MATEC Web of Conferences **364**, 05006 (2022) https://doi.org/10.1051/matecconf/202236405006
ICCRRR 2022

Effectiveness of concrete curing compounds in extreme windy and dry conditions

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Abstract. Curing is one of the most crucial phases of concrete conditioning as it determines not only the long-term strength, but also influences the durability. Curing compounds are useful for reducing the evaporation rate of water from the concrete surface. They are typically sprayed on concrete as soon as possible after consolidation, especially for concrete members that have large areas exposed to the environment. These compounds have been proven to work well, however, how effective are different curing compounds in a variety of high wind and high temperature with low relative humidity conditions? The focus of this work is the effectiveness of different types of curing compounds at windy and dry conditions. The tests were done in a state-of-the-art Mobile Climate Chamber (MCC) where the weight of all samples was measured constantly to determine the water loss. It was concluded that the resin-emulsion based curing compound performed best at all environmentally tested conditions. The acrylic-based curing compound performed worse than the control, where nothing was applied to the top surface.

1 Introduction

Curing is one of the most important, yet frequently neglected steps in placing and finishing concrete [1]. Curing is defined as the process of preserving a suitable moisture content in concrete in order to enhance the mechanical, microstructural, and durability properties of the concrete [2]. Adequate curing is thus necessary to avoid plastic shrinkage cracking in fresh concrete which typically has a negative impact on the final hardened structure's durability [3]. The development of plastic cracking also affects the structure's aesthetics [3,4].

Water-adding techniques, such as ponding and spraying, and water-retaining procedures, such covering the top of the concrete with plastic sheeting or using membrane-forming curing compounds, are the two main groups of curing practices. Although water spraying is generally the favoured way of curing on building sites [5], there is a growing need for adequate alternative methods, particularly in less developed regions where there is a lack of potable water resources. Curing compounds are a solvent-based suspension of pigments and polymers that are either sprayed or brushed onto the concrete surface. Over time, the solvent evaporates and leaves the polymers densely packed, ultimately forming a uniform layer on the concrete surface. If properly applied, this layer aids in preventing moisture loss and lessens volumetric fluctuations while the concrete cures. Thus, preventing plastic drying, shrinking and cracking.

ASTM C309 (2015) [6] is identical to the South African standard SANS 423 (2016) [7] and contains the specifications pertaining to curing compounds. ASTM C309 also classifies curing compounds based on the compound colour as well as the type of solid constituent that forms the membrane.

A direct method of determining a curing compound's efficiency is to assess its evaporation retaining capabilities. Environmental variables including wind speed, temperature, and relative humidity have an impact on how quickly bleed water evaporates from the surface of concrete [8, 9]. Theoretically, the greatest rate of evaporation occurs when the temperature disparity between the air and the concrete is as great as it can be, along with the greatest wind speed and lowest relative humidity [3]. Uno published an equation in 1998 [8] that allows the estimation of the evaporation rate of the bleed water of a concrete sample by considering air temperature, concrete temperature, relative humidity and wind velocity, namely:

$$\mathrm{ER} = 5 \times \left[(\mathrm{T_C} + 18)^{2.5} - \frac{\mathrm{RH}}{100}(\mathrm{T_A} + 18)^{2.5}\right] \times (\mathrm{V} + 4) \times 10^{-6} \quad (1)$$

where: ER: Evaporation Rate [kg/m^2/hr]

$\mathrm{T_C}$: Concrete temperature [°C]

$\mathrm{T_A}$: Ambient temperature [°C]

RH: Relative humidity [%]

V: Wind Speed [km/h].

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Uno's [8] formula assumes a constant internal temperature of the concrete. In reality this is not the case, as the exothermic reaction between cement and water in a concrete mix, known as hydration, causes a significant increase in heat in the concrete matrix. Estimates of concrete maturity and subsequently the concrete strength are made possible by the observation of this temperature change.

In this paper, the effectiveness of three different types of curing compounds in various environmental conditions, with respect to wind speed, relative humidity and temperature, was examined directly by means of the curing compound's evaporation reducing abilities. The experimental data was plotted against theoretically calculated values. The internal temperature fluctuations were also observed with respect to the concrete's initial and final setting times.

2 Experimental work

The experimental work presented in this paper consists of determining a suitable mix design as well as determining the initial- and final setting times. The details of the applied curing compounds are also considered. The MCC, measurement equipment and experimental procedure are also discussed.

2.1 Materials and mix design

In order to simulate a typical concrete mix used in local construction projects, the mix design for the experimental phase was based on the availability of standard, regional materials. The application of the curing compounds as quickly as possible after finishing required a low bleed rate. The small application window ensures that the curing compound's effect occurs as soon as possible. To guarantee that the fresh concrete, which contained measurement equipment, could be worked adequately, a medium slump reading of around 80 mm was necessary. The concrete mixture's constituents are listed in **Table 1** along with a summary of their details, relative density (RD) and mass per cubic meter.

Table 1. Mix design constituents and details.

Constituent	Details	RD	Mass (kg/m^3)
Cement	CEM I 52.5 R	3.14	500
Water	Tap water	1.00	250
Sand	Crushed dolomite	2.84	783
Stone	Crushed 9.5mm dolomite	2.84	957
Total:			2490

2.2 Setting times

By measuring the penetration resistance of mortar that had been sieved from the concrete mixture, the setting times of the concrete mix were established in accordance with ASTM C403 (2008) [10].

2.3 Curing compounds

The three curing compounds used in the experimental phase are given and detailed in **Table 2**.

Table 2. Curing compound details.

Curing compound	CC 1	CC 2	CC 3
Base	Water	Water	Solvent
Emulsion	Wax	Acrylic	Resin
Application rate (m^2/l)	5	5	5-8
Application time	As soon as possible but within 30 minutes of casting	Immediately after finishing	As soon as possible on fresh concrete
Physical state	Liquid	Liquid	Liquid
Colour	Milky white	Milky white	Light yellow
Odour	Slight, faint	Slight, faint	Strong, resinous
RD at 25°C	0.98	>1	0.84 +/- 0.02
pH (+/- 0.5)	7	10	5-6
Solubility in water	Partially soluble	Dilutable	Insoluble
Harmful?	No	No	Yes
Compliant to ASTM C309?	Yes	Yes	Yes
Colour classification	2	2	1
Solid classification	A	A	B

The application of curing compounds was done by filling 50 ml spray bottles with each respective curing compound and spraying the surface of the concrete as soon as possible after finishing and within 30 minutes of casting

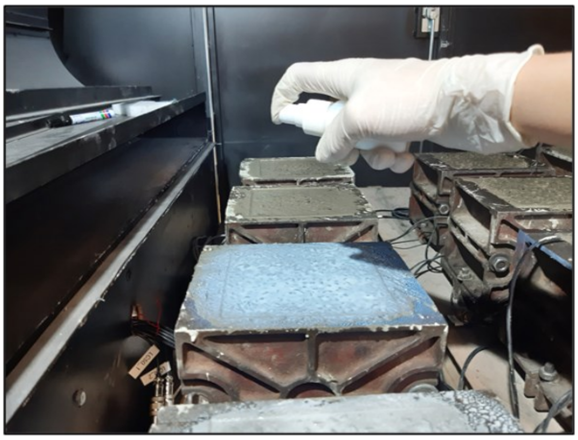


Fig. 1. Spraying of curing compound.

and is shown in **Fig. 1**. The quantity of curing compound required for each sample was determined using the prescribed application rate and the surface area of each sample. The following equation provides the formula for calculating the necessary amount of curing compound, in millilitres.

$$\text{CC [ml]}= \frac{\text{Surface Area [m}^2\text{]}}{\text{Application Rate [m}^2\text{/l]}} \times \frac{\text{1000 [ml]}}{\text{1 [l]}} \qquad (2)$$

The average number of sprays required to yield 1 g of curing compound was tested experimentally and is shown in **Fig. 2.** The number of sprays were then modified according to the sample's specific gravity and required volume in ml.

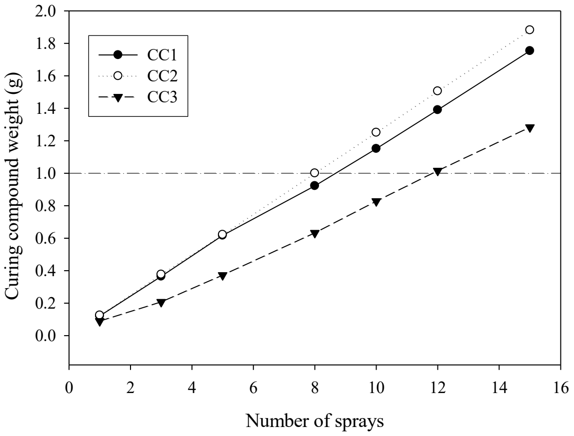


Fig. 2. Number of sprays of curing compound.

2.4 Mobile climate chamber (MCC)

The experimental work of this paper was conducted in the state-of-the-art, mobile climate chamber (MCC). The MCC allows the user to specify the wind speed, temperature and relative humidity required for the samples placed in the specimen area. The cables of the measurement equipment inside the concrete samples were guided to the data acquisition system at the back of the MCC with space for the display monitors, which allow for constant visualisation of the acquired raw data. **Fig. 3** shows the experimental setup in the specimen area of the MCC.

Fig. 3. MCC specimen area with experimental setup.

The environmental conditions of the MCC specimen area were monitored by using a Wave BME280 environmental sensor, capable of sensing temperature, humidity, and barometric pressure. The wind speed was monitored with an anemometer with pulse output.

2.5 Measurement equipment

In order to conduct evaporation tests, the mass loss of concrete samples with known surface areas was continuously measured. Scales were designed and built by mounting a custom-made plate to a loadcell. HBM SP4M single point, 50 kg load cells with off-centre load compensation were used in this experimental work.

DS18B20 temperature sensors inside a sealed tube were used to measure the temperature inside the concrete samples. The waterproof sensors offer a useable temperature range of -55 to 125°C and an accuracy of 0.5 °C from -10 to +85°C.

The measurement equipment was connected via cables to a raspberry pi single-board computer. Data was recorded every 5 seconds and plotted immediately for visual inspection of trends as well as logged for further processing.

2.6 Experimental procedure

The experimental procedure consisted of four tests running for 24 hours each in the MCC at varying environmental conditions. The four environmental combinations are given in **Table 3**.

The theoretical evaporation rates for T1, T2, T3 and T4, based on Equation 1, with an average internal concrete temperature of 20°C was calculated and is also shown.

Table 3. Experimental combinations.

	Relative humidity (%)	Temperature (ºC)	Wind speed (km/h)	Evaporation Rate (kg/m^2/hr)
T1	20	25	5	0.291
T2	20	30	20	0.742
T3	20	25	30	1.101
T4	20	30	40	1.290

Each experiment consisted of casting eight 150 mm concrete cube samples. Three different curing compounds were used as well as one control, where no curing compound was applied to the top surface. A stepwise procedure for the 24-hour experimental process is given below:

Step 1: Set MCC to required relative humidity, temperature and wind speed.
Step 2: Connect temperature sensors and scales to the data acquisition system.
Step 3: Weigh materials for the concrete mix.
Step 4: Dry mix materials before adding water and allowing concrete to mix well in order to obtain a workable consistency. Record water contact time.
Step 5: Cast and vibrate, in three layers, eight samples in 150 mm cube moulds. Finish the top surface with a float.
Step 6: Transport samples to MCC and load them into the specimen area.
Step 7: Place the temperature sensors inside four of the concrete samples and place the remaining four samples on the scales.
Step 8: Spray each cube with the required number of sprays of the respective curing compound.
Step 9: Close the MCC doors and let the test run for 24 hours.
Step 10: Collect the data. Turn MCC off. Demould samples and remove temperature sensors.

3 Results

The results for the setting times as well as the main experimental results with respect to evaporation and concrete temperature are given for each test, T1 to T4.

3.1 Setting times

The penetration resistance, PR (MPa) was plotted against the elapsed time, t (min) from water contact during concrete mixing as shown in **Fig. 4.** Note that the scale of PR on the y-axis is logarithmic.

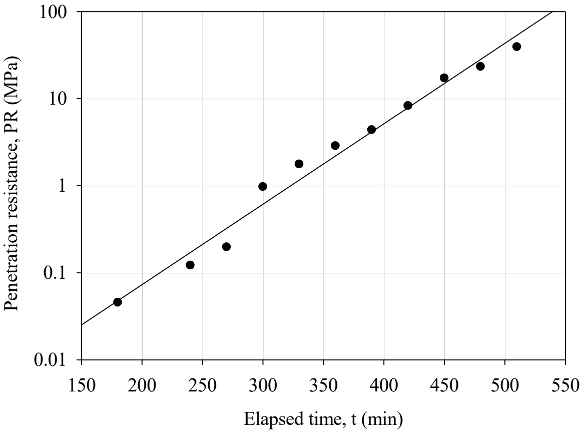


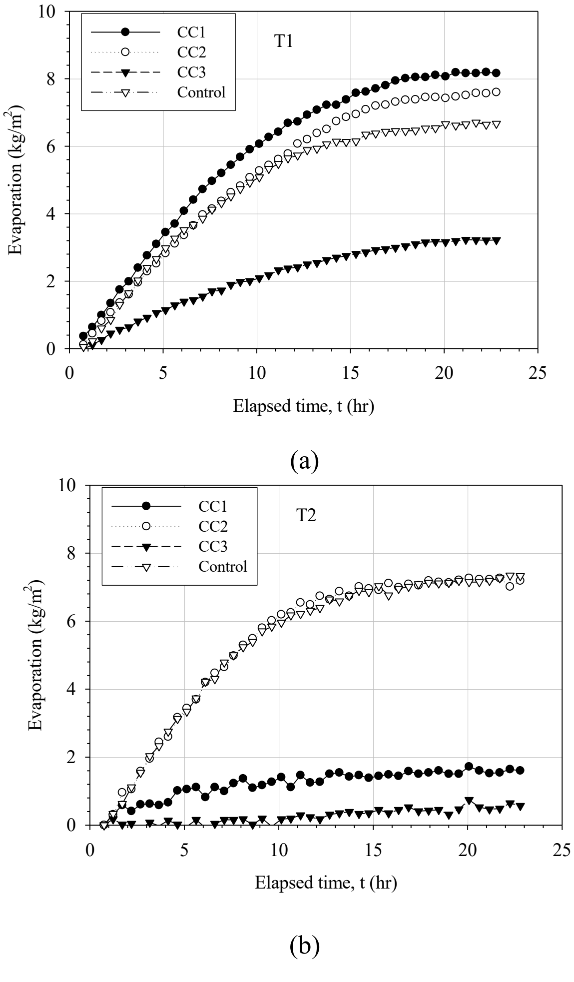
Fig. 4. Setting times results.

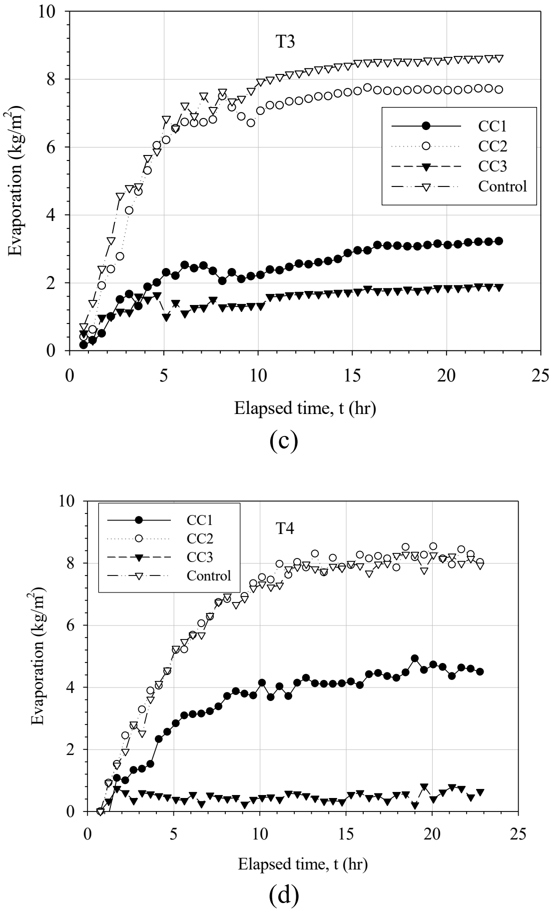
The trendline of the datapoints in **Fig. 4** is given and the equation has a correlation coefficient of 0.98. The experiment resulted in an initial setting time of 383 minutes (6.4 hours) and a final setting time of 480 minutes (8.0 hours).

$$\mathrm{PR} = 0.001\ e^{0.0213\,t} \tag{3}$$

3.2 Evaporation

The evaporation results for T1 to T4 is given in **Fig. 5** for curing compound 1, 2, 3 and the control.





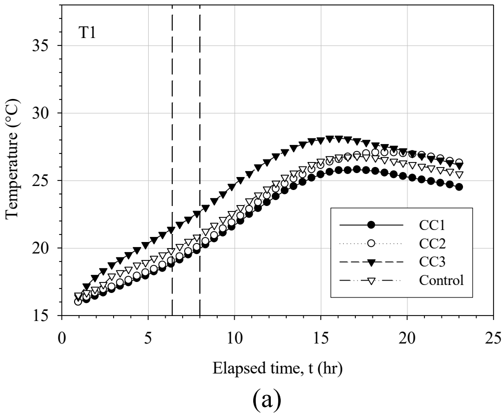
(c)

(d)

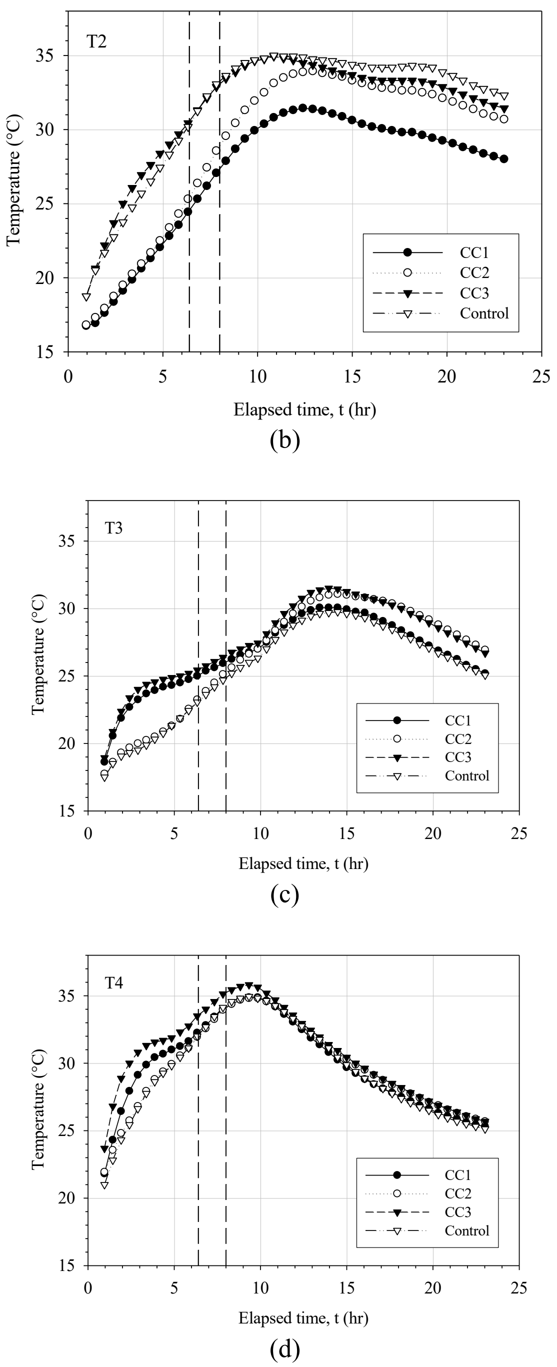
Fig. 5. Evaporation test results for T1 to T4.

3.3 Temperature

The temperature results for T1 to T4 is given in **Fig. 6** for curing compound 1, 2, 3 and the control. The initial- and final setting times are shown in the figures with vertical dashed lines.



(a)



(b)

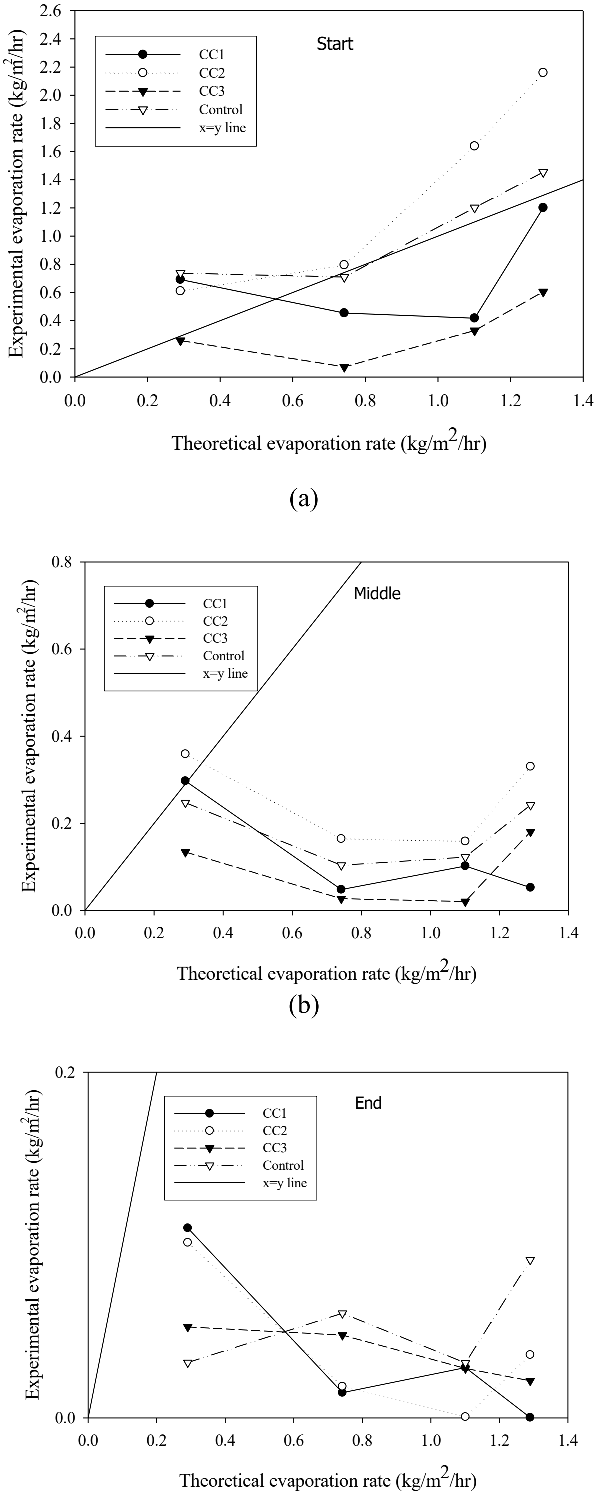
(c)

(d)

Fig. 6. Temperature test results for T1 to T4.

4 Discussion

The experimental evaporation rate for the first half-hour of test measurement, at the half-hour at midpoint of the test, and the last half-hour of testing was plotted against Uno's theoretical evaporation rate (kg/m^2/hr) in **Fig. 7**Fig. 7. Comparison between theoretical and experimental evaporation rates at the (a) start, (b) middle and (c) end of the experiments. for CC 1, 2 and 3 as well as for the control. The scale of the y-axis was changed in each figure, in order to better see the small evaporation rates for the middle and end of the tests. The x=y line, where the theoretical and experimental evaporation rates are equal is indicated in each figure. Thus, if the data point falls below this line, the experimental result is lower than the theoretical value.



(a)

(b)

(c)

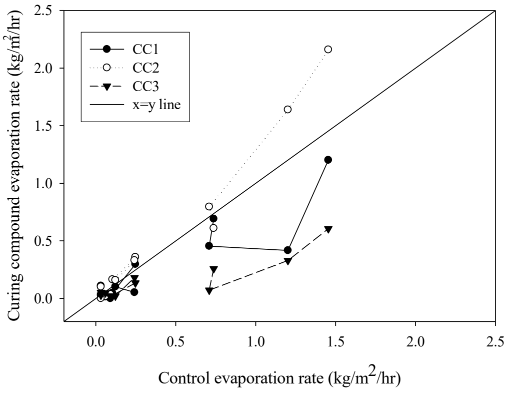
Fig. 7. Comparison between theoretical and experimental evaporation rates at the (a) start, (b) middle and (c) end of the experiments.

From Fig. 7 (a) it is seen that at a lower theoretical evaporation rate, the experimental evaporation rate for CC 1, 2 and the control is higher than the theoretically calculated evaporation rate with CC 3's evaporation rate being nearly identical to the theoretical value. As the theoretical evaporation rate increases, CC 1 and 3's experimental evaporation rate remains under the x=y line. As the theoretical evaporation rate increases the experimental evaporation rate also increases from 0.742 kg/m^2/hr, except for the outlier from CC 1 at 1.101 kg/m^2/hr. CC 3 has the lowest experimental evaporation rate out of the tested curing compounds during the first half-hour of testing.

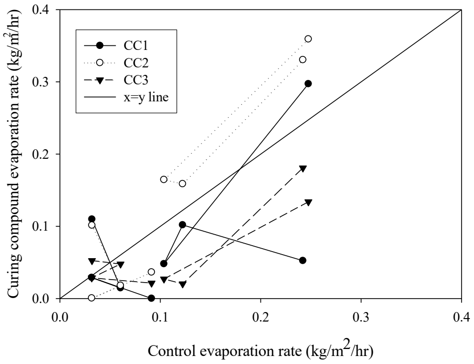
A possible explanation for the difference in values between the theoretical and experimental evaporation rates for the control is that Uno's equation assumes a constant internal concrete temperature, whereas the internal temperatures increase anywhere from 5 to 17 °C in the first 8 hours as seen in **Fig. 6** (a) to (d).

In **Fig. 7** (b) and (c) it is seen that the experimental results are much lower than the theoretically calculated evaporation rates, expect for CC 1 and 2 in (b) at the lowest theoretical evaporation rate. The lower evaporation rates as shown **Fig. 7** (b) and (c) are understandable as the mass loss over the surface area slows down at the middle and nearly stops at the end of each test as shown by the flattening of each line in **Fig. 5** (a) to (d). There is less of a pattern in the results in **Fig. 7** (c) as the experimental evaporation rates are small and all evaporation has stopped.

The experimental evaporation rate at the start, middle and end of all three of the curing compounds were also plotted against the control's experimental evaporation rate as shown in **Fig. 8.**



(a)



(b)

Fig. 8. Comparison between the experimental evaporation rates of the curing compounds versus the control.

A x=y line was added to **Fig. 8** (a) and (b) where the curing compound's evaporation rate is equal to the control's evaporation rate. **Fig. 8** (b) offers a zoomed-in view of the lower evaporation rates. If the data point falls above the x=y line, the curing compound sample performed worse than the control, where nothing was applied to the top surface of the concrete.

From **Fig. 8**, CC 2 performs consistently worse than the control at all evaporation rates. CC 3 performs better than the control at all evaporation rates and CC 1 performs mostly better than the control, except for an outlier at the lowest evaporation rate in the middle of the test.

The temperature results show a similar trend for the curing compounds and the control for all four tests. T2 shows that the control sample reached the highest temperature out of all the samples whereas, in T3 and T4, the control sample recorded the lowest temperature out of the samples. As T2 and T4 had the same environmental temperature of 25 °C, it is understood that the increased wind speed of T4 had a significant effect on the internal concrete temperature.

5 Conclusion

In this study, the performance of different types of curing compounds were compared at varying environmental evaporation rates. The following conclusions can be made:

- As the theoretical evaporation rate increased for CC 1, 2, 3 and the control, the actual evaporation rate also increased, which is expected.
- CC 2, the acrylic-emulsion curing compound performed the worst out of all the samples tested, by having a higher concrete evaporation rate than nearly all the other samples, including the control. The mechanism causing this consistently poor test results is not yet investigated.
- CC 3, the resin-emulsion curing compound performed by far the best out of all three curing compounds having consistently the lowest tested evaporation rate.
- CC 1, the wax-emulsion curing compound performed well by having an evaporation rate less than the control, but not as well as CC 3, the resin-emulsion curing compound.

Thus, based on the moisture loss from the concrete samples due to evaporation the effectiveness of the curing compounds, from best to worst, were found to be the resin-emulsion curing compound, the wax-emulsion curing compound and then the acrylic-emulsion curing compound.

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