Optimization of Cost of Building with Concrete Slabs Based on the Maturity Method

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Abstract. The maturity method is a well-known technique for determination of mechanical properties of the concrete (e.g. compressive strength) based on the development of temperature during hardening. The compressive strength of concrete can be used to determine necessary striking time of the formwork. Use of this method for this purpose is economically effective and provides necessary safety measures. This method is used in many construction sites. Time of formwork striking depends on many factors e.g. class of concrete, grade of cement, type of cement, temperature, size of the element and air humidity. The existing technical Standards and scientific research on the striking of formwork present different estimated for the striking time. Striking time for the main structural elements ranges from 14 to 21 days. For structural elements such as slabs or beams with a span of more than 6 m need to reach the minimum of 70-85% of their designed strength to remove the formwork depend on the Standards. During the construction of the buildings in summer concrete acquires the required strength for striking of the formwork faster due to the higher ambient temperature. Knowing the maturity method, we are able to estimate the compressive strength of concrete. If concrete have the required strength, the striking time can be shortened. This allows to reduce the overall costs of construction. The more concrete works are done during the construction phase the bigger the generated savings. In this article formwork striking time for concrete slabs in building based on maturity method was determined. The structure was subjected to 10 different simulated weather conditions typical for the Central and Western Europe that varied by localization of the construction. Based on simulated weather conditions the temperature in structural elements was established. The results allowed to determine the formwork striking time using the maturity method. Presented analysis shows that use of the maturity method on construction site can result in lower overall costs due to shorter time of constructing.

1. Introduction

The most commonly used material for production of slabs in multi-storey office and housing buildings is concrete. Concrete elements are used in vast number of buildings due to their strength, durability and ability to assume the shape and size of the mould. However, the casting process of concrete requires using temporary structures (formwork) which purpose is to provide support for the fresh mix. Formwork as one of the most important engineering structures support all loads during structure execution including weight of concrete, workers, equipment and other loads according to EN 1991-1-6 [1]. The formwork, which is usually rented, generates one of the highest costs during concrete works on the construction sites. Hanna & Senouci [2] and Kopczyński [3] independently reported that formwork costs are significant and account to between 40 and 60% of general costs of concrete works.
Another problem is formwork’s striking time. Late removal of the formwork can result in increased overall rental costs. Many engineers don’t know the basic method for establishing the striking time. For example according to [4]: “Over a hundred people survey has been conducted in Uruguay; this analysis shows that the 88% of the interviewed claim not to have a method or rule for determinate the minimum striking times, while 70% of the people who use a method to predict the minimum striking times, declare that it is empirical”. According to various Standards and specifications [5–10] the striking time depends on the type of the element. Table 1 shows the striking time according to selected Standards [6–8], presented data assumes that concrete was properly cured under ambient temperature higher than 16°C. Vertical elements have shorter striking time than the horizontal ones. With current technology the element can often be demoulded after less than a day. In addition many researchers [4,11,12] reported that striking time for vertical elements can be shortened even more. Main focus of the optimization of formwork striking time are horizontals elements like beams or slabs. In many cases striking time for this elements ranges from 14 to 28 days (Table 1). In majority of Standards reaching 85% of designed concrete strength by element with span of more than 6m is sufficient for removal of the formwork [8,9,13]. Even remove the soffit formwork need up to 10 days [7]. The recommended striking times are too long, particularly in hot climates, where the concrete reaches its required strength faster.

| Type of element | Formwork striking time |
|-----------------|------------------------|
| Slabs (spanning up to 2.5m) | 5 days or 50% of designed \( f_c \) |
| | IS 456: 2000 [8] |
| | BS 8110: 1997 [7] |
| Soffit formwork to slabs (Props to be refixed immediately after removal of formwork) | - |
| | 3 days |
| | 4 days |
| Soffit formwork to beams (Props to be refixed immediately after removal of formwork) | - |
| | 7 days |
| | 10 days |
| Props to slabs (spanning up to 4.5m) | 10 to 12 days or 70% of designed \( f_c \) |
| | 7 days |
| Props to slabs (spanning over 4.5m) | - |
| | 14 days |
| Props to beams and arches (spanning up to 6m) | 10 to 12 days or 70% of designed \( f_c \) |
| | 14 days |
| | 14 days |
| Props to beams and arches (spanning over 6m) | 28 days |
| | 21 days |

Development of concrete strength depends on many factors e.g. class of concrete, grade of cement, type of cement, temperature, size of the element and air humidity. In some cases the striking time should be lengthened beyond recommendations, because premature striking can cause damage to concrete [12,14]. Decision on the removal of formwork can be made based on the maturity method which is a well-known technique for determination of mechanical properties of the concrete (e.g. compressive strength) based on the development of temperature during hardening.

The research presents optimum time for formwork striking calculated with maturity method. The temperature in structural elements was determined under different simulated weather conditions. Presented analysis shows that use of the maturity method on construction site can result in lower overall costs due to shorter time of constructing.

2. Background of maturity method
Registration of the temperature in hardening concrete allows to determine its mechanical properties (such as compressive strength) based on so called maturity method (Carino 1991 [15]). The method allows to determine the formwork striking time which is important considering financial aspects of the investments [12] and construction safety [14]. Current maturity functions of ordinary concretes are well verified and practically implemented [12,16,17]. For example, there is a Standard in the United States (ASTM C1074 [18]) which describes the application of maturity functions based on premises determined by Carino in 1991 [15].

\[ M = \sum \frac{1}{N} (T - T_0) \cdot \Delta t \]  

where: \( M \) – maturity index [°C-hours or °C-days]; \( T \) – average concrete temperature during the time interval \( \Delta t \) [°C]; \( T_0 \) – datum temperature (usually taken to be -10°C); \( t \) – elapsed time [hours or days]; \( \Delta t \) – time interval [hours or days].

\[ t_e = \sum e^\left( \frac{E_a}{R \cdot \frac{1}{T_r} - \frac{1}{T_e}} \right) \cdot \Delta t \]  

where: \( t_e \) – the equivalent age at the reference temperature; \( E_a \) – apparent activation energy \( \frac{J}{mol} \); \( R \) – universal gas constant, 8.314 \( \frac{J}{molK} \); \( T \) –average absolute temperature of the concrete during interval \( \Delta t \) [K]; \( T_r \) – absolute reference temperature [K].

The maturity method was firstly used in 1949 by Nurse [19] and MacIntosha [20]. The studies were continued by Saul [21] in 1951. Then determined function based on so called maturity index (1). The hydration process however does not develop linearly as described by Saul [21] which resulted in a new approach introduced by Freiesleben Hansen and Pedersen [22] in 1977. Their method utilized the Arrhenius equation and introduced the idea of equivalent time which determines the time in which a concrete in specific temperature (e.g. on site) will reach the same strength as concrete cured in reference temperature. Many researchers (inter alia Carino [15], Kaszyńska [23]) proved that the equation (2) better reflects the maturity of concrete in structures than Saul’s formula (1).

The maturity method has numerous applications in practical use. At first the main premise for its use was structure safety. After several construction disasters caused by premature striking, the method gained recognition [24]. The method currently is broadly used in optimization of structures [4,11,16]. In recent years the method was modified to better reflect the activation energy [25] and adjust to High Performance Concrete [26].

3. Research methodology

3.1. Overall

Weather data from 10 different cities in Europe was gathered. Analyzed places are shown in Table 2. Using average daily temperatures in each month the time of reaching required strength for striking was calculated. The computations were performed based on the maturity method. It was assumed that the temperature in structure will be equal to the surrounding temperature. Assuming slab thickness of up to 30 cm and use of ordinary concrete, the hydration heat will not significantly impact the calculations. The same recommendations for the thickness of the slabs can be found in the Standard [27].

Next for chosen cities we showed the development of required formwork striking time depending on the temperatures in current month and type of cement. The article presents the quantitative analysis of the influence of Ordinary Portland Cement (OPC) and Rapid Hardening Cement (RHC).
Table 2. List of analysed cities.

| No | City          | Country                  |
|----|---------------|--------------------------|
| 1. | Warsaw        | Poland                   |
| 2. | Madrid        | Spain                    |
| 3. | Rome          | Italy                    |
| 4. | Edynburg      | Scotland (United Kingdom) |
| 5. | Cannes        | France                   |
| 6. | Minsk         | Belarus                  |
| 7. | Oslo          | Norway                   |
| 8. | Athens        | Greece                   |
| 9. | Bucharest     | Romania                  |
| 10. | Amsterdam     | Netherlands              |

3.2. Weather data

Weather data was collected from Norwegian Meteorological Institute and the Norwegian Broadcasting Corp [28]. Presented data are the mean extreme daily temperatures in a specific month. For example: in Madrid the max average temperature in January is 9.7°C and the minimum average temperature is 2.6°C, this means that on an average day in January temperature varies between 2.6°C (at about 4AM) to 9.7°C (at about 4PM). To approximate the temperature distribution, the quadratic function was used. Figure 1 shows how the quadratic functions $f_1(x)$ and $f_2(x)$, which depend on mean value of maximum ($T_{\text{max}}(\text{mean})$) and minimum ($T_{\text{min}}(\text{min})$) daily temperatures were established.

Acquired functions allowed to determine the equivalent time ($t_e$) according to equation (2) which was calculated as sum of the areas at consecutive time intervals $\Delta t$. Presented in Figure 1 $t_0$ mean daily time. Figure 2 shows temperature distribution in Madrid from January to May for a typical day in every month. Generally, the temperature distribution based on quadratic function approximation can be inaccurate. In recent studies on concrete maturity similar models of temperature are used [17,29]. For example Wade et al. [17] used more simplified model, which does not consider monthly temperature but only temperatures in two seasons (cold and warm). To sum up, for the purpose of this research temperature distribution achieved by approximation will be sufficient.

![Figure 1. Procedure for calculation of equivalent time and quadratic functions](image-url)
3.3. Compressive strength function based on maturity concept

Compressive strength function was determined based on Carino’s [12,24] maturity concept. Equivalent age was established according to formula (2). Activation energy ($E_a$) in this analysis was constant for each type of cement which is in accordance with Carino’s and ASTM C1074 concept. Many researchers [25,26] showed that activation energy can depend on time and temperature, however constant activation energy is used most of the time. For this research hyperbolic equation for strength was used, showed in formula (3). Table 3 shows established function coefficient and activation energy values. Activation energy for presented in research concrete was established in correlation of the type of cement. Study focuses on comparison between Ordinary Portland Cement (OPC) and Rapid Hardening Cement (RHC). Obtained activation energy was 41 kJ for OPC and 57 kJ for RHC according to Carino and Tank research [15]. Similar values for OPC and RHC were presented by many researchers [17,23]. Additionally, some kind of high caloric concrete mixes exhibit “cross-over” effect [30]. In considered in this study mixes with low w/c ratio and cured in temperature slightly higher than the reference one, the effect should not be visible [31,32].

$$S = S_u \cdot \frac{k(t-t_0)}{1+k(t-t_0)}$$

where: $S$ – strength at age $t$; $S_u$ – limiting strength; $k$ – rate constant, [1/day] $t_0$ – age at start of strength development; $t$ – elapsed time.

$$t = t_0 - \frac{s}{k(S-S_u)}$$

Table 3. Established coefficient for functions in formula (4) and activation energy value

| grade (class) of concrete | type of cement | $E_a$ [kJ] | $k$ [-] | $t_0$ [h] | $S_u$ [MPa] | $t_{50\%}$ [h] | $t_{70\%}$ [h] | $t_{85\%}$ [h] | $t_{50\%}$ [days] | $t_{70\%}$ [days] | $t_{85\%}$ [days] |
|--------------------------|----------------|------------|---------|--------|-------------|---------------|---------------|---------------|----------------|----------------|---------------|
| C20/25                   | OPC            | 41         | 0.019   | 11.35  | 25          | 63.13         | 2.63          | 132.16        | 5.51           | 304.74         | 12.70          |
|                          | RPC            | 57         | 0.032   | 8.83   | 25          | 40.26         | 1.68          | 82.16         | 3.42           | 186.92         | 7.79           |

Marking for Tables 3-5: $t_{e,24}$ – equivalent time evaluated for typical day in analysed month, which was calculated according to formula (2); $t_{50\%}$ / $t_{70\%}$ / $t_{85\%}$ - time which is needed to reach by concrete respectively 50% / 70% / 85% of designed compressive strength cured in reference temperature (20°C), which is calculated according to formula (4) (transformed formula (3)); $t_{e,50\%}$ / $t_{e,70\%}$ / $t_{e,85\%}$ - equivalent time which is needed to reach by concrete respectively 50% / 70% / 85% of designed compressive strength in construction site temperature condition.
Table 4. Detailed values for chosen months in Madrid

| Localization | Madrid |
|--------------|--------|
|              | Month | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
| minimum temperature (mean) | 2.6 | 3.7 | 5.6 | 7.2 | 10.7 | 15.1 | 18.4 | 18.2 | 15 | 10.2 | 6 | 3.8 |
| maximum temperature (mean) | 9.7 | 12 | 15.7 | 17.5 | 21.4 | 26.9 | 31.2 | 30.7 | 26 | 19 | 13.4 | 10.1 |
| \( t_{e,24} \) [h] | OPC | 10.54 | 11.77 | 14.09 | 15.64 | 19.52 | 26.09 | 32.42 | 31.75 | 25.27 | 17.78 | 13.16 | 11.05 |
| | RHC | 7.70 | 9.00 | 11.60 | 13.41 | 18.26 | 27.39 | 37.10 | 36.02 | 26.15 | 15.97 | 10.49 | 8.21 |
| \( t_{50\%} \) [days] | OPC | 5.99 | 5.36 | 4.48 | 4.04 | 3.23 | 2.42 | 1.95 | 1.99 | 2.50 | 3.55 | 4.80 | 5.71 |
| | RHC | 5.23 | 4.47 | 3.47 | 3.00 | 2.20 | 1.47 | 1.09 | 1.12 | 1.54 | 2.52 | 3.84 | 4.90 |
| \( t_{e,50\%} \) | OPC | 10.54 | 11.77 | 14.09 | 15.64 | 19.52 | 26.09 | 32.42 | 31.75 | 25.27 | 17.78 | 13.16 | 11.05 |
| | RHC | 7.70 | 9.00 | 11.60 | 13.41 | 18.26 | 27.39 | 37.10 | 36.02 | 26.15 | 15.97 | 10.49 | 8.21 |
| \( t_{e,70\%} \) | OPC | 12.54 | 11.23 | 9.38 | 8.45 | 6.77 | 5.06 | 4.08 | 4.16 | 5.23 | 7.43 | 10.04 | 11.96 |
| | RHC | 7.80 | 6.98 | 5.83 | 5.25 | 4.21 | 3.15 | 2.53 | 2.59 | 3.25 | 4.62 | 6.24 | 7.43 |
| \( t_{e,85\%} \) | OPC | 28.92 | 25.89 | 21.62 | 19.49 | 15.61 | 11.68 | 9.40 | 9.60 | 12.06 | 17.14 | 23.16 | 27.57 |
| | RHC | 17.74 | 15.88 | 13.26 | 11.95 | 9.58 | 7.16 | 5.77 | 5.89 | 7.40 | 10.51 | 14.20 | 16.91 |

4. Results and discussions

4.1. Computation analysis results

For each of considered locations showed in Table 2 calculations of equivalent time reflecting reaching 50%, 70% and 85% of concrete’s compressive strength were performed (chosen results were showed in Table 5). The \( t_e \) was determined depending on the daily temperature changes and type of the cement (changing activation energy) based on formula (2). Tables 4 and 5 show the calculated results of \( t_e \).

The analysis of the results showed that in many cases use of maturity method can significantly improve formwork striking time. Comparing the striking time acquired in the maturity method and required by the Standard (Table 1) we can observe considerable time savings. For the comparison elements with span of more than 6m were chosen (time of formwork removal should be between 14 and 28 days (Table 1)). It was assumed that the concrete that reached 85% of its designed strength meets the requirements for formwork removal [7,13]. Results of performed analysis presented in Table 5 include outside of times \( t_{e,50\%}, t_{e,70\%}, t_{e,85\%} \) also differences between time \( t_{e,14}-t_{e,85\%} \) and between \( t_{e,14}=14 \) days a \( t_{e,85\%} \) (\( t_{e,14}-t_{e,85\%} \)). If the result of the calculation is a positive number, then there is a time gain in the formwork striking time comparing to calculations from Table 1. If the result is a negative number, then the time showed in Table 1 was too short and the formwork removal can cause structure failure. The results bolded in Table 5 show time gain. For example if the time \( t_{e,85\%} \) is 5.26 days then \( t_{e,14}-t_{e,85\%}=14-5.26=8.46 \) day, which means that the formwork can be removed over 8 days earlier than showed by the Standard [7] which requires 14 days to achieve necessary strength by concrete.

Based on the data presented in Table 5 we can notice that the striking time calculated in Table 1 is too long considering spring and summer months. On the other hand, in some cases the striking time in winter months was too short. For example, in Minsk, Belarus, despite low daily temperatures in spring and summer months, use of the maturity method allowed to achieve time gains of up to 12 days (in August for Rapid Hydration Cement). It is worth noticing that in spring and summer months thanks to precise estimation of formwork striking time it is possible to remove simultaneously formwork for soffit and props.

Another important advantage of using maturity method is the determination of required striking time of elements under decreased temperature. Analysing data in Table 5 it is necessary to notice that
even in cities with high daily temperatures the recommended striking time shown in Table 1 need to be extended. Faster removal of the formwork can cause structural damages.

The analysis showed that time gain from faster removal of formwork and construction safety is higher for concretes with RHC. Use of RHC for production of concrete can accelerate its hardening even by several. This is the result of higher activation energy for this type of cement.

| City                  | Month | $t_{e,50\%}$ (construction site temperature) [days] | $t_{e,70\%}$ (construction site temperature) [days] | $t_{e,85\%}$ (construction site temperature) [days] | $ts,14-te,85\%$ [days] | $ts,21-te,85\%$ [days] |
|-----------------------|-------|---------------------------------------------------|---------------------------------------------------|---------------------------------------------------|-------------------------|-------------------------|
| Warsaw, Poland        | I     | 11.25                                            | 15.44                                             | 31.28                                             | -34.71                  | -17.57                  |
|                       | II    | 10.42                                            | 14.84                                             | 29.67                                             | -35.81                  | -18.67                  |
|                       | III   | 7.68                                             | 10.68                                             | 23.28                                             | -30.68                  | -15.68                  |
|                       | IV    | 5.29                                             | 8.69                                              | 20.56                                             | -22.86                  | -12.86                  |
|                       | V     | 3.78                                             | 5.09                                              | 15.82                                             | -18.09                  | -10.09                  |
|                       | VI    | 3.12                                             | 5.06                                              | 15.04                                             | -15.39                  | -9.39                   |
|                       | VII   | 2.90                                             | 6.06                                              | 13.98                                             | -15.39                  | -9.39                   |
| Rome, Italy           | I     | 5.61                                             | 6.97                                              | 12.12                                             | -21.12                  | -12.12                  |
|                       | II    | 5.15                                             | 6.24                                              | 11.20                                             | -21.12                  | -12.12                  |
|                       | III   | 4.54                                             | 5.42                                              | 10.20                                             | -19.20                  | -10.20                  |
|                       | IV    | 3.82                                             | 4.32                                              | 9.20                                              | -16.20                  | -9.20                   |
|                       | V     | 2.98                                             | 3.48                                              | 8.20                                              | -15.20                  | -8.20                   |
|                       | VI    | 2.40                                             | 3.06                                              | 8.00                                              | -13.00                  | -7.00                   |
|                       | VII   | 2.02                                             | 2.64                                              | 7.40                                              | -12.40                  | -6.40                   |
| Edinburgh, UK         | I     | 6.95                                             | 8.08                                              | 18.00                                             | -21.00                  | -12.00                  |
|                       | II    | 6.24                                             | 7.38                                              | 17.00                                             | -20.00                  | -11.00                  |
|                       | III   | 5.56                                             | 6.82                                              | 16.00                                             | -19.00                  | -10.00                  |
|                       | IV    | 4.66                                             | 5.76                                              | 15.00                                             | -18.00                  | -9.00                   |
|                       | V     | 3.91                                             | 4.82                                              | 14.00                                             | -17.00                  | -8.00                   |
|                       | VI    | 3.48                                             | 4.42                                              | 13.00                                             | -16.00                  | -7.00                   |
|                       | VII   | 3.02                                             | 3.96                                              | 12.00                                             | -15.00                  | -6.00                   |
| Minsk, Belarus         | I     | 14.39                                            | 18.44                                             | 34.54                                             | -30.54                  | -17.54                  |
|                       | II    | 13.12                                            | 17.54                                             | 32.64                                             | -29.64                  | -16.64                  |
|                       | III   | 9.64                                             | 12.14                                             | 28.74                                             | -25.74                  | -12.74                  |
|                       | IV    | 5.87                                             | 8.24                                              | 22.84                                             | -19.84                  | -10.84                  |
|                       | V     | 3.87                                             | 5.44                                              | 18.04                                             | -15.04                  | -7.04                   |
|                       | VI    | 3.21                                             | 4.26                                              | 14.04                                             | -13.04                  | -6.04                   |
|                       | VII   | 2.99                                             | 3.86                                              | 12.04                                             | -11.04                  | -5.04                   |
|                       | VIII  | 3.12                                             | 4.00                                              | 12.04                                             | -11.04                  | -5.04                   |
| Athens, Greece        | I     | 8.11                                             | 8.46                                              | 16.46                                             | -13.46                  | -6.46                   |
|                       | II    | 7.65                                             | 8.03                                              | 15.03                                             | -14.03                  | -7.03                   |
|                       | III   | 4.86                                             | 5.09                                              | 12.09                                             | -11.09                  | -4.09                   |
|                       | IV    | 3.28                                             | 4.06                                              | 10.06                                             | -9.06                   | -3.06                   |
|                       | V     | 2.53                                             | 3.36                                              | 8.36                                              | -7.36                   | -2.36                   |
|                       | VI    | 1.96                                             | 4.09                                              | 6.96                                              | -5.96                   | -1.96                   |
|                       | VII   | 1.69                                             | 3.38                                              | 6.06                                              | -4.06                   | -1.06                   |
|                       | VIII  | 1.72                                             | 3.59                                              | 5.29                                              | -3.29                   | -1.29                   |

To sum up, almost for every country there are month in which use of maturity method on site can bring real gains. This shows that in cities with colder climates it is necessary to use Rapid Hardening Cements (RHC) to increase the gains from maturity method. For cities in warmer climate the maximum time gained from maturity method is almost 13 days (12.83 days for Athens, Greece in...
July) for Ordinary Portland Cement (OPC) and almost 16 days (15.99 for Athens, Greece in July) for Rapid Hardening Cement (RHC).

Maturity method can not only be used for cost optimization but also for monitoring of structure safety in case of work under lower thermal conditions [24,33]. Almost in every analyzed country there were observed issues of too fast striking of formwork. For example, in January in Minsk removal of the formwork should be significantly postponed to achieve required concrete strength.

4.2. Discussion and problems

The results of the analysis show that surrounding temperature by increasing the hardening temperature can be beneficial to the concrete. It is necessary to notice that in many cases elevated temperature of the concrete can cause damages, especially in mass structures in which lower temperatures and their gradient is required [34]. Several scholars proved that considered maturity method can have a broad use in monitoring of structures [12,16,17] and stepping up of construction process [4]. It needs to be remembered that the method can estimate wrongly the values for concretes with significantly elevated temperatures during hardening [30] which is especially visible in mass structures [31]. Another issue is improper curing of concrete, where changing humidity can lower the strength [35].

Different issue is the aspect of developing structures in decreased temperatures. Table 5 presents results for winter months where the temperature is below 0 degrees. Total retention of hydration in concrete theoretically occurs in -10°C [12], but with improper curing the process might not start at all [36]. In thermal conditions where the temperature is below 5°, except of using maturity method it is also necessary to provide proper curing, particularly in the early phase. The analysis showed that the development of strength under such conditions is stagnant and requires increased time in formwork. It is generally safer to cast the elements in low temperatures. The choice of proper maturity function of considered concrete requires knowledge, experience and often additional analysis before implementation. Improper choice of maturity function influences the safety of structure during the investment which can cause damages or even failure.

5. Conclusions

To sum up, the maturity method can be a useful tool for optimization of investment costs of multi-storey buildings. The more concrete is used the bigger the savings. In case of cities in warmer climates the time gains can reach dozen days in one casted section of the structure (even using the OPC). Optimization of costs using this method can provide not only financial savings from shortening of formwork rental time [2,3], but also overall time of structure development. Another undisputed benefit from the maturity method is the construction safety in case of work done in lower temperatures, where the development of strength is lower than in reference temperature.

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