Using Radiant Heater for Curing Concrete in Cold Weather

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***Abstract*—This research investigates using radiant heaters to maintain the cured concrete temperature within the required limits. Several passive and active methods were used to maintain concrete temperature within the required limits during curing. These temperature limits depend on several factors, such as the type of concrete, required compressive strength at a certain duration, concrete exposure to extreme weather, concrete location and thicknesses, and code requirements. Several active curing strategies are used to maintain the required climate conditions, including steam, microwave heaters, hot water tubing embedded in concrete or under concrete slabs, and electric heated blankets. A main challenge that faces maintaining the concrete temperature within the required limits in cold climates is to reduce heat loss through the concrete surface. This research introduces radiant heating for maintaining concrete temperatures within the required limits in cold climates. Radiant heaters provide direct, instantaneous, uniform heating to the concrete and formwork surface. The Infrared heating method was tested using an environmental control chamber. Six concrete samples were placed in the climate chamber that simulated cold weather. Thermocouples were used to record the temperature at the concrete samples' surface, middle, and bottom. An infrared camera was also used to measure and verify the concrete surface temperatures. The data analysis showed that concrete surface temperature dropped quickly and became significantly lower than the ambient temperature without solar radiation. However, introducing radiant heating brings the concrete surface temperature and the core temperature of the concrete samples to the required temperature in a short period of time. A comparison between this research and other research that investigated the performance of other curing methods showed that using radiant heating for concrete curing is more effective than conventional methods.**

***Keywords*—radiant heating, concrete curing, cold weather**

I. Introduction

Concrete curing in cold weather is a major concern in concrete construction. Concrete gains strength through a chemical interaction between the concrete mixture components, mainly gravel, sand, cement, water, and additives if needed. This chemical reaction occurs when the mixture temperature is within certain limits. The required concrete curing temperature and relative humidity are a function of several factors, including the type of cement and additives used in the concrete, size, and shape of the concrete members, The use and exposure of concrete elements, required compressive strength at a certain duration, cost of curing, and project duration [1]. The curing temperature should generally be below 40 ℉ (about 4.4 ℃). Achieving higher compressive strength concrete after the first day of pouring concrete will allow contractors to remove formwork and load the concrete elements early, speeding up the construction and reducing costs. One of the main strategies to achieve early strength in concrete is curing concrete at a higher temperature (Fig. 1). Some research suggests using microwave thermal processors to achieve accelerated curing and higher compressive strength. However, this research addresses cuing concrete for pre-cast units in the shop [2]. Electrically conductive carbon nanotubes were introduced to the concrete members to accelerate the concrete curing. This research showed that it improved early strength after 24 hours by 40% [3]. However, this method requires using advanced technology and new techniques that might not be suitable for the existing standard practices that our research is addressing. The construction industry adopted several concrete curing methods to achieve that.

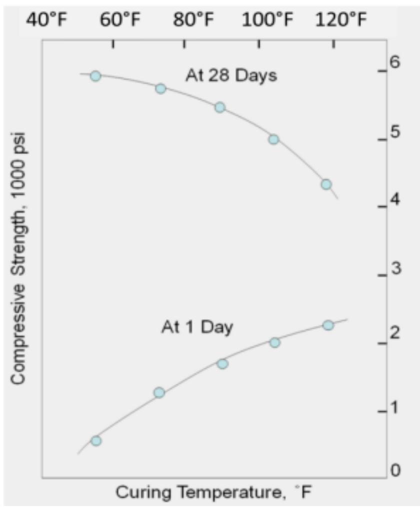

Fig. 1. Relationship between curing temperature, compressive strength, and curing duration [4].

Manuscript received May 18, 2023; revised July 2, 2023; accepted October 25, 2023; published February 26, 2024.

doi: 10.18178/ijscer.13.1.24-30

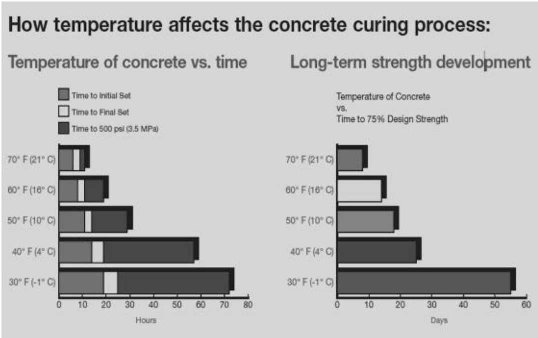

Fig. 2. Correlation between curing temperature and short and long-term concrete strength [6].

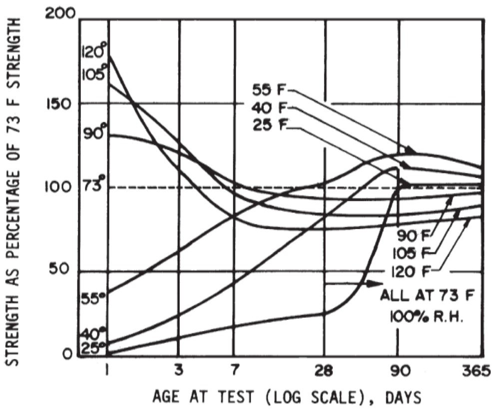

Fig. 3. Effect of temperature conditions on the concrete compressive strength, Source; Guide to cold weather concreting [7].

II. Methods of Curing Concrete in Cold Weather

Curing concrete can be done in a passive mode or active mode.

A. Passive Mode

When ambient temperature is above 50 ℃, the common method of curing concrete is to keep the concrete wet. This can be achieved by relatively simple means such as applying curing agents to the concrete surface [5, 7], covering the concrete with synthetic acrylic membrane, wrapping concrete elements with wet canvas, spraying concrete with water in short time intervals, keeping forms in place, create ponds on top of the concrete slabs (ponding) or soaking concrete with water. However, when concrete temperature drops below 40 ℉, measures are usually taken to maintain adequate concrete temperature required to achieve the required curing time. In addition, when concrete temperature drops below freezing during curing time, a significant reduction in the final concrete strength and quality will result. Several passive and active methods are usually used to maintain the concrete temperature within the required limits. Some passive methods are used when the concrete temperature drops below 32 ℉ to cover the concrete with natural materials such as straw and hay or by using one or more insulated blankets. These methods can work only when the temperature does not significantly go below freezing and when covering the concrete with thermal barriers is practical.

When pouring concrete slabs, the ground temperature should not be less than 40 ℉. In cold weather, insulation materials with steam or hydronic heaters were used to maintain the ground temperature above 40 ℉. However, this system has limitations because work on steel reinforcement or other construction activities cannot be performed if a slab cover is placed.

B. Active Mode

When passive curing means are not adequate to achieve the required curing temperature and relative humidity, active methods are usually used. The main active curing methods include the following

1) Steam curing

Steam curing is used to cure concrete in the field or a factory setting [8]. Steam at atmospheric pressure is usually used to cure cast-in-place concrete, and high steam pressure can cure precast concrete in a factory setting. Maximum steam temperatures are usually set at 175 ℉. Steam temperature is a function of the desired concrete strength after a certain period of time. Figs. 2 and 3 show the relationships between steam temperature and the concrete compressive strengths achieved at different time intervals. Also, the period of starting use of steam curing for concrete plays a crucial role in improving concrete compression strength. Optimal compressive strength can be achieved by delaying the start of steaming by 4–5 hours after casting, as shown in Fig. 4.

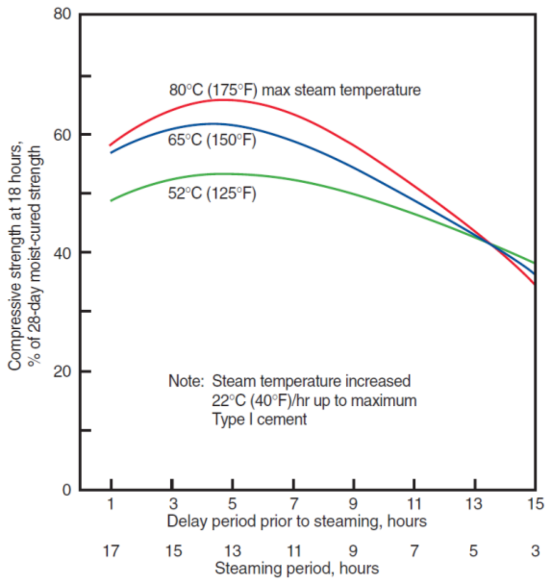

Fig. 4. Effect of delay curing on concrete compressive strength [6].

2) Temporary enclosure

This system uses convection heat to maintain the concrete temperature to the desired levels, a temporary structure is built to enclose the cured area, and an active heating system is used to maintain the required temperature. Sometimes, a portion of the building or a certain floor can be enclosed, and heaters are placed to maintain the required curing temperature.

There are two methods to heat the enclosed space: unvented fire, as shown in Fig. 5, and vented fire (indirect fire). When workers need to work in an enclosed space, vented heaters must be used because this system vents the CO_2 and other combustion gases outside the enclosed space, as shown in Fig. 6 [9]. This method is relatively expensive and might delay the project as it limits mobility during curing.

Fig. 5. Unvented fire-enclosed space for curing concrete [5].

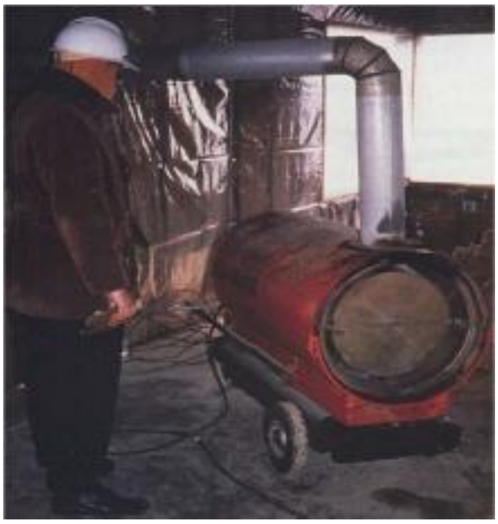

Fig. 6. Petroleum fuel-fired heater to maintain curing temperature in enclosed space [10].

3) Hydronic heating system

This system uses conduction heat to maintain the concrete temperature at the desired level. In this system, pipes are placed under a concrete slab, and hot water is circulated in these pipes to maintain the soil temperature above 40 ℉. Concrete is placed on top of these pipes, and hot water will continue circulating during the curing period to maintain the required level of concrete temperature, as shown in Fig. 7. This system is relatively expensive and requires extensive installation time. Hydronic heating can also be attached to the formwork for preheating and maintaining the desired curing temperature, as shown in Fig. 8. Insulation blankets can add more insulation. The system is also used on elevated slabs. The hydronic pipes are placed on top of the concrete slab and covered with thermal blankets after the final set of concrete.

Fig. 7. A hydronic heating system installed under the slab and attached to the formwork [10].

Fig. 8. Hydronic heating system attached to the formwork [10].

III. NEW APPROACH

This paper suggests using radiant heaters to maintain the concrete and underground soil at the required temperature. Mathematical models and lab testing were made to examine the effectiveness of the proposed system. In this system, infrared heaters heat the formwork and the concrete directly through radiation. These heaters use electricity or gas as an energy source [11]. Radiant heaters are used for snow melting and heating outdoor commercial and recreational areas, as shown in Figs. 9 and 10. Research was conducted to use radiant heating for precast units [12]. This research investigated using Infrared heaters with a curing compound surface for curing precast units and compared it to steam heating in a lab setting. The research found temperature variations in the concrete surface when using radiant heaters. However, the curing process using the Infrared system produced acceptable concrete quality related to concrete compressive strength, Freeze-thaw, and concrete permeability. The research suggested extra precautions to ensure uniform heating when placing the infrared heating elements. Since this research covered the effect of infrared radiation on concrete curing, the scope of our research was limited to the practicality of using infrared heat to cure onsite concrete.

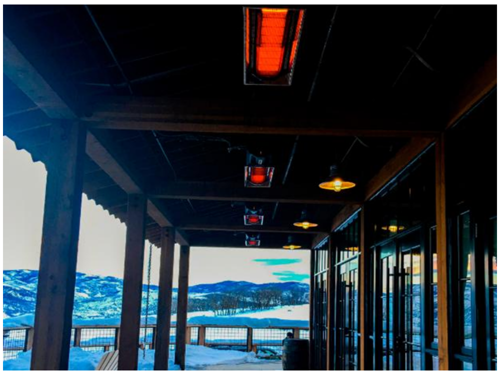

Fig. 9. Infrared heaters used for heating outside areas [12].

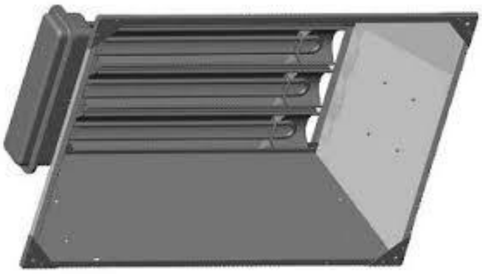

Fig. 10. Infrared heater device for heating outside areas [12].

To calculate radiant heating load, most companies suggest general design guidelines that use the rule of thumb to size radiant systems for heating open spaces [13]. These methods will give a general idea of the cost-effectiveness of these systems but do not give scientific proof of the basis for these calculations. This research expands the analysis to include a mathematical model and lab testing to investigate the viability of using this system to maintain the required cured concrete temperature.

A. Mathematical Model

The basic radiation theory is based on Stephan-Boltzmann law ($eb = \sigma T^4$) where eb = emission rate of a surface (W/m^2), $\sigma = 5.67 \times 108$ W/m^2 K4, T = the absolute surface temperature [14, 15]

For a heat source emitting at a certain angle at a target area as in Fig. 11, The target area dA can be related to the distance R by the polar coordinates; $dA = R^2 \cdot \sin\theta \, d\theta \, d\varphi$.

These formulas indicated that radiation intensity on a surface is a function of the emission rate of the surface, the distance from the source, and the directional angles from the source.

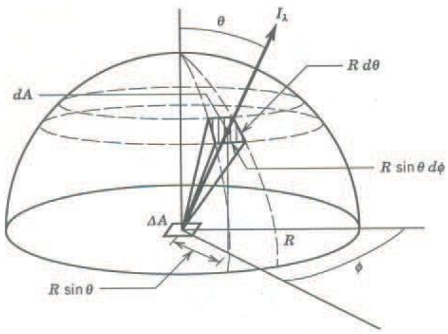

Fig. 11. Intensity definition.

Another useful formula representing a directional heat source similar to Fig. 12 is Ee = radiant power impinging upon a surface or area of this surface =Φe/ 4π r ²[16].

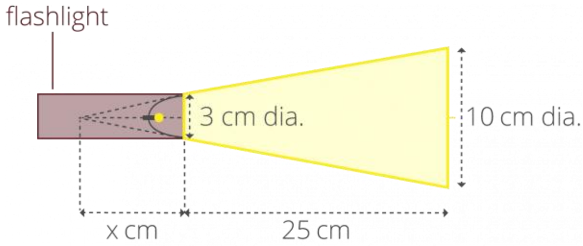

Fig. 12. Calculating the irradiance caused by a flashlight [7].

B. Case Study

To demonstrate using a radiant heater to raise the concrete temperature, a thermal control chamber was used to simulate cold weather. The chamber can be programmed to control air temperature from −20 ℃ to 60 ℃ and the relative humidity from 10% to 100%. The chamber can be programmed to simulate the weather data of cold climates, as shown in Fig. 13.

Fig. 13. Climate control chamber.

Two concrete samples, 4 inches × 4 inches × 8 inches, were placed inside the chamber. A regular concrete mixture of 5000 psi was used in the concrete samples. A 12-channel data logger with thermos couples was used to record the temperature inside the chamber. The thermocouples were placed on the top, middle, and bottom of the sample on the front and the back of the sample (total of 6 points). A hole was drilled, and a thermocouple was installed in the sample's middle thickness (2 inches deep) to measure the sample's internal temperature. The surface thermocouples were placed in 1/8 inches deep holes that were drilled on the surface to measure the surface temperature because we found out that the surface-mounted thermocouples did not accurately measure the surface temperature (Figs. 14 and 15). A 40 W, 100 W, and 200 W incandescent light source was used to simulate solar radiation. An infrared camera was used to measure the surface temperature of the concrete sample and check on the uniformity of the surface temperature. A light meter was also used to measure the luminous flux of the light source.

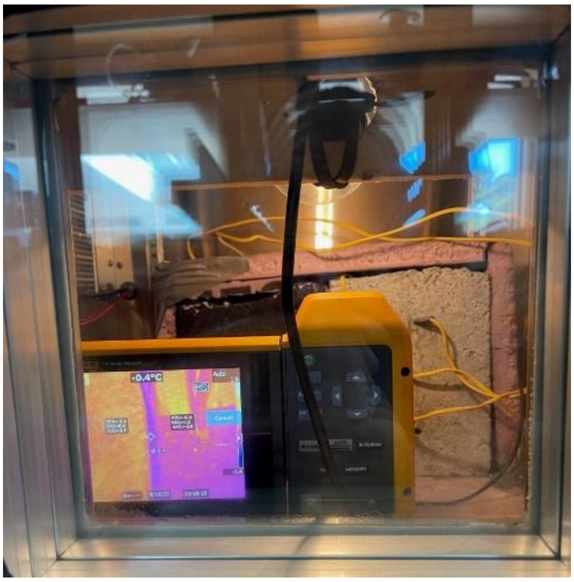

Fig. 14. An infrared camera is used in the chamber to calculate surface temperature.

Fig. 15. Concrete samples are placed in the chamber with the thermocouples attached to the samples.

To determine the radiation flux amount ($Watt/Ft^2$) that reached the concrete sample's surface the following formula was used:

luminous flux ΦV in lumens (lm) = 0.09290304 × illuminance Ev in lux (lx) × the surface area A in square feet [8]:

$$\Phi V(\text{lm}) = 0.09290304 \times Ev(\text{lx}) \times A(\text{ft}^2)$$

where 0.09290304 is a conversion factor of m^2 to ft^2.

Expressed as an equation, the power P of a light source in watts (W) can be represented as the luminous flux ΦV in lumens (lm) divided by the luminous efficacy η in lumens per watt (lm/W):

$$P(\text{W}) = \Phi V(\text{lm}) / \eta(\text{lm/W})$$

When combining both formulas, the power P in (W) is equal to 0.09290304 multiplied by the illuminance Ev in lux (lx) and the surface area A in square feet (ft^2) divided by the luminous efficacy of the light source η in lumens per watt (lm/W):

$$P(\text{W}) = 0.09290304 \times Ev(\text{lx}) \times A(\text{ft}^2) / \eta(\text{lm/W})$$

So

Watts = 0.09290304 × lux × (square feet) / (lumens per watt)

The field readings for luminous flux in the chamber when using 40 W, 100 W, and 200 W incandescent light bulbs at a distance of 5–5/8 inches are listed in Table I.

TABLE I. LUMINOUS FLUX IS MEASURED ON THE SURFACE OF THE CONCRETE.

	Luminosity (Lux)		
Bulb Wattage	Top of sample	Middle of sample	Bottom of sample
40 W	450	365	280
100 W	2350	1800	1250
200 W	4500	3350	2250

The environmental chamber was used to simulate cold weather. Two concrete samples were placed in the chamber; one was painted with 90% black absorbent paint, and the other had a natural concrete color. A light source of luminous efficiency of 15% was used in the chamber readings. From Table I, the energy flux in the middle of the sample when using a 40 W source was 2.26 W/ft^2. The weather chamber was run for 24 h before the data were collected to reach the temperature equilibrium. Figs. 16 and 17 present the data logger output.

IV. RESULTS

The chamber readings showed that the surface temperature of the concrete was raised by an average of 2.6 ℃ when a radiant heat source of 2.26 W/ft^2 was used, which can be translated to 1.15 ℃/Watt of radiant heat. The maximum temperature increase under the same radiant heat flux level was when the outside temperature was −3.4 ℃ and the concrete maintained a surface temperature above 0 ℃. That is when the concrete is covered with translucent plastic sheets. When concrete is not covered with Plastic sheets, the temperature difference was 1.8 ℃ with the same radiant heat source, which can be translated to a 0.79 ℃/Watt temperature increase rate per W of radiant heat as shown in Figs. 16 and 17.

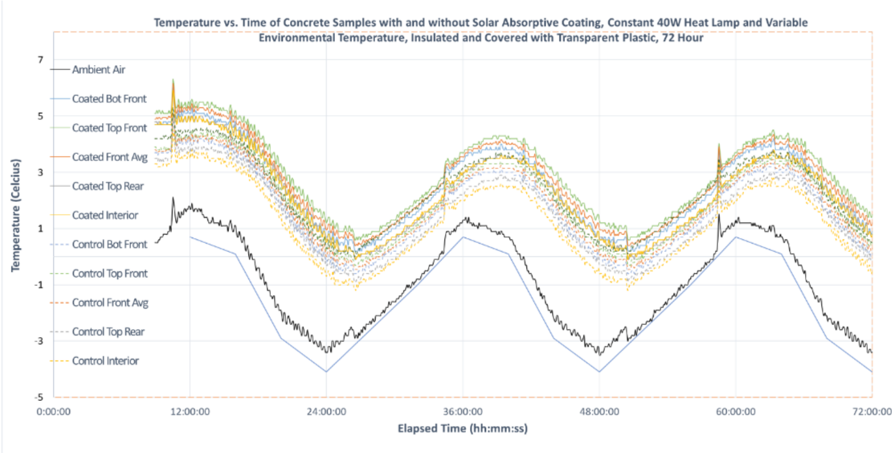

Fig. 16. Thermocouple readings inside the climate chamber without plastic cover over the concrete samples.

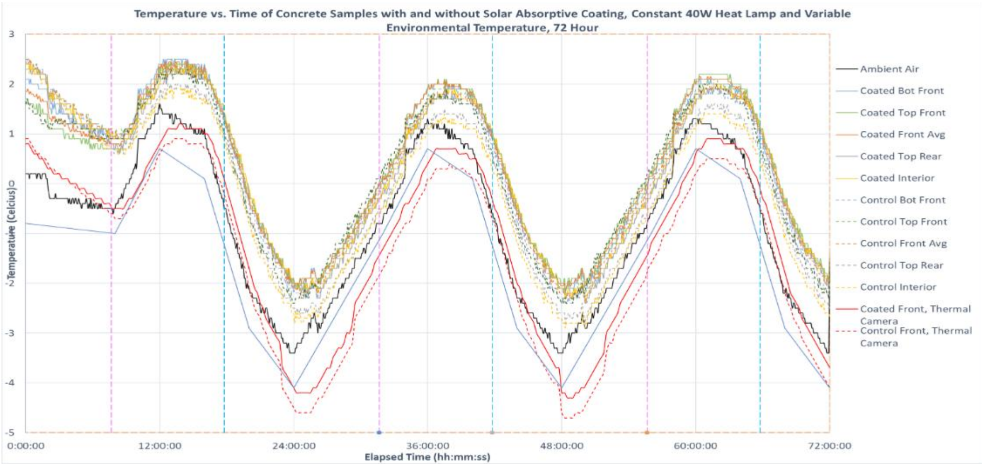

Fig. 17. Thermocouples readings inside the climate chamber with a plastic cover over the concrete samples.

The lab data also showed that black-colored surfaces have an average surface temperature of 0.5 ℃ above the regular concrete-colored surfaces (approximately 1.8 ℉). The complete temperature profiles are shown in Figs. 16 and 17.

These results can be compared with the manufacturers' recommendations of using radiant heaters for outside space.

Liberty Electric Products suggests using 2 W for every 1 ℉ desired temperature rise [13]. However, this company used a general rule of thumb and did not base their calculations on actual field or lab testing.

As an example, if a concrete slab is to be maintained at 40 ℉ (4.4 ℃) when the outside temperature is 20 ℉ (−6.6 ℃), then the total radian heating will be 12.65 W/sqft.

To demonstrate the viability of the heating system, a floor slab of 100 ft long × 40 ft wide was simulated as in Fig. 18. Eight electric infrared heaters were mounted on the long sides of the slab and at a height of 12 ft. Electric infrared heaters with a capacity of 6,500 Wh were used. This system is commercially available at 240 V and 208 V, typically at commercial and residential sites. The total ampacity needed for the system is 216–250 Amp. These loads can be accommodated with regular temporary electric power service to construction sites. The radiation beam from the heaters was tilted at 15° from the perpendicular line of the slab to distribute the radiant heat evenly to the entire slab as in Fig. 19. These units provided 13 W/sqft of radiant heat on the slab.

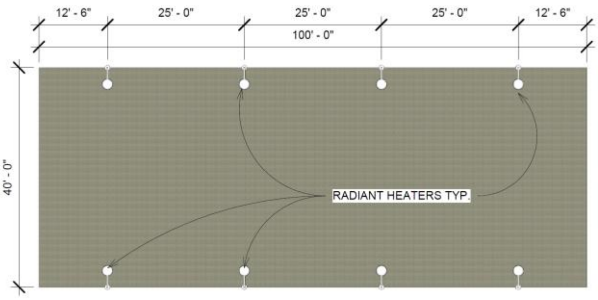

Fig. 18. Floor plan of a concrete slab with radiant heaters.

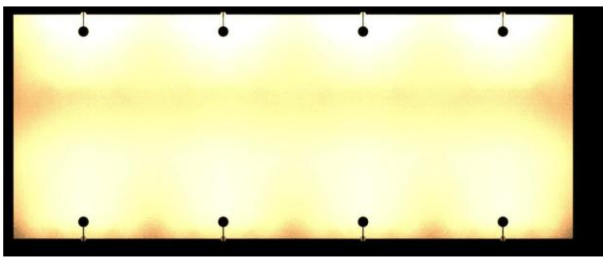

Fig. 19. Radiation analysis rendering of the radiant heaters to the concrete slab.

In addition to maintaining the required temperature, the radian heaters will also provide heating for workers who perform work above the slab, making them feel more comfortable and increasing their mobility and productivity.

V. Conclusion

Maintaining minimum concrete temperature during curing is a critical challenge to guarantee the quality of concrete and to ensure that concrete achieves the required strength in a timely manner. This research suggests a new method of using radiant heaters to maintain the desired concrete temperature. Previous research proved the effectiveness of using radiant heating for curing concrete and concluded that an acceptable level of concrete quality can be achieved when using radiant heat.

Lab testing and computer modeling in our research were used to determine the viability of this option. The research showed that this system can provide the required heating by using electric radiant heaters that can be mounted on posts. The system provides the required heating level for curing concrete and will also help maintain thermal comfort for workers who can continue to perform their work while freshly poured concrete is curing. In the case of larger curing areas or colder climates, higher radiant heaters that usually use natural or propane gas can be installed. These systems are easy to install and move, economical, and readily available in the market.

Conflict of Interest

The authors declare no financial, professional, personal, or other conflict of interest with this research.

Author Contributions

Al Shenawa participated in developing the research scope of work, supervised the data collection, and participated in the research analysis; Abaza participated in developing the scope of work, the literature review, and the planning of experiments; Semmelink participated in setting up the experiments and collecting and analyzing the lab data; all authors had approved the final version.

Funding

Funding agency for the project is Kennesaw State University, Kennesaw, GA, USA.

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