hydration decelerates. Hence, the hydration process accelerates with the temperature increase, resulting in temperature variations. The properties of various cementitious pastes significantly affect numerous parameters that further affect environmental parameters i.e., humidity and temperature. Thus, it is worthwhile to study the effect of temperature on the hydration mechanism.

3. Materials and Methods

In the present research, materials used in the mixture composition include Type I OPC conforming to ASTM C 150 [26], which was purchased from Kohat Cement Factory and is well-known for its primary binding properties. Specific gravity, fineness, and particle size were measured to be 3.15, ~2800 cm²/g, and 10–30 micron, respectively. Additionally, class C fly ash with a specific gravity of 2.10 and silica fume with a specific gravity of 2.25 were purchased from Matrixx Company, Karachi, as partial replacement for cement. Specifications of silica fume are as per ASTM C 1240 [27], while fly ash conforms to ASTM C618 [28]. Table 1 represents the chemical composition of ordinary Portland cement, silica fume, and fly ash. Physical properties are given in Table 2. Six samples of cementitious mixes were prepared with various cementitious materials with a water-to-binder ratio of 0.3. Silica fume and fly ash were added as partial replacement for cement. Mixture designations and ratio proportions are listed in Table 3. All cementitious materials were in powdered form and weighed with a physical balance. According to the mix proportion presented in Table 3, each mixture was mixed thoroughly and water with a w/b ratio of 0.3 was added, forming paste. The mixing time was about 2 minutes to produce a workable mixture. Each mixture, when cast in the tray, was covered. The testing procedure was conducted at a room temperature of 20°C.

4. Assessment of Hydration, Rheological Parameters, and Sorptivity

4.1. Assessment of Hydration, Rheological Parameters, and Sorptivity Using Conventional Methods. The test equipment includes a calorimeter, a rheometer, and sorptivity apparatus. The heat of the hydration test was carried out using E061N model hydration equipment. The specific equipment was purchased from MATEST, Italy. Cementitious samples were placed in containers while keeping the container at a particular temperature. A thermocouple was used to record the temperature of samples. At the early hydration state, thermocouples recorded the variation in temperature during the hydration reaction over 32 hours. An ICAR rheometer with approximately 22 liters was used to evaluate the rheological behavior of cementitious samples. The ICAR rheometer has a maximum torque of 20 N-m and about 60 rev/min rotational speed. Sorptivity values were assessed by keeping the oven-dried sample cubes in water. The cubes were prepared, surface dried, and weighed before placing them in the oven for 24 hours at about 105°C. After oven drying for 24 hours, the weight of the cubes was noted again. Subsequently, the cubes were placed in edge rod triangular-shaped buckets. Up to 5 mm of water was poured into a bucket and the sample cubes were kept for about 24 hours. After that, the remaining surfaces of the cubes were sealed using paraffin wax. Data were recorded at intervals, i.e., after 30, 60, 110, and 120 minutes. Afterward, the samples were removed. The weight of the samples was noted to find the absorbed amount of water.

4.2. Assessment of Hydration, Rheological Parameters, and Sorptivity Using Sensor-Based Equipment

4.2.1. Sensors

(1) Soil Moisture Sensor. A two-legged soil moisture sensor FC-28 of 60cm × 20cm × 5cm size with two pins at its top connected to an amplifier and integrated with Arduino Mega 2560 was selected for moisture and sorptivity analysis in this research. The calibration of the moisture sensor was carried out. The moisture sensor records the data in digital form in % from 0 to 100. Two probes of the sensor were embedded inside the sample. These probes were in contact with the cementitious paste prepared to record water content. More water in the mixture confirms more electrical conductivity, leading to lower resistance. Therefore, the moisture level will be higher. Some important specifications of soil moisture sensors are represented in Table 4. The calibration of the soil moisture sensor and the temperature sensor is shown in Figure 1.

(2) DS18B20 Waterproof Sensor-Temperature Sensor. A precise and heat-shrink version of the digital and programmable (1-wire) DS18B20 waterproof temperature sensor integrated with Arduino Mega 2560 was used, facilitating the analysis of the hydration mechanism inside cementitious pastes. The temperature range varies from −55°C to +125°C with ±50°C accuracy, while the minimum voltage on which this sensor operates is 2V–5V. The temperature sensor was calibrated to avoid discrepancies.
4.2.2. Testing Methods for Analyzing Hydration, Rheology, and Sorptivity

(1) Assessment of Heat of Hydration, Rheology, and Sorptivity Using Conventional Techniques. A calorimetric test was performed to measure the degree of hydration of cementitious pastes using a calorimeter (TAM air isothermal). A total of 4 g samples from each cementitious paste were taken after the paste was prepared. The samples were tested for 32 hours at a temperature of 20°C.

Rheological parameters were analyzed using a rheometer. Materials include OPC, SF, and FA with the addition of water (a w/b ratio of 0.3). At a room temperature of 25 ± 1°C, the cementitious paste was prepared and mixed thoroughly. Water was poured into the Hobart blender, and cementitious paste was introduced, forming slurry. Before the experiment was started, a shear rate of 0.1 s⁻¹ was applied to remove memory effects and maintain the microstructure undisturbed during the pouring of paste. The cylinder and surface of the container were roughed, while the gap between them was kept at 0.97 mm. Afterward, the cementitious paste was tested for 5 minutes. The prepared slurry was poured into the rheometer and mixed at a low rotational speed of 1 minute. To obtain a consistent cementitious paste, the slurry was mixed at an interval of 0.5 minutes. Subsequently, after the homogeneity of samples, it is further mixed continuously for about 2 minutes. To avoid the risk of plug flow, a coaxial cylinder was selected. A few drops of oil were introduced at the top surface to reduce water evaporation. A linear increase from a 0 s to 1 to 100 s⁻¹ shear rate was applied within 90 seconds, followed by a 15 s⁻¹ shear rate for about 50
minutes. After continuous shearing, the applied shear rate was stopped for about 15 seconds. Continuous readings were then taken after 50 minutes, measuring the rheological behavior of all cementitious pastes with proper proportions given in Table 5 and Table 6.

Herschel–Bulkley for estimation of rheological parameters is as follows:
\[
\tau = \tau_0 + K\gamma^n.
\] (1)

Moreover, the sorptivity test was conducted to analyze capillarity in prepared cementitious pastes. Sample cubes were cast from each proportioned cementitious paste. Dry mortar cubes after casting were weighed, and weights were noted, respectively. Oven-dried weights were also noted. Moreover, moisture content and hydration were recorded. Later, the cubes were immersed in water so that the level of immersion from the base of the specimen was 5 mm. The remaining surfaces were sealed with paraffin wax. Before weighing the cubes, the surface was wiped off with a tissue. The weighing process was conducted in 30 seconds. This test was conducted at a room temperature of 20 °C. The time for immersion of the cubes in water was 24 hours. Sorptivity data were recorded after 30, 60, and 120 minutes. Figure 2 shows the capillary water absorption test’s calorimeter, rheometer, and experimental setup. \( t = \text{time elapsed in minutes} \), \( I = \Delta w/\Delta A \Delta w = \text{change in weight} = W2 - W1 \), \( W1 = \text{dried weight of mortar cubes in grams} \), \( W2 = \text{weight after capillary suction (after 30 minutes)} \), \( d = \text{density of water} \), \( A = \text{water penetrated at the surface area of the specimen} \).

\[ I = t \text{ therefore } S = I/t, \] (2)

(2) Assessment of Heat of Hydration, Rheology, and Sorptivity using Arduino-Integrated Sensors. The heat of hydration, rheological parameters, and sorptivity of six samples of cementitious pastes were monitored using sensors (integrated with an Arduino microcontroller device). The heat of hydration was assessed using a temperature sensor. Rheological parameters were assessed using a moisture sensor in terms of moisture content in percentage. It was presumed that the moisture content of cementitious mixes is dependent on rheological parameters. The sorptivity of cement paste was estimated using soil moisture sensors. Moisture sensors were allowed to sense the moisture content of cement mixes. The platform for determining the temperature inside cementitious mixes is shown in Figure 3. Figure 4 shows the platform for analyzing the rheological behavior of cementitious mixes at a 5-minute test. A setup was made for the home environment and remote environment. The setup of the home environment was shielded to protect the surface of cementitious samples and to avoid errors in temperature and moisture readings due to environmental changes, thus leading to more accurate results. This setup formulates a remote monitoring system responsible for data collection and processing.

The heat of the hydration test was performed to analyze the hydration mechanism of six samples of cementitious mixes prepared, as discussed in section 3.1. All the six samples were tested one after another by inserting the temperature sensor in cementitious mixes for 32 hours. Temperature data were recorded in °C by connecting the Arduino device to the power supply. The data were logged in the Arduino centrale free Android application. A datasheet was created from an excel file using the Arduino centrale free application. Temperature data were recorded at an interval of 2 hours.

Similarly, the rheological parameters of six samples of cementitious mixes were assessed using a moisture sensor. Moisture sensors were placed in the samples so
that both probes of the sensor were properly in contact
with cementitious mixes. A 5-minute test was conducted.
A constant shear rate of 0–15 s−1 was applied to ce-
mentitious pastes for 1 minute to analyze rheological
behavior. The mixture was then set to homogenize for 0.5
minutes. After 0.5 minutes, a shear rate was applied for 2
minutes after resting the mixture to homogenize for 0.5
minutes. A shear rate of 1 minute was applied again.

Moisture content was recorded for 5 minutes. Rheo-
logical parameters were assessed in terms of moisture
content.

Sorptivity analysis, i.e., capillarity was performed to
examine the permeability of cementitious pastes inside
the cube specimens of 50 × 50 × 50 mm dimension. Six
cubes were prepared from cementitious pastes with the
same proportion, as discussed in section 3.1. Moisture
sensors were inserted during the casting of cubes. The cubes were surface dried and weighed after casting. Afterward, the cubes were oven-dried and weighed again. After that, the cubes were immersed in water for 24 hours in such a way that the immersion level was about 5 mm from the base of the specimen, sealing the remaining surfaces of the cubes with paraffin wax. Sensors were connected to the Arduino device and power supply. The application was installed on an android phone and connected to an Arduino device. The moisture content data were recorded in percentage for 24 hours. A test of all six specimen cubes was conducted, and sorptivity values in terms of moisture content were plotted against original weights. Moisture absorbed by the specimen cubes was noted at 0, 30, 64, 110, and 120 min. The lowest sorptivity value was found for SF5FA50 and the highest for OPC.

The sorptivity values obtained from the conventional method were compared with moisture content values obtained by fixing moisture sensors inside specimen cubes. Figure 3 shows the platform for Arduino-based sensor testing, preparation of cement pastes, and placement of temperature sensors in cementitious pastes.
(3) Data Acquisition and Remote Monitoring. A data acquisition platform was prepared to collect, process, and transmit the recorded data. The acquisition arrangement comprises an acquisition device powered by a battery capable of transmitting information about cementitious pastes and their constituent materials to a data collection center through a data link wirelessly. The acquisition device consists of a wireless digital transmitter, a vibrational mechanical sensor, a battery, and a data circuitry for acquisition. The central device capable of collecting data comprises a digital receiver. The function of a digital receiver is to receive data, while a microprocessor processes data. In this research, Arduino Mega 2560 was a primary contributor to data collection. An Arduino centrale free application was installed on an android phone to record data from the acquisition device. Using Bluetooth, data were transmitted from the acquisition device to the Arduino centrale free application. A schematic representation of the monitoring platform is shown in Figure 5. The Arduino board, an IRIS mote, facilitates the creation of an IEEE 802.15.4 network for collecting data from moisture and temperature sensors placed inside cementitious pastes. Data acquisition was performed by interacting it with devices, i.e., Zigbee-capable cell phones and laptops. The access point (AP) receives reports periodic values each second.

4.2.3. Data Analysis and Correlation. The results obtained using the sensor-based system were correlated with the results obtained using conventional methods performed in our present research work. The conventional apparatus includes the calorimeter, rheometer, and sorptivity experimental setup, while the smart technique is based on Arduino-integrated sensors. The heat of hydration and water content can be analyzed from the amount of calcium hydroxide hydrated during the hydration reaction, while water content remains unevaporated.

5. Results and Discussion

5.1. Rheological Study. The present research work encompasses the comparative analysis of assessment using conventional apparatus and integrated sensors. A rheological test was performed to investigate shear-thinning behavior, viscosity, and shear-thickening behavior of cementitious mixes. At a shear rate of 0 to 15 s⁻¹, shear-thickening behavior and shear-thinning behavior were examined. Moreover, the impact of replacing OPC with 5, 25, and 50% of SF and FA as a binary and ternary cementitious paste on the behavior of rheological parameters was investigated. The results of up and downflow curves of the apparent viscosity of cementitious mixes using the conventional apparatus are illustrated in Figure 6. It was examined that when shear stress was applied at the same rate, the downflow curves were always lower than the upflow curves of apparent viscosity. The reason for this fact is the structural breakdown due to the shear rate applied [30].

From the comparison of the flow curves of OPC with that of binary cementitious pastes, a smaller difference between the up and down flow curves was observed for binary cementitious pastes.

The up and downflow curves of cementitious pastes at a 5-min shear rate test are illustrated in Figure 6(b). In comparison with the reference curve of OPC in Figure 6(b), shear stress decreased with the addition of 25% of FA, while FA50 further reduced the shear stress. The incorporation of SF5 increased the shear stress due to which SF5 showed less fluidity, while the addition of FA showed a reverse effect. This indicated that replacing 5% of SF modified rheological behavior, i.e., shear-thickening behavior was changed to shear-thinning behavior. This fact agrees with the results obtained from differential viscosity [31–33]. During the applied shear rate, the downflow curves of all the cementitious pastes were seated at the lower side than the upflow curves. This suggested a structural breakdown during the rheological test, confirming the thixotropic behavior of cementitious pastes at an early age [34]. Both up and downflow curves of OPC and binary cementitious mixes (FA25 and FA50) were smooth. However, the curves of cementitious pastes containing SF confirm a stress overshoot, followed by reaching a steady state. This fact might be due to the breakdown of the structural build-up of silica fume having a higher specific surface area after applying a high shear rate [35]. The incorporation of fly ash with silica fume in cementitious mixes resulted in decreased stress overshoot intensity. This fact, to some extent, means that the replacement of fly ash in cementitious mixes causes a reduction in the structural build-up.

Comparing the apparent viscosity and moisture content of cementitious mixes shown in Figure 7, OPC was considered a reference cementitious paste. It was examined that moisture content affects rheological parameters. The incorporation of 5% of silica fume with OPC reduces the moisture content. SF5 possesses the lowest moisture content value among cementitious mixes. This might be due to the strengthened bond between SF and OPC. Thus, SF5 was considered more viscous due to less moisture content, while the addition of silica fume in cementitious mixes caused a reduction in moisture content; i.e., viscosity increased. There is a significant decrease in the moisture content with the incorporation of SF5FA25 and SF5FA50. The incorporation of fly ash with silica fume in a cementitious mix increased the moisture content. From the above discussions, the moisture content is observed to be inversely related to viscosity.

5.2. Heat of Hydration Analysis. The heat of hydration curves of cement pastes containing OPC, SF5, FA25, SF5FA25, FA50, and SF5FA50 is depicted in Figure 8. In Figure 8, the influence of silica fume and fly ash on heat of the hydration phase was discussed using several parameters. Incorporating SF5, SF5FA25, SF5FA50, FA25, and FA50 affects the retardation and acceleration process in the hydration mechanism. The time to reach the peak was delayed significantly with the increase in fly ash quantity as it was shown that fly ash retarded the heat of the hydration process. The declination of the heat of hydration is consistent with the results.
However, resting for about 1 hour slightly impacted the hydration process for the FA25 sample. Silica fume was mainly responsible for increasing the heat of the hydration process, thus attaining the peak value. The SF5 in binary cementitious pastes positively influenced the hydration mechanism. The rate of the heat of hydration was increased after the incorporation of SF5, and the 1.1 h period was the time to reach the accelerated peak, which conformed to the results in [37–39]. However, adding fly ash with silica fume in SF5FA25 and SF5FA50 decelerated the heat of the hydration process.

Figure 9 depicts the temperature curves of cementitious pastes for 32 hours plotted from the result obtained using an Arduino-integrated temperature sensor. The temperature versus time graph of cementitious pastes was analyzed. The temperature curve consists of four major phases [40].

The reaction between cement and water induces heat evolution during the first stage, which causes a rise in the temperature of the cement paste. During the second phase of the hydration mechanism, the temperature of the system decreases due to the decrease in an exothermic reaction. The duration of the induction or dormant period depends on the setting time of cementitious pastes. One main reason for the dormant period is nucleation of ettringite crystals during cement hydration reaction. The period of the first phase is denoted as t1. During the third phase, the temperature of the
cementitious paste reaches its peak value. Calcium silicate hydrates and portlandite formed during the third phase due to reaction of alite and belite with water. The maximum period is denoted by $t_2$ where $T_{max}$ denotes the temperature at the maximum time period. In the last phase, i.e., the fourth phase, the exothermic reaction reduces, resulting in the cooling of the cement paste. In Figure 8, the effect of the heat of hydration of all the cementitious pastes was analyzed in terms of temperature and compared with that of the results obtained using the conventional method shown in Figure 9. The OPC sample was considered a reference cementitious paste. An increase in temperature was observed with the incorporation of SF5. The SF5 sample attains the maximum peak during the hydration mechanism. The time to attain the maximum peak for SF5 was from 0 to 4 hours. A decrease in the temperature value was observed for FA25 and FA50. Using fly ash with silica fume for the samples (SF5FA25 and SF5FA50), the temperature value dropped. The lowest and delayed temperature peak was observed for the SF5FA50 sample.

5.3. Sorptivity Analysis. Sorptivity is a material property, indicating a porous material’s tendency for water absorption and transmission through capillarity [42]. The sorptivity test supports the water retention test and specifies the volume of voids. Figure 10 illustrates the sorptivity of six specimens containing pure cement, fly ash, and silica fume in binary and ternary compositions. The sorptivity value ranges from 0.007 to 0.0021 cm/min$^{0.5}$. The sorptivity values decreased with the increase in the fly ash amount in the binary cementitious paste. The reason is that fly ash has high water-holding capacity [43]. Moreover, it was experimentally proved that the compressive strength of cement-containing mixtures was affected due to porosity [44, 45]. The more porosity, the lower the compressive strength [46, 47]. The sorptivity values of specimens containing SF5 were lower than the sorptivity values of all the specimens except SF5 as a binary cementitious specimen [48]. Moreover, comparing the compressive strength with sorptivity also concluded that the specimen cubes prepared from binary and ternary cementitious pastes have high sorptivity coefficient values and lower compressive strength. Figure 10 represents the sorptivity coefficients of specimen cubes containing OPC, FA25, FA50, SF5, SF5FA25, and SF5FA50. Figure 11 shows the moisture content of specimen cubes using a moisture sensor. The compressive strength of 28 days cured specimen cubes of cementitious pastes is shown in Figure 12.

5.4. SEM Analysis. The SEM analysis of 28 days cured specimens of OPC, FA25, FA50, SF5, SF5FA25, and SF5FA50 was performed to check orientation, positioning, and morphology. The microscopic images of six specimens cured for 28 days at 20°C are shown in Figure 13. The morphology of the sample containing 100 grams of OPC is demonstrated in Figure 13(a). The major hydration product is portlandite. The micrographs taken at 12000x magnification show a plate-like structure. Figure 13(b) depicts the morphology of the sample containing 25% FA at 5000x magnification. After 28 days, C–S–H was formed. More C–S–H bonds were formed in the sample containing 50% FA, as shown in Figure 13(c). Ca (OH)$_2$ formed as the hydration product in the SF5 sample. Morphology is shown at a magnification of 10000x in Figure 13(d). In Figures 13(e) and 13(f), ettringite (needle-like shape) was formed. Figure 14 shows EDX analysis of various cement pastes after 28 days of hydration.

5.5. Data Transmission Using Bluetooth. In this study, low-cost Arduino-integrated sensor technology detected the moisture and temperature of various cementitious pastes. In the designed remote environment, all the process, including data acquisition, was outside except the sensor, embedded
inside the specimens. The battery was used as an operating component. However, battery service life was a major concern for an electronic component. Thus, we preferred the possibility of replacing the battery with direct voltage, facilitating long-term data monitoring. Furthermore, the heat of hydration and moisture at a single point was studied. A centralized data monitoring system could also be introduced by fixing the sensors at multiple points, thus analyzing the heat of hydration and moisture content of overall cementitious pastes, where all sensors could be connected to the base station. Furthermore, significant data could be collected during long-term monitoring. Data could be stored in a memory card or database for long-term monitoring. Moreover, shielding the proposed cementitious pastes from environmental deterioration assists in recording accurate results.

The data transmitted using Bluetooth from the Arduino device to the android application, i.e., an Arduino centrale free app, were recorded. The process of the recorded data using the app is shown in Figure 15. Figure 16 shows the recorded temperature data, and Figure 17 depicts the recorded moisture content data.
Figure 12: Compressive strength of 28 days OPC, FA25, FA50, SF5, SF5FA25, and SF5FA50-based cement paste specimen cubes.

Figure 13: Continued.
Figure 13: SEM images of cement pastes after 28 days: (a) OPC, (b) FA25, (c) FA50, (d) SF5, (e) SF5FA25, and (f) SF5FA50.

Figure 14: Continued.
Figure 14: EDX Analysis of cement pastes cured for 28 days. (a) OPC, (b) FA25, (c) FA50, (d) SF5, (e) SF5FA25, and (f) SF5FA50.
5.6. Data Transmission Using the Internet. The data were transmitted using a Wi-Fi network connection. In the present setup shown in Figure 18, the Wi-Fi router and the modem connected to an Arduino device send data wirelessly. The Wi-Fi was connected without an Ethernet cable or wired LAN. The schematic diagram of the Wi-Fi modem and the router system is shown in Figure 19. In this system, Arduino Mega 2560 acts as a center that sends the recorded data to the router and then to the data processing center. The router connected to the integrated modem sends the Internet-monitored data and receives the commands from the website to Arduino. A local network router was used, which was integrated with the modem.

The result was obtained using Internet-based platforms. If the Wi-Fi network is unavailable, an Ethernet cable can be
used. The router, Ethernet card, switch hub, and modem are some of the supporting tools of the LAN (local area network) [49]. Temperature, rheological behavior, and moisture content data were analyzed wirelessly using a Wi-Fi shield. The sensors were connected with an Arduino device, i.e., Mega 2560. Furthermore, the modem was interfaced with the Arduino to connect it to the Internet via a wireless router. Data logging was saved on an SD card. This system enabled monitoring of temperature and moisture content. The Ethernet shield and the Arduino device were used to create a web server. The Ethernet library was used for HTML requests. After opening the browser and
navigating to the specific IP address of the Ethernet shield, input values were displayed on the web server provided. The temperature and moisture data were displayed on the web using an Ethernet shield. After accessing the IP address assigned to the Wi-Fi module, the temperature and moisture values were displayed over the HTML web page. The request was sent from the given IP address of the web server to Arduino. In response, data were displayed on the Arduino web server. The web page was refreshed every five seconds. The block diagram of

**Figure 18:** Schematic diagram of data transmission through the Internet.

**Figure 19:** Block representation of data transmission using the Wi-Fi modem and the router.
data transmission using the Wi-Fi modem and the router is shown in Figure 19.

Moreover, data were wirelessly transmitted to a self-developed Android phone-based application. The temperature and moisture content data were recorded and displayed on the screen of the Android application. Temperature and moisture content data logging is shown in Figure 20 and Figure 21.

6. Conclusions

This work studied the comparison of moisture and temperature variations of cementitious pastes containing OPC, SF5, FA25, SF5FA25, FA50, and SF5FA50 using conventional and sensor-based equipment. The effects of SF and FA on hydration and rheological behavior of cementitious pastes were studied.
Following conclusions were obtained from this study:

(1) Based on the results obtained from the hydration study of cementitious pastes containing OPC, SF5, FA25, SF5FA25, FA50, and SF5FA50, using a DS18B20 waterproof temperature sensor, heat evolution rate curves were obtained. The retardation in the hydration process was observed with the incorporation of FA. With the incorporation of SF, a positive influence was observed on the hydration curve. However, 25% of SF slightly reduced the total heat of hydration of cementitious pastes.

(2) From the rheological curve, it was observed that the shear-thickening behavior of cementitious pastes was converted to shear-thinning behavior at a low shear rate range. FA content retards the shear stresses curve.

(3) In binary composition, incorporating SF (5%) reduced the moisture content due to the strengthened bond with SF. On the other hand, in ternary compounds of cementitious pastes, the incorporation of 25% FA and 50% FA increased the moisture content, and hence, fluidity also increases. Thus, the dependency of moisture content on rheological behavior was confirmed.

(4) The potential of the proposed network was confirmed from a comparative study of plotted graphs of the heat of hydration and moisture content using conventional methods with those obtained using sensor-based equipment.

(5) The process of data transmission comprises the data acquisition device. The processed temperature and moisture data were transmitted using an Android phone-based application. Periodic values were reported. The sensor system provides continuous and long-term monitoring. Moreover, data were also transmitted via the Internet using a Wi-Fi modem and a router. Afterward, the temperature and moisture content data were logged in the Android application. This technique provides an advanced approach for data monitoring.

(6) The microscopic details of 28 days cured specimen cubes obtained by scanning electron microscopy (SEM) and EDX analysis confirmed the presence of portlandite, calcium silicate hydrate, and portlandite content.

**Data Availability**

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

**Conflicts of Interest**

The authors declare no conflicts of interest regarding the publication of this research work.

**Authors’ Contributions**

KA and MAS were responsible for conceptualization; MA, AH, and BZ were responsible for data curation; MMSS, MAS, MA, and BZ were responsible for formal analysis; MMSS was responsible for funding acquisition; KA, MAS, AH, and BZ were responsible for investigation; KA, MAS, and AH were responsible for methodology; BZ, MAS, and MMSS were responsible for project administration; MMSS was responsible for collecting resources; KA and MAS were responsible for writing the original draft of the manuscript; BZ, MA, and MMSS were responsible for writing and reviewing and editing the manuscript.

**Acknowledgments**

The research was partially funded by the Ministry of Science and Higher Education of the Russian Federation under the strategic academic leadership program “Priority 2030” (Agreement 075-15-2021-1333 dated 30 September 2021).

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