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# Structural Temperature Determination: A Review

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**ABSTRACT:** The structural temperature sensors measure the temperature of a structural unit and thereby help in monitoring the rate of hydration and strength development of concrete. With recent advancements in sensor technology, structural health monitoring systems have been developed and implemented in various civil structures such as bridges, buildings, tunnels and power plants. Early age temperature related behaviour of concrete is critical for its long term performance and durability. Therefore, measuring and monitoring thermal response of concrete components over time, at various points, plays a crucial role in determining structural health. While, in case of mass concrete works like dams and huge footings, temperature stresses have high potential to create cracks due to space restraints in concrete, affecting its longer performance. Therefore, temperature measurement has significant importance in mass concreting. In modern era, structural temperature measurement is not only done during the construction phase but post construction, the longer term temperature monitoring is also crucial. Many residential, commercial and industrial buildings are in a race to save energy consumption. Sophisticated software controls the air-conditioning requirements which again rely upon the actual temperature measurement of structural elements. Over the last few decades, many advanced types of sensors and data communication technologies have been developed to continuously measure and monitor structural temperature condition through real-time and historical data collection. However, there are still a considerable number of questions associated with the use of temperature sensors. One of the critical questions is discovering how to determine an appropriate type of sensor that can efficiently meet the requirements of temperature measurement and therefore the monitoring system. In this paper, a brief review on various types of structural temperature measurement and prediction is presented with a focus on different types of sensors and data communication techniques. Their advantages and disadvantages are tabulated in order to quickly help potential researchers to decide on the selection of a sensor type.

**KEYWORDS:** Structural temperature monitoring, Temperature determination, Sensors,

## I. INTRODUCTION

Determining the thermal response of concrete is important in determining structural health. Also, it has significant importance in mass concreting. Also, structural temperature measurement is not only done during the construction phase but post construction, the longer term temperature monitoring is also crucial. Many residential, commercial and industrial buildings need energy consumption optimization systems. There are more than fifty different types of sensors whose deployment into practical devices facilitates long-term monitoring of structural changes, reinforcement corrosion, concrete chemistry, moisture state and temperature [6]. To name a few are Humidity sensor (Sensirion SHT21), Temperature sensor (Texas Instruments TMP006 IR), Pressure sensor (Epcos T5400), Accelerometer (Kionix KXTJ9), Gyroscope (InvenSense IMU-3000), Magnetometer etc. [7] however scope of the present paper is restricted to review the structural temperature determination methods.

There are different kinds of temperature measurement techniques; including those used in the civil engineering applications (ref. 1-12). The present paper outlines the potential structural temperature determination as shown in Fig 1.

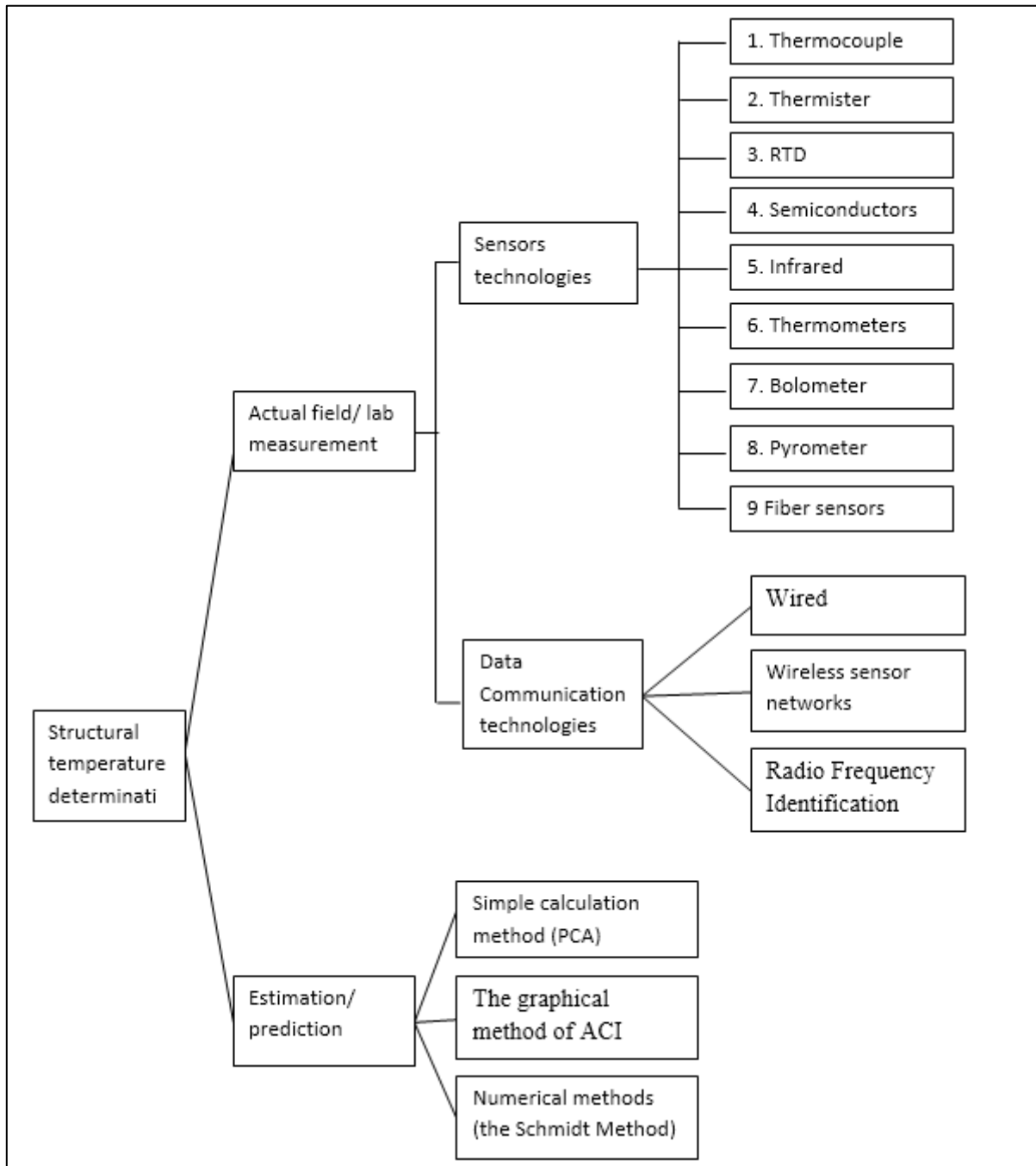


Fig. 2. Structural temperature determination outline by broader level classification

## II. LITERATURE REVIEW

Tremendous amount of literature is available on different kinds of temperature estimation and measurement methods along with the sensors and data communication techniques. However ‘big picture level’ review study is still missing to guide a user on selection of a particular method or a sensor. This issue has been tried to address in this paper with the help of following literature review followed by the discussion.

**2.1. Kyle. A. Raiding et al. (2006):** Authors of this study compared calculated temperature values from three commonly-used concrete temperature prediction methods to actual temperatures in eight different concrete bridge members measured during construction. A simple temperature calculation method, the graphical method of ACI



207.2R, and a numerical heat transfer method (the Schmidt Method) were used to predict peak temperatures. The Schmidt Method performed the best when semi-adiabatic calorimetric results were used in the analysis. Suggestions were made on ways to improve the best technique for the Schmidt Method. According to the authors, temperatures predicted using Schmidt method could be significantly improved by accounting for the heat generated in the concrete by more current hydration models that can account for the effect of modern cements and various SCMs.

**2.2 MaciejSibinski et al. (2010):** In this paper authors focused on the elaboration of miniaturized flexible temperature sensors. Examined sensors were manufactured on a single yarn, which ensures their high flexibility and good compatibility with textiles. Stable and linear characteristics were obtained by special technological process and applied temperature profiles. As a thermo-sensitive materials the innovative polymer compositions filled with multiwall carbon nanotubes were used.

**2.3. XiaotianZou, et al. (2013):** Authors presented a fiber type sensor in this study. The, a cost-effective Fabry–Perot fiber optic temperature sensor fabricated by using controllable chemical etching and adjustable splicing was introduced. The fiber optic temperature sensors offer unique advantages, including good durability against harsh environments, superior stability and repeatability, high resolution, and fast response. The experimental results in this study revealed effects of w/c ratios on surface and core temperature developments during early age hydration, as well as demonstrating that FP fiber optic sensors are capable of capturing temperature variation in the concrete with reliable performance

**2.4. Fangming Deng et al. (2015):** Authors presented a CMOS (semiconductor type sensor) temperature sensor for RFID applications. The study focuses on RFID temperature data communication system with ultra-low embedded power temperature sensor for passive RFID tags. The temperature sensing part of the sensor converted the temperature variation into a PTAT current, which was then transformed into a temperature-controlled frequency. The sensor interface, based on a PLL architecture, could transform the temperature-controlled frequency into the corresponding digital output directly without an external reference clock. The fabricated sensor occupied an area of 0.021 mm<sup>2</sup> using the TSMC 0.18 1P6M mixed-signal CMOS process. The measurement results showed that the proposed sensor achieves 92 nW power dissipation

**2.5. ElisabettaMoisello et al. (2021):** This study reviews the theory behind thermal detectors, considering the different types of sensors, bolometers, pyrometers, thermopiles and micromachined CMOS transistors, proposed during the last ten years. While the study is focused on the COVID-19 pandemic related issues the principle of operation given for the different sensors and detector technologies could help temperature determination problems in civil engineering as well. According to authors, bolometer feature high performance characteristics however they suffer from the significant disadvantage of requiring medium-high fabrication cost. Pyroelectric are particularly suited for appliance automation, such as, for example, noncontact sanitizing gel dispensers. Thermopiles feature low responsivity values, ranging from 30 to 1150 V/W: this drawback, however, is compensated by the very low fabrication cost, In the last ten years, however, the traditional temperature sensing has emerged, combining low fabrication cost, typical of thermopiles, and high performance, typical of bolometers.

### III. LITERATURE BASED DISCUSSION

The outline sketched in fig has been discussed briefly in following sections based on the various literatures (ref. 1-12) available.

#### 3.1 Estimation/ Prediction of structural temperature:

Various types of temperature estimation or prediction method have been seen in literature. To choose between measurement or prediction/estimation depends on the accuracy required, purpose of temperature data collection and funding available for the study.

Basic temperature prediction methods: [2] are a) A simple temperature calculation method (PCA method), b) The graphical method of ACI 207.2R, and c) Numerical heat transfer method (the Schmidt Method). In above methods, temperature (generally maximum temperature developed) prediction is done based either on the amount of cement used, or established empirical charts and tables or numerical equations. Also infrared photography [9] and infrared pyrometers [8] are discussed in the literature.

Estimation/ prediction of structural temperature is done either in temperature behavior studies where calculated temperature is cross verified with measured temperature or where rough idea of maximum temperature is required for various purposes and studies. Here, no actual sensors are used and no actual temperature is measured. So it's a theoretical way of temperature estimation. Essentially sufficient where approximate temperature estimates are enough





for the study. However, accuracy needs a cross checking exercise with actual temperature measurement. To develop a better prediction model, a good set of actual temperature measurement data is generally required.

### 3.2 Sensor types for actual field or lab measurement

Actual field or lab measurement is generally achieved with the help of sensors and data communication / collection unit. The effectiveness of structural temperature measurement and its cost depends mainly upon sensing material, sensing unit, data communication or transfer unit and its efficiency, data collection and its interpretation, software program for various purposes like temperature (and therefore health) monitoring, temperature profile preparation, energy consumption optimization etc. Deciding on a temperature sensor for any study mainly depends on the desired temperature range, tolerable limit to the error in the measurement, conditions under which the measurement is to be performed and performance plus cost constraints. A brief review of different types of sensors mentioned in the literature is presented in following sections.

#### 3.2.1 Thermocouple

Thermocouple is a common method of temperature measurement because of their user-friendliness, availability, cost, simplicity, and their speed of response to temperature change. Thermocouples indicate temperature measurement with change in voltage [10]. Typically, it consists of two different metals bonded at two junctions. One junction is kept at a constant temperature, while the other is the measuring junction. When the temperature of the two junctions varies, a voltage is produced across the junction, that is then sensed as the temperature. Generally, thermocouple is protected in a metal pipe to avoid its direct environmental exposure.

Thermopile [4]. Sensors consist of N thermocouple elements placed in series: this allows increasing the sensor output voltage signal to N times the one of a single thermocouple. Thermopiles, therefore, measure a temperature difference between the junctions. Hence, in order to perform absolute temperature measurements, the temperature of the cold junction should be known,

#### 3.2.2 Thermistor

Thermistors are generally made up of semiconductor material (like polymer or ceramic material and oxides of manganese, nickel, or cobalt) allowing them to deform easily that changes resistance with change in temperature. Thermistors present a nonlinear resistance-temperature diagram. As a result, it can supply a large resistance variation for a very small temperature modification in the working range. This makes it a highly sensitive instrument, ideal for high-tech and set-point applications.

#### 3.2.3. Resistance Temperature Detector (RTD)

Resistance Temperature Detector or RTD works on a simple principle that the electrical resistivity of any metal varies with temperature. RTDs are temperature sensors generally, a thin film or wire-wound, of a pure material like platinum, nickel or copper, with a highly predictable resistance/temperature relationship.

The connecting wires are used between the sensing element and measuring instrument. A constant Current is applied to the sensing element and output voltage is measured to determine the RTD resistance which then provides the temperature of the structure. Unlike thermistor, their external voltage is extremely linear, generating very accurate measurements between temperature sensors.

#### 3.2.4. Semiconductors

Semiconductor-based temperature sensors are dual-integrated circuits. Two identical diodes with temperature-sensitive voltage-current characteristics are used arrive at changes in temperature. They offer a linear response but have the lowest accuracy of the basic sensor types. Semiconductors consist of different types, such as Current output, Digital output, Voltage output, Resistance output silicon, and Diode temperature sensors. Literature [4] thrown light on a type of thermal sensor based on a micromachined thermally isolated transistor, fabricated in a standard CMOS-SOI process, embedded in a membrane able to absorb IR radiation from a target object, inducing a variation of the transistor temperature and, therefore, generating a signal by changing the transistor I-V characteristics.

#### 3.2.5 Infrared

Infrared sensors are a non-contact type of temperature sensor. They're photo-sensitive devices that detect infrared (IR) radiations from the surrounding area or an object to measure heat.

#### 3.2.6 Thermometers

Thermometers are liquid expansion devices; the rate of volume change is directly correlated to the temperature reading. Generally they are classified as the mercury type and the liquid type. They were not seen much in the



literature for the purpose of structural temperature measurement propable due to their safety hazard associated with mercury and their poor user-friendliness.

### 3.2.7. Bolomeater

As discussed in literature [4] bolometers and their miniaturized version (microbolometers) consist of an absorbing layer, implementing the membrane that collects radiation, an active layer, that acts as an embedded resistor whose resistance value varies with temperature (similar to thermistors), and support arms which provide electrical connection to the circuitry while maintaining the sensor suspended and thermally isolated. The incident IR radiation absorbed by the bolometer membrane warms up the embedded resistor and as a result, its resistance is changed. The resistance variation is expressed by the temperature coefficient of resistance.

### 3.2.8 Pyrometer

Pyroelectric detectors are made of crystals which display a variation in polarization depending on their temperature: when the crystal temperature changes, charges originate on its faces. This mechanism, known as pyroelectric effect, is analogous to the one that occurs in piezoelectric materials [4]. In the presence of changes in the temperature, the variation in the polarization and the resulting variation in the charge  $Q$  can be, therefore, expressed in terms of the pyroelectric coefficient. Pyroelectric detectors thus display a current transient in response to temperature variations and need a constant current biasing: they are AC devices and cannot provide measurements at DC.

### 3.2.9 Fiber Sensors (fiber optics sensors)

Literature [3] described about fiber sensor in good depth. The sensor could consist of a piece of single mode fiber (SMF), a multimode fiber (MMF), and a piece of borosilicate glass. The SMF is used to propagate the light and to illuminate the MMF and the borosilicate glass. An cavity is fabricated along the axial of the MMF by wet etching the core. A piece of borosilicate glass is thermally deposited in the cavity of the wet etched MMF. According to the thermal expansion of the borosilicate glass, the structure can work as a temperature sensor in multiple engineering applications by monitoring the changes in the reflection spectra.

There are different fiber materials available in literature like carbon fibers, basaltic fibers, copper fiber, silver-plated fiber, polyvinylidene fluoride fiber. The most appropriate fiber, the PVDF monofilament, was chosen as the sensor substrate in the literature [5] owing to its higher flexibility and lower mass factor with sufficient thermal resistance.

Brief advantages and shortcomings are tabulated below to help potential researcher choose the appropriate type of sensor.

Table.1.Brief advantages and shortcomings of different sensors types

SR No	Sensor type	Advantage	Shortcomings
1	Thermocouple	Moderate convenience, works good in real-time monitoring, has moderate cost, moderate lifespan, and has good accuracy. [11]. Range $-260^{\circ}\text{C}$ to $+2300^{\circ}\text{C}$	High cost and complex layout, employed for sample testing [11]. Large in size to measure point temperature, can be disruptive of heat flow, insensitive to small or transient temperature changes, and susceptible to noise [12]
2	Thermister	Rapid response time, good stability, large resistance change with temperature, repeatability, low-cost moderate size, low complexity, Range $-100^{\circ}\text{C}$ to $+500^{\circ}\text{C}$ .	Current source required, the temperature coefficient does not decrease linearly therefore Calibration dependent accuracy.
3	Resistance Temperature Detector (RTD)	Linear over wide operating range, high temperature operating range $-240^{\circ}\text{C}$ to $+600^{\circ}\text{C}$ , Platinum RTDs can be highly accurate and very linear across a very wide temperature range, Moderate size.	More expensive (platinum) no point sensing, affected by shock and vibration Require current excitation; Self heating is a concern involves complex circuitry and design challenges. Require calibration during manufacturing, and in the field.
4	semiconductors	Very linear with accuracies of $\pm 1^{\circ}\text{C}$ or better, electronics can be integrated onto the same die. Can be easily interfaced with control systems, making different digital	Slow responsiveness (between 5 and 60 seconds)



		output configurations possible, Relatively inexpensive.	
5	Infrared	Contactless measurement possible, excellent for surface measurements, compact, lightweight, and easy to use.	Measurement environment needs to be clean without dust, high humidity, the accuracy can be marginal and specialty meters can be expensive.
6	Thermometers	Simple to use.	Transportation safety of mercury and it is environmental contaminant property is a concern. Generally not suitable for structural temperature measurement.
7	Bolometer	Widely used in marine and military system, automated thermographic surveillance.	Feature good temperature Sensitivity property, the materials employed to raise the embedded resistor, such as vanadium oxide requires post CMOS processes, lithography and material
8	Pyrometer	Measures the amount of heat radiated, rather than the amount of heat conducted to the sensor. Contactless measurement possible.	Sensitive only to the variation of incident IR radiation, suited for very short-range detectors.
9	Fiber sensor	Not so convenient to use, and outstanding accuracy. [12]. Fiber optic sensors showed stable performance, high resolution measurement with low cost. Point temperature measurement because of their miniature sensing element [1]	High cost and need complex layout, risk of breaking fiber easily, requires regular maintenance, difficult to calibrate. Moderate lifespan.

### 3.3. Data communication:

Simple wired communication can be seen when sensors are connected to the data collection unit with the help of a wire. This type is particularly economical but not that user friendly especially, in automatic temperature collection system. Radio Frequency Identification (RFID) and Wireless Sensor Networks (WSN) are the two key technologies of the Internet of Things. RFID is a technology to automatically identify objects or humans by utilizing radio waves and WSN is a technology to cooperate in network for monitoring environmental conditions by utilizing various sensor nodes. [1] WSNs are formed by tiny devices, known as motes that incorporate a microcontroller, sensors, memory, a power unit and a communication module. They are able to sense the environment and communicate the information gathered from the sensors to the sink node through wireless links. Their capabilities include reading the value of physical variables at a given location, detecting the events of interest, whilst performing collaborative signal processing. [6]. An important application of WSN that attracts the interest of the construction companies is the automatic non-destructive measurement in the curing process of concrete slabs or pre-cast production [3]. WSN are suitable for long operating range and high transmission rate, they are convenient to use and works outstanding in real-time monitoring. It has low cost, moderate lifespan, and has moderate accuracy [11]. However, restricted by the battery power supply, the working life of a WSN node lasts only two or three years, hence, the cost of the WSN technique is still high for large-scale commercial applications.

RFID is a technology to automatically identify objects or humans by utilizing radio waves. RFID can extend the ability of a WSN by providing sensible properties to otherwise unsensible objects. Moreover, in an RFID system, reader-tag communications are conducted in single hops without inter-communication among tags [1]

## IV. CONCLUDING REMARKS

Different methods to determine the structural and material temperature are reviewed in this paper. Also different sensors and communication technologies required for actual temperature measurement are reviewed. The advantages and shortcomings are tabulated for an easy selection of the sensors type and communication technology.

To choose between measurement or prediction/estimation depends on the accuracy required, purpose of temperature data collection and funding available for the study. The effectiveness of structural temperature measurement and its cost depends mainly upon sensing material, sensing unit, data communication or transfer unit and its efficiency, data collection and its interpretation, software program for various purposes like temperature (and therefore health) monitoring, temperature profile preparation, energy consumption optimization etc. Deciding on a temperature sensor



for any study mainly depends on the desired temperature range, tolerable limit to the error in the measurement, conditions under which the measurement is to be performed and performance plus cost constraints. By far, the semiconductors and fiber optics sensors have been widely used in literature along with WSN or RFID units.

**Conflicts of Interest:** The authors declare no conflict of interest.

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