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INFRARED IMAGING AS A NON-DESTRUCTIVE TESTING METHOD FOR GEOPOLYMER CONCRETE

Non-destructive testing (NDT) is generally used to estimate the compressive strength of concrete material without compromising its structural integrity. However, the available testing methods on the market have particular limitations that may restrict the accuracy of the results. Therefore, this study aimed to develop a new technique for measuring the compressive strength of geopolymer concrete using infrared imaging analysis and Thermal Diameter Variation (TDV) rate. The compressive strength range was designed within the target strength of 20, 30 and 40 MPa. The infrared image was captured on the preheated concrete surface using FLIR-ONE infrared camera. Based on the correlation between TDV rate and compressive strength, higher accuracy was obtained in the orange contour with an R^2 of 0.925 than in the red contour with an R^2 of 0.8867. It is apparent that infrared imaging analysis has excellent reliability to be used as an alternative NDT by focusing on the warmer region during the procedure.

Keywords: geopolymer; concrete; infrared image; non-destructive testing

1. Introduction

Manufacturing Portland cement is labelled as an anti-green activity due to the enormous emission of carbon dioxide (CO_2), which could lead to the greenhouse effect and global warming. The production releases more than 4.8 million tons of CO_2 in 2020 [1], responsible for 5-7% of worldwide emissions [2]. In addition, the production consumes a massive amount of energy and non-renewable source materials. This situation requires a prompt solution to minimise these negative impacts and adopt a greener approach.

Alkali-activated binder or geopolymer is introduced as one of the remedies to produce clinker-free cement. Production of geopolymer concrete via the alkali-activation of aluminosilicate resources is dubbed economical and sustainable due to the lower CO_2 emissions and waste materials utilisation approach. First developed in 1978 by a French researcher, Davidovits, geopolymer represents a broad spectrum of substances defined by networks of inorganic molecules [3]. Geopolymer composite is a novel class of low carbon emission binder, produced by combining aluminosilicate source materials and alkaline solution and solidified through a polymer reaction. In geopolymer system, the aluminosilicate precursors would react in the alkali-based solution to produce three-dimensional polymeric Si-O-Al amorphous microstructure [4]. Former research has identified that Si/Al ratio and Na_2O/SiO_2 ratio play a critical role in geopolymer's mechanical and durability properties [4-6].

Geopolymer has several features that make it a cost-effective structure [7-11]. Better durability in an aggressive environment and a higher initial strength development rate are among the significant features of geopolymer [12,13]. The presence of aluminosilicate frameworks and the use of elevated temperature provide the major support to this superior performance, particularly in the early strength development [14,15]. Despite the different framework compositions, geopolymer can use the similar destructive and non-destructive testing methods as in conventional Portland cement concrete to evaluate its properties.

Non-destructive testing (NDT) is a standard method that will evaluate the properties of a material without destructively damaging the specimen. According to the British Standard Institution (1896), there are about 24 types of NDT, such as Pull-Out Test (POT) Method, Rebound Hammer, Ultrasonic Pulse Velocity (UPV) and others. Some of these tests can be carried out in situ to estimate the concrete strength, while others are used to identify additional concrete characteristics such as deterioration, voids, cracks and flaws [16]. Nevertheless, despite their conveniences, these methods require careful operation and analysis due to their constraints. For example, rebound hammer

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value is significantly affected by the presence of voids and aggregates near the surface; hence requires many testing points to assure its accuracy. As for the UPV, the degree of moisture saturation must be carefully included in the analysis to produce accurate results [17].

In this study, the process focuses on developing an alternative method to estimate the compressive strength of geopolymer concrete based on infrared imaging analysis. This method is considered efficient since it does not leave damage to the specimen, and it tests an area instead of a pointy spot. Infrared has been progressively used in the structural evaluation, yet its adoption in strength estimation requires further analysis and investigation [18]. Therefore, this article aims to analyse the accuracy of infrared imaging as an NDT method for geopolymer concrete by correlating the thermal diameter variation (TDV) rate from different heat contours to the compressive strength data. The results are expected to provide new insight into the infrared analysis and a new alternative NDT method for geopolymer concrete.

2. Experimental Method

Geopolymer concrete was designed using fly ash as the source material in this research. This source material was activated using sodium hydroxide (NaOH) and sodium silicate solution (Na_2SiO_3), and mixed with fine and coarse aggregate to produce geopolymer concrete. Fly ash was taken from a coal-fired power plant in Manjung, Malaysia, while sodium hydroxide pellets and sodium silicate solution were purchased from the local supplier. NaOH solution was prepared in 8M solution by diluting 297 g of NaOH pellets (99% purities) with 703 g of distilled water, and it should be prepared at least 1 hour prior to the mixing process to prevent the liberation of excessive heat. This study also used Na_2SiO_3 solution with the proportion of Na_2O: 14.73%; SiO_2: 29.75%; and H_2O; 55.52%. TABLE 1 shows the chemical oxide composition of fly ash used during this experimental work.

In the specimen preparation, the mixing process adopted the conventional hand mixing method as in Portland cement concrete. First, dry materials (fly ash, fine aggregate, and coarse aggregate) were hand-mixed until the fine particles were thoroughly dispersed and mixed. The alkali solution was then introduced into the dry mixture, and the mixing was continued until a homogenous fresh geopolymer concrete was obtained. The overall mixing process was completed in under five minutes. TABLE 2 shows the detail of mix proportions used in this study.

The fresh geopolymer concrete was cast into 100 mm cube moulds and left for 24 hours at room temperature. The specimens were then demoulded and prepared for the oven curing at 65°C. To prevent the excessive moisture evaporation, the specimens were wrapped in LDPE plastic during the entire oven curing process. After 24 hours of oven curing, the specimens were taken out and kept at room temperature until the testing day. Fig. 1 shows the oven curing process of geopolymer concrete cube.

TABLE 2

Detail of Geopolymer Concrete Mixture Proportions

Grade of GPC	G20	G30	G40
Fly ash (kg/m^3)	327	360.65	394.3
Fine aggregate (kg/m^3)	672	659.4	646.8
Coarse aggregate (kg/m^3)	1248	1224.6	1201.2
NaOH (kg/m^3)	54.33	49.70	45.06
Na_2SiO_3	108.67	110.66	112.64

Fig. 1. Oven curing process of geopolymer concrete

The infrared image of the concrete's surface was captured by first applying heat onto it using a portable gas torch. The selected surface was torched for three seconds, and the first image was taken 10 seconds after the heat was taken out. The image was captured using a FLIR ONE infrared camera, as shown in Fig. 2. A total of six images were taken from a concrete surface every 10 seconds after the heat was taken out. Each of the captured infrared images was then processed using MATLAB to generate the contour profile, and the changes in the diameter of each surface were calculated and referred to as Thermal Diameter Variation (TDV) rate. The accuracy of this method was also compared with Rebound Hammer as the standard NDT tool.

Fig. 3 shows a sample of infrared images captured from the concrete surface. The generated contour from MATLAB is also illustrated in Fig. 4. From the available colour profile in the infrared image, two colours were selected in the analysis of TDV, which are red and orange. These colours satisfied the measurement of full diameter and its changes.

TABLE 1

Chemical Oxide Composition of Fly Ash

Oxide	Al_2O_3	SiO_2	CaO	Fe_2O_3	MgO	K_2O	SO_3	TiO_2	LOI
Percentage (%)	36.37	17.57	10.58	12.43	3.05	1.77	1.39	0.88	1.19

Fig. 2. FLIR ONE infrared camera

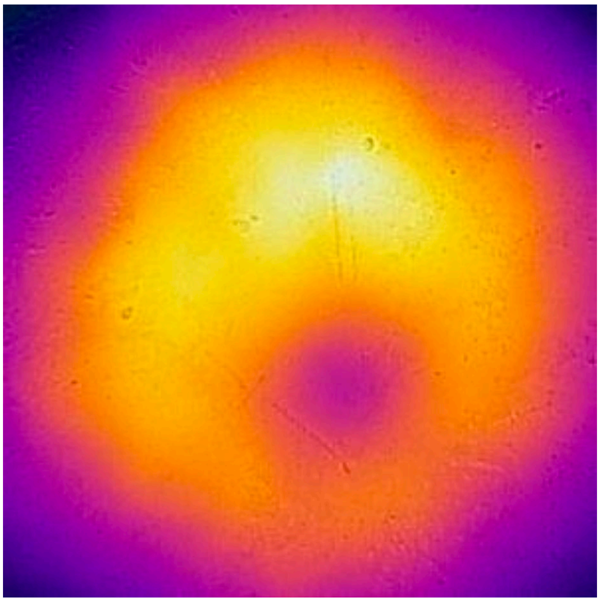

Fig. 3. Sample of an infrared image captured using FLIR ONE

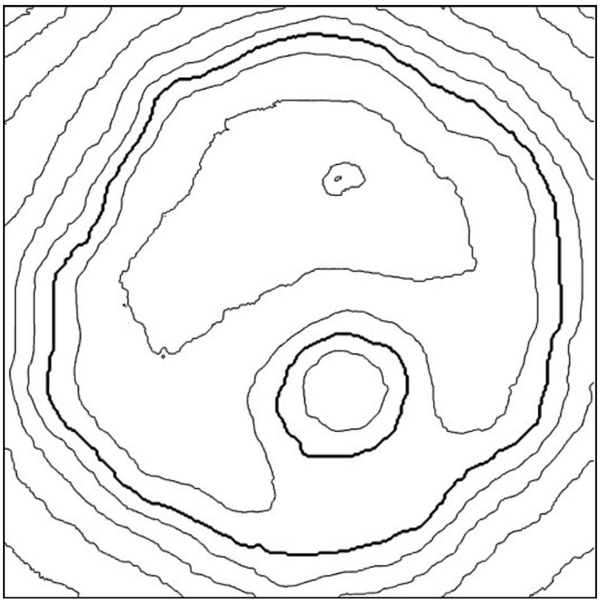

Fig. 4. Thermal contour generated using MATLAB

3. Results and Discussion

The accuracy of infrared image analysis to estimate the compressive strength of geopolymer concrete was determined based on the coefficient of determination of the generated model. In here, individual results will be presented based on the time intervals, namely 10s, 20s, 30s, 40s, 50s, and 60s, to show which time stamp and thermal colours fit better with the generated model. In this study, the exponential regression model was preferred since it simulated the rapidly-changing diameter value better than other regression models.

3.1. Correlation between Strength with Infrared Contour

Fig. 5(a-f) shows the correlation of infrared contour's diameter with the compressive strength based on the red and orange thermal colour profile. The figure is differentiated based on the time the image was taken. These figures show that the strength estimation based on the red contour during the early period presented a poor accuracy, with an R^2 of 0.658. However, the accuracy of this colour profile slightly improved if the infrared image was captured 60 seconds after the surface was heated ($R^2 = 0.832$).

Nevertheless, the orange colour profile consistently showed a high R^2 throughout different timestamps. It is believed that the outward movement of heat during the heating process has a significant role in this trend. The centre of the infrared image representing the surface's hottest part has the lowest cooling rate; hence, accurately measuring the TDV in this colour range would be difficult. In contrast to the centre, the near-the-edge part is the coolest region on the surface. Acquiring the TDV from this range posed a similar challenge with the centre part, which lacked diameter variation due to smaller thermal movement. The warmer region of the orange line has substantiated the consistent accuracy of its regression model in estimating the compressive strength of geopolymer concrete.

In addition to that, the data is also presented as a TDV rate. This rate acts as a comprehensive measurement that would cater for the changing of diameter from the first to the last timestamp (10 s to 60s). Fig. 6 shows the regression models generated for both red and orange colour lines. As shown in this figure, the accuracy of red line was enhanced to an R^2 of 0.887, while the orange line maintained high at 0.925. By measuring the difference in thermal diameter from the first to the last timestamp, the process has identified two states representing colder and warmer temperatures. This method was proven to be more convenient and accurate in estimating the compressive strength of geopolymer concrete

3.2. Correlation of Rebound Hammer

Rebound hammer (RH) test was carried out as a comparative study since it is among the renowned standard NDT for

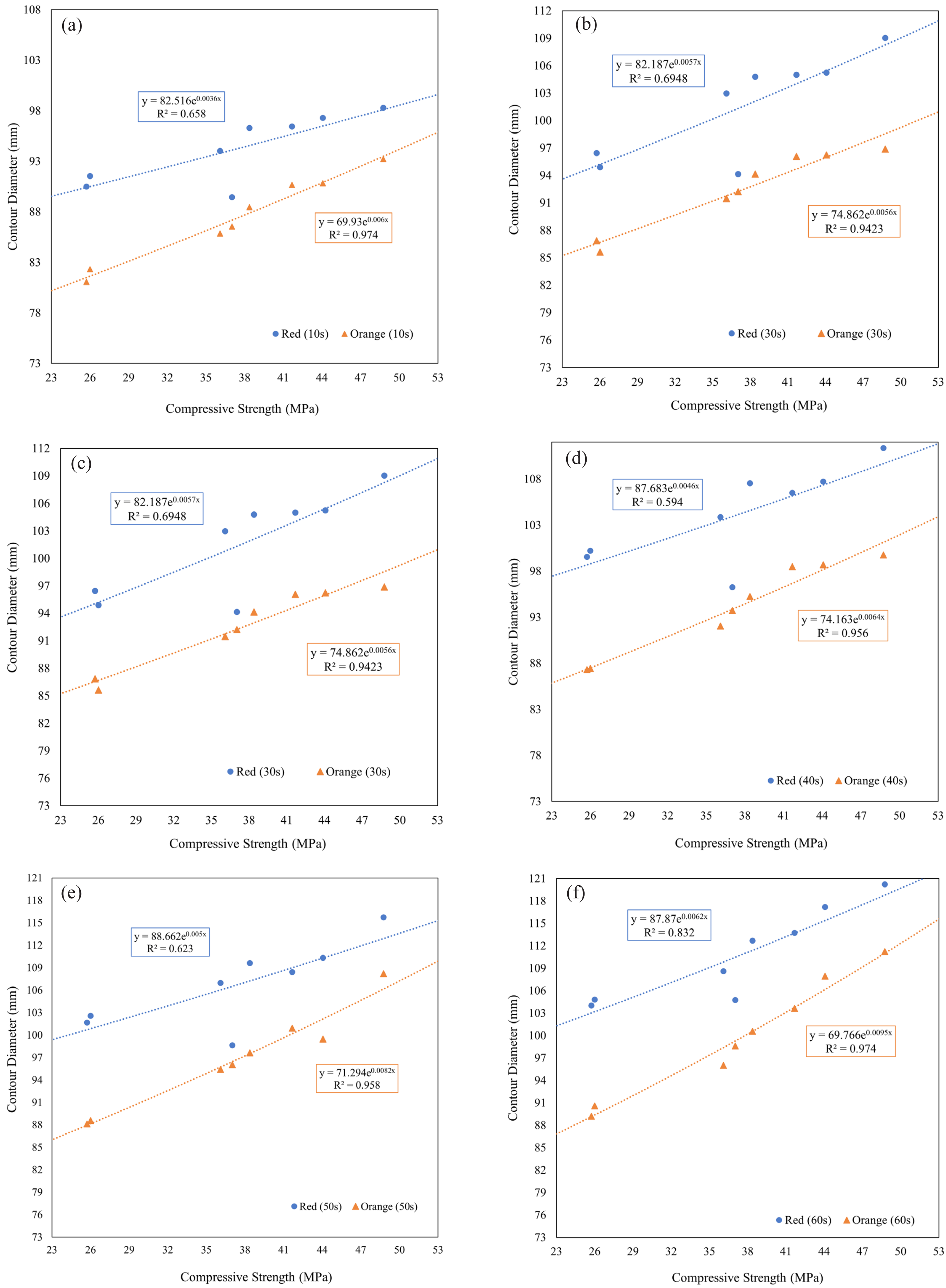

Fig. 5. Regression model of compressive strength and thermal contour diameter of infrared images captured after: (a) 10 s; (b) 20 s; (c) 30 s; (d) 40 s; (e) 50 s, and (f) 60 s

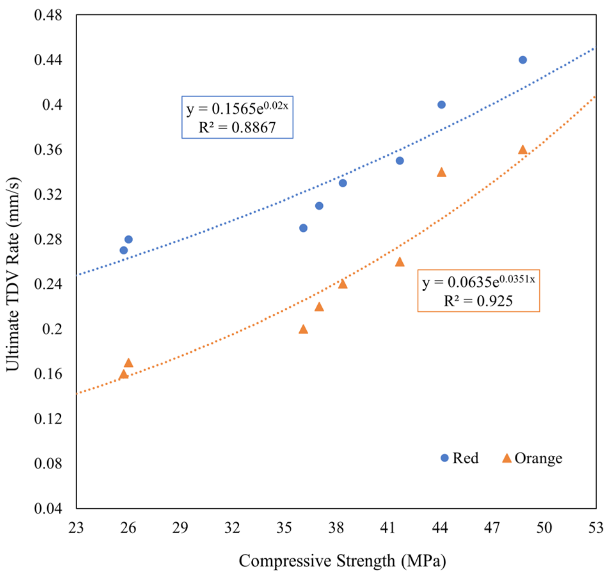

Fig. 6. Regression model of TDV rate and compressive strength

concrete. Fig. 7 shows the accuracy of rebound hammer in estimating the compressive strength of geopolymer concrete based on its regression model. With the R^2 of 0.901, the rebound hammer is relatively capable of estimating the compressive strength accurately. It was also supported by the maturity of geopolymer's framework that had been fully developed from the oven curing process.

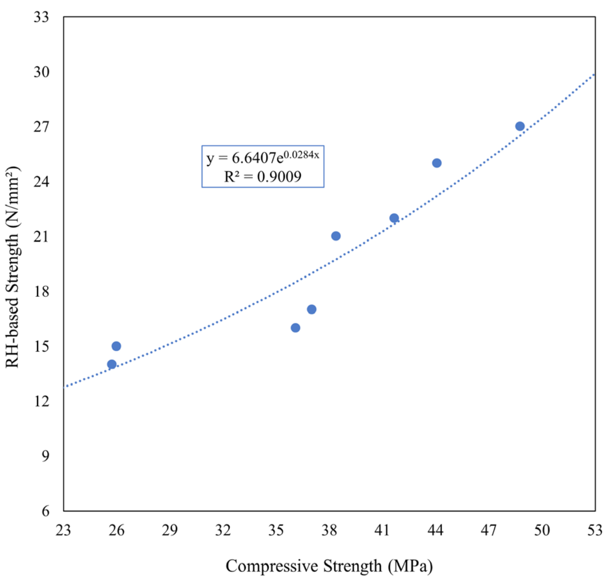

Fig. 7. Regression model of RH – based strength and destructive compressive strength

The use of elevated temperature to produce a uniform and strong aluminosilicate network in geopolymer has provided a solid rebounding platform [19,20]. The number of testing spots per specimen, which was carried out at nine different spots per surface, also assisted in achieving this accuracy. Similar to the infrared image analysis, where the method focused on the near-surface integrity, rebound hammer and TDV value both have performed excellently in estimating the compressive strength of geopolymer concrete.

An interesting trend was observed when the compressive strength correlation was observed from another perspective of concrete density. As shown in Fig. 8, the increasing compressive strength was also followed by the declining density. However, with the poor coefficient of determination at the R^2 of 0.724, the perfect correlation between density and compressive strength could not be confidently established. The explanation for this trend would refer to the geopolymer mixture proportions used in this study. These mixtures used less aggregate and higher binder in the higher compressive strength mix.

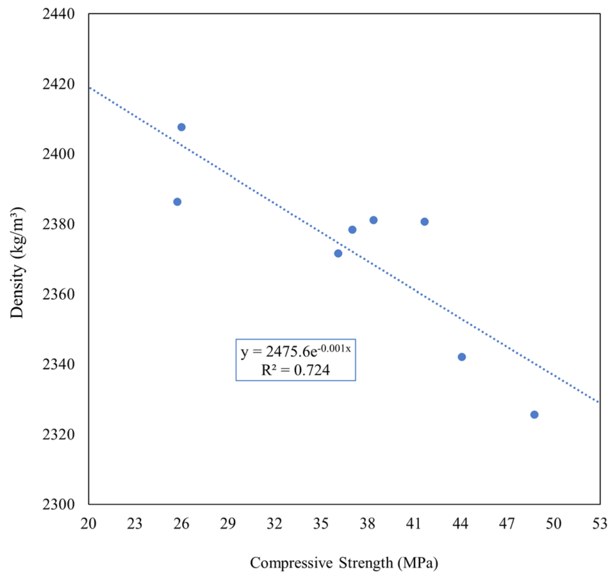

Fig. 8. Regression model of concrete density and compressive strength

4. Conclusion

The statistical fit of measure using the coefficient of determination from a regression model has presented TDV rate as a more reliable variable in the infrared image analysis than individual timestamp analysis. Nevertheless, the colder and warmer region on the concrete surface also played a role in the accuracy of this method. The warmer region was proven more reliable in estimating the compressive strength of geopolymer concrete, with the statistical fit level slightly higher than rebound hammer as the renowned NDT. From here, it is apparent that infrared image analysis could be used as the alternative NDT for geopolymer concrete. It has the required accuracy and is also efficient for in-situ testing.

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