CORRELATION BETWEEN LABORATORY EXPANSION AND FIELD EXPANSION OF CONCRETE: PREDICTION BASED ON MODIFIED CONCRETE EXPANSION TEST

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Abstract

This paper presents a correlation between laboratory expansion tests and field expansion of concrete and a prediction model of ASR expansion at ambient environments. Modified concrete expansion tests and numerical simulation using some predictive models were integrated. In the concrete prism test, the method consisting in wrapping concrete specimens with clothes containing alkali solution was applied in order to avoid alkali leaching and drying (AW-CPT). The parameters in the models for expansion and temperature dependency were calibrated with AW-CPT and implemented in the predictive calculation. The environmental actions such as temperature and precipitation were modelled on the basis of meteorological information of exposure sites.

The results with some simplified assumptions showed that the calculated expansion using AW-CPT exhibited satisfactory agreement with measured expansion of field-exposed concrete. It is also clear that the results of field exposure tests are strongly influenced by meteorological conditions. From these results, the methodology of the prediction and correlation between laboratory tests and field performance of concrete are discussed.

Keywords: prediction, concrete prism test, alkali-wrapping, meteorological condition, modelling

1 INTRODUCTION

Prediction of concrete expansion is one of the concerns in terms of assessment of concrete structures affected by alkali-silica reaction (ASR). Prediction of ASR expansion also enables the performance-based approach for newly constructed concrete. Some advanced models have been developed to predict the expansive behaviour of concrete structures using numerical tools. In these models, some unknown parameters for each material need to be calibrated with materials tests. Some of them use a free-expansion test of concrete but it is quite difficult to get a reasonable result to agree well with the field performance of concrete (except if some coupling laws are taken into account in the model to account for the phenomena leading to have significant differences between laboratory and field expansion). In some cases the predicted results underestimate the experimental results.

One of the critical issues for concrete expansion tests is alkali leaching. When concrete is stored over water in a sealed container, a significant amount of alkalis is leached from the specimens [1]. Since water condensation is formed on the inner wall of container, water drops on dried concrete by a temperature difference between container and concrete specimens when the container is cooled before measurement. When the container is heated after measurement, water condensation is generated on the concrete surface reducing alkali content. Consequently, the alkalis in the concrete specimens diffuse out of the specimens.

Also, the drying of the concrete with low alkali content is one of the concerns. When a concrete has a low alkali content, equilibrium vapor pressure and resultant equilibrium relative

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humidity become higher due to lower salt concentration, resulting in drying [2]. This leads to fail to evaluate the potential expansion of the concrete. Concrete expansion tests such as RILEM AAR-3 and AAR-4 [3] allow the concrete specimens to have 5.5 kg/m^3 of total alkali content so that the equilibrium relative humidity remains high and limited drying can be observed. However, as a performance test, alkali amount is reduced, drying can progress more than in the case of higher alkali contents. This problem should be taken into account especially for the performance test on the concrete and expansion test on cores extracted from existing affected structures. Leaching also induces a size effect depending on the S/V ratio of the specimens.

Based on this background, it is essential to avoid or minimize these inevitable effects to evaluate the expansive performance of the concrete for safer predictions in the laboratory. To avoid alkali leaching, concrete specimens sometimes have been wrapped in a moist cotton cloth [4]. Though a cloth-wrapped concrete specimen is also affected by alkali leaching, the amount of alkalis leached is limited compared to concrete specimens exposed to humid atmosphere without wrapping within a container [5].

The authors have developed a new concrete expansion test called AW-CPT (Alkali-Wrapped Concrete Prism Test) [5, 6]. In the concrete prism test, the method to wrap concrete specimens with wet clothes containing alkali solution was applied in order to avoid alkali leaching and drying. The concentration of alkali hydroxide in the pore solution was thermodynamically calculated considering the interaction between cement hydrates and pore solution [7]. Therefore the alkali concentration of clothes can be designed so as to balance with concrete pore solution (the cloth simulates the pore solution). It should be noted that a certain amount of alkali is supplied from AW depending on alkali reactivity of aggregate because ASR consumes alkalis during the test and concrete absorbs alkaline water from the wet clothes. However the amount of alkali supplied is less than around 20% of initial alkali content of 3.0 kg/m^3) [8]. This alkali supply is inevitable but gives safer prediction.

From "performance-based approach" point of view, the most important aspect is whether AW-CPT can correlate to the field performance of the concrete. This paper focuses on this point and presents a new approach to predict the field performance of concrete by using AW-CPT. This approach compares the discrepancy of expansions between AW-CPT and field concrete. Finally the future perspective for this research is described.

2 EXPANSION BEHAVIOR OF CONCRETE IN LABORATORY TESTS

2.1 Difference of expansion between conventional CPT and AW-CPT

Conventional CPT

Figure 1 shows the expansion behaviour of concrete specimens (75×75×250 mm) having total alkali content of 3.1 kg/m^3 at 40 and 60 ºC without alkaline-wet clothes. This test is the conventional concrete prism test (hereafter, conventional CPT) basically according to AAR-3 and 4 so that the concrete specimens are subjected to alkali leaching. Different temperatures give different expansion behaviours. At 60 ºC, due to high reactivity of the aggregates containing opal and cristobalite, expansion starts just after the test and tends to increase up to 100 days. Then expansion reaches almost a plateau at 0.08 % over the period. At 40 ºC, on the other hand, expansion starts at 14 days but terminates at 100 days. After 100 days, concrete shows slight shrinkage and the final expansion is only 0.02 % although this aggregate showed serious damage in a real structure. The difference of expansion is believed to be influenced by alkali leaching and drying even in a sealed humid chamber. In the conventional CPT, alkali leaching starts right at the beginning of the test. At 40 ºC, a significant amount of alkali might be leached before starting expansion so that the concrete cannot show as much expansion as when stored at 60 ºC. It can also be pointed out that internal water saturation might affect the expansion although mass gain could be observed in both cases according to weight measurement of specimens.

AW-CPT

The expansion curves of concrete specimens (75×75×250 mm) having total alkali content of 3.0 kg/m^3 at 20, 40 and 60 ºC with an alkaline-wet cloth are shown in Figure 2 (namely AW-CPT). The cloth contained 50 g of 0.73 mol/l NaOH solution. The concentration of the solution was calculated to simulate the pore solution of concrete having total alkali content of 3.0 kg/m^3. At each measurement, the weight of the cloth was measured and not alkaline solution but pure water was added to the cloth in order to have the same water content (50g). This process enables to supply sufficient water for ASR expansion without excessive alkali supplying from the cloth. In fact, the amount of alkali supplied from the wet cloth was estimated to be 0.3-0.4 kg/m^3 [8]. The concrete of AW-CPT shows quite different expansive behaviour from that of conventional CPT at each temperature in spite of the same mixture: all the concretes of AW-CPT show expansion above 0.1 % and do not reach a plateau over the test period. This difference clearly shows the importance of alkali-wrapping on concrete prisms. It can also be pointed out that the concrete at 40 ºC shows the larger expansion, followed by 60 ºC and 20 ºC. Temperature-dependency of ASR expansion is quite complicated although it has been described as following Arrhenius law in a first approach [9]. Since expansion continues over the period, the monitoring is planned to be carried out for long-term.

2.2 Temperature dependency modelling of ASR expansion

AW-CPT shows complicated expansion behaviour at each temperature. Here, in order to evaluate the temperature dependency of ASR expansion for this specific concrete, the experimental data were fitted with the equations explained detailed hereafter:

$$\varepsilon_t = \varepsilon_\infty \frac{1-\exp\left(\frac{-t}{\tau_C}\right)}{1+\exp\left\{-\frac{(t-\tau_L)}{\tau_C}\right\}} \tag{1}$$

$$\varepsilon_t = \varepsilon_\infty \frac{1-\exp\left(\frac{-t}{\tau_C}\right)}{1+\exp\left\{-\frac{(t-\tau_L)}{\tau_C}\right\}}\left(1-\frac{\phi}{t+\delta}\right) \tag{2}$$

where, t: time (day), ε_t: expansion at time t (%), ε_∞: asymptotic final expansion (%), τ_C: characteristic time (day), τ_L: latency time (day) and ϕ, δ: empirical constants (day).

Equation (1) is devised to simulate ASR expansion and shows S-shaped curve [9]. Equation (2) is modified one for DEF expansion [10]. As a result shown in Figure 3, equation (1) underestimates the long-term expansion whilst equation (2) gives well-fitted result. Each parameter calibrated by fitting is summarized as a function of the inverse of absolute temperature. The results are shown in Figure 4. Logarithmic value of each parameter shows linear relationship with the inverse of temperature. Hence each parameter can be expressed according to the following equation (derived from Arrhenius law):

$$\frac{X_{(T1)}}{X_{(T2)}} = exp\left[\frac{U_X}{R}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right] \tag{3}$$

where, X and U_X denote each parameter and its activation energy, respectively. R is 8.314 [$JK^{-1}mol^{-1}$], T_1 is the temperature [K] at the targeted environment and T_2 is the temperature [K] at the laboratory. Each activation energy is summarized as follows: $U_{\varepsilon\infty}$ = 24.0 [$kJmol^{-1}$], U_C = 82.6 [kJ/mol^{-1}], U_L = 191.8 [kJ/mol^{-1}], U_δ = 63.6 [kJ/mol^{-1}], U_ϕ = 63.5 [kJ/mol^{-1}]: these values are identified by fitting with least square method (see Figure 4).

According to Larive [9], who investigated the temperature effect on ASR expansion, temperature is believed to have no influence on the asymptotic final expansion whereas it has strong influence on characteristic and latency times. The expansion does not reach a plateau so that fitting might mislead the result. In fact, at 20 ºC, calibrated asymptotic final expansion is approximately 0.4 % that is far from the experiments. Further long-term expansion monitoring is necessary to adjust the fitting of the corresponding parameter. Therefore the mechanism underlying the results is not clear but these parameters can be practically useful to convert each parameter at the temperature in the laboratory to one at the actual temperature, from the viewpoint of prediction.

3 PREDICTION USING AW-CPT AND PREDICTIVE MODELS

3.1 Targeted field-exposed concrete block

A concrete block (400×400×600 mm) using the same aggregate with the same aggregate size has been exposed to field conditions in Fukuoka, Japan. The total alkali content in concrete is 3.0 kg/m^3. The meteorological history is shown in Figure 5. These meteorological data were collected by Japan Meteorological Agency [11]. Annual mean temperature in Fukuoka is 17.0 ºC and annual precipitation is 1612.3 mm.

The expansion behaviour of the concrete block is shown in Figure 6. The expansion of concrete starts at 100 days and increases roughly linearly with time during the exposure period. The expansion after 3 years exceeds 0.2 % and is higher than those obtained by conventional CPT and AW-CPT.

3.2 Calculation method

The procedures to calculate expansion

The expansion calculation of field-exposed concrete block was performed thanks to AW-CPT results. However modelling of meteorological conditions such as solar insolation and rainfall still remains controversial. Therefore some simple assumptions were first made as follows:

(1) Temperature of concrete is the same as the ambient temperature measured,
(2) Any shrinkage is not considered,
(3) Moisture content is constantly distributed in concrete block, and
(4) There is no alkali leaching nor supplying

Another assumption was made for water supply, the details of which are described in the following section. Calculation of expansion without considering mechanical interactions was performed. Mechanical calculation would be necessary because dried or alkali-leached part would not expand and form the non-expansive layer [12-14] which resists against the expansive pressure by ASR. This point will be investigated in the future research.

In calculating expansion behaviour of concrete block exposed to the field, the calculation was carried out up to 1500 days with time interval (Δt) of 1 day. The calculation procedures are shown in Figure 7. At each time step, the parameters were calibrated with Arrhenius law according to the actual temperature. Here, since the asymptotic final expansion depends on the temperature, chemical reaction advancement is clearly different when the temperature changes. The corresponding time to have the same expansion as that of the different temperature should be calculated (Figure 8). At time step t_i, the virtual time vt_{i-1}, at which the master curve of expansion calculated with the parameters at time step t_i is equal to that at time step t_{i-1} (ε_{i-1}), was calculated. Then the incremental expansion at vt_i ($v_{ti} = vt_{i-1} + \Delta t$) was calculated by substituting the calibrated parameters according to the actual temperature in the rate form of Equation (2). Finally expansion at time t_i (ε_i) was calculated by adding calculated incremental expansion ($\Delta\varepsilon_i$) to the former expansion ($\varepsilon_i = \varepsilon_{i-1} + \Delta\varepsilon_i$).

Modelling water supplying condition

A model of expansion for relative humidity dependency has been proposed by various researchers [14-17]. The threshold relative humidity is generally thought to be 80 – 90 %, though there are large variations for relative humidity threshold [17], depending on the type of aggregate and experimental procedures and maybe on alkali content also. Three representative models for relative humidity with some experimental results are compared in Figure 9. As described above, large variations derived from aggregate type and experimental procedures can be observed. It is obvious that the higher the relative humidity, the larger the expansion. It is definitively correct that high moisture state gives larger ASR expansion.

It should be noted that field-exposed concrete block is subjected not only to relative humidity of the environment but also to rainfall. Direct water supply by rainfall, consequently wet block surface subjected to swelling and equipped for expansion measurements, makes the expansive behaviour more complicated. It is claimed, however, that there are no obvious differences between the specimens exposed to ambient rainfall and those partly immersed in water, according to "PARTNER" project [18]. This result suggests that the core part of concrete blocks is always in wet conditions so that external water supply does not affect significantly the expansion. It is also well known, on the other hand, that the part submitted to water supply by rainfall is apparently damaged by ASR. Although the modelling of such wetting-drying process by rainfall remains controversial, the effect of water supply by rainfall is essential to be considered.

In the calculation, therefore, simplified calculations with the following four assumed conditions for water supply were performed:

Calc. (1): Expansion of concrete block is incremented every day
Calc. (2): Expansion of concrete block is incremented when the daily precipitation is above 3 mm
Calc. (3): Expansion of concrete block is incremented when there is any precipitation.
Calc. (4): Expansion of concrete block is incremented at the days when there are any precipitation and the next day (total 2 days).

These cases were set to clarify the impact of rainfall on ASR expansion of field-exposed concrete block. In Case 1, the moisture condition of concrete block is the same as CPT (always saturated) so concrete block expands with time continuously. Therefore Case 1 calculation would give more severe results (pessimistic) with respect to ASR expansion whilst Case 2 corresponds to the optimistic view (lower bound value).

3.3 Calculated results

Four calculated results are shown in Figure 10 as well as the experimental data. The expansion results obtained by AW-CPT at 40 °C were used in the calculation. Moreover, for "CPT Calc. (1)", the results by the conventional CPT are used assuming that the temperature dependency is the same as according to Figure 4 obtained by AW-CPT.

Calc. (1) result gives larger expansion than the experiment. The expansion simulated at 1200 days is approximately 1.5 times of the experiment. This result suggests that the expansion of concrete block is influenced by drying. Calc. (2) result, on the other hand, is half smaller than the experiment. This water supplying condition is not sufficient to have consistent result with the experiment. The calculated results by (3) and (4) better agree with the experiment. It is also interesting to note that the experiment exhibits good accordance with Calc. (3) up to 350 days and then with Calc. (4) up to 1200 days (Figure 10 (b)). Though the simplified calculations without mechanical interactions were performed, it is apparently clear that water supply condition by rainfall has critical impact on expansive behaviour of concrete due to ASR.

The calculated results with the conventional CPT result have shown quite smaller expansion (see Figure 10). The expansion at 1500 days is only 0.03 %, far from the experiment though it is assumed that the expansion proceeds every day, whatever the precipitations are. This underestimated computed expansion probably derives from experimental artifacts such as alkali leaching and drying in the CPT test, so it is quite important to avoid these influences.

4 DISCUSSIONS

Correlation of expansion between laboratory and field-exposure tests

From the experimental results and simplified calculations, it is quite clear that AW-CPT gives consistent result with the field-exposed concrete block. Since the conventional CPT is subjected to alkali leaching especially at higher temperature and drying especially at lower alkali contents, the calculated expansion turns out smaller than AW-CPT and the concrete block. It is generally claimed that the expansion of actual concrete structure is larger than that obtained from the conventional CPT. At least some of the calculated results with AW-CPT give larger expansion than the field-exposed concrete block. Taking the meteorological conditions into account in the calculation, the calculated result with AW-CPT has turned out quite consistent with the field-exposure test.

Regarding the conventional CPT, expansion of concrete tended to cease due to alkali leaching and drying over the test period. The expansive behaviour obtained by the conventional CPT is a S-shaped curve so that this kind of expansive curve can be well fitted by Larive's equation (1) [9]. AW-CPT, on the contrary, gave expansion sustained all over the test period, because no alkali leaching occurred and drying happened over the test period. This fact agrees well with the field experience. In this case, equation (1) is not satisfactorily calibrated to the experimental result.

From these results, it can be concluded that AW-CPT is a promising performance test for concrete to have a good correlation with field-exposure behaviour.

Influence of environmental conditions

The simplified calculations emphasize the importance of modelling environmental conditions, especially precipitations. Simplified trial calculations were carried out in this study and the influence of rainfall on the expansive behaviour is clearly shown. It is believed that the core part of massive concrete is wet while the skin is strongly influenced by the external moisture condition. When the thickness of the skin is thin compared to the core, ASR can take place in core part, irrespective of external water supplying conditions. According to Kagimoto et al. [13], who measured the non-expansive layer of large concrete cylinder specimens (D: 450 mm, L: 900 mm) subjected to drying (R.H. = 60%), the thickness of non-expansive layer is approximately 40 mm. Non-expansive layer can form possibly due to drying and alkali leaching. Assuming that non-expansive layer is 40 mm for this field-exposed concrete block, the dimension of core part can be calculated as, which is 55% of the total volume. Nevertheless the simply calculated result by Calc. (1) gave excessive expansion which is 1.5 times larger than the experimental result. Since the mechanical calculation should take into account both non-expansive layer and core part, it is reasonable to conclude that ASR expansion of a concrete block of this size is influenced by drying. In fact, when a larger block (1000×1000×500 mm) is exposed, not presented here, the calculated result by Calc. (1) has given consistent result with the experiment. In this case, core part can be calculated as 71 % of total volume (non-expansive layer =

40 mm). Thus the moisture content of inner part of larger concrete block is so high that the core part can expand without considering precipitation. Although the size of concrete block is 300 × 300 × 300 mm in the PARTNER project [18] and the core part is only 40% of total volume, the effect of water supply condition is less. This is a contradictory result with the estimation of non-expansive layer near the surface. At this stage, there are many factors to be taken into account and which deserve future researches.

From these results, it should be concluded that the results of field exposure test are so highly influenced by meteorological conditions that much care has to be taken in implementing the field exposure test results of a certain site to other places where the meteorological conditions are different.

Future perspectives for performance testing with AW-CPT

From the viewpoint of performance testing or future prediction, AW-CPT appears as a more promising way than the conventional CPT. But future research shall be performed. Here, future perspectives related to AW-CPT are described.

The first is the design of alkalinity of wet cloth. To avoid alkali leaching and drying it is required to reach equilibrium between the pore solution of concrete and alkaline-wet cloth. Therefore a key point is how to determine the alkalinity of pore solution. For example, when appropriate amount of supplementary cementitious materials (SCMs) replaces cement, the alkalinity of pore solution is reduced. The most reliable method is thought to extract pore solution and analyse its composition. In addition, a recent study has revealed that the reduction in alkalinity by SCMs can be calculated by considering the interaction between pore solution and C-S-H gel [7]. This calculation will help design the alkalinity of the wet cloth.

The second point is that the modified predictive model to simulate ASR expansion sustained for long-term is necessary. Though Brunetaud's equation fitted the experimental results correctly, the calculation tends to reach a plateau though the expansion is thought to sustain for long-term. Thus activation energy of ASR expansion obtained from AW-CPT for expansion might be different. The activation energy for 2 parameters in Brunetaud's equation (ϕ, δ) have not been investigated. Physical meaning of these parameters is also questionable.

Finally, research works on the performance testing and future predictions using AW-CPT are just getting started so that the applicability of AW-CPT for various concretes should be validated. Other influencing factors for future prediction such as alkali accumulation might appear. In either case AW-CPT would be recommended in order to separate other influencing factors from alkali leaching and drying, since the results by the conventional CPT are influenced by many factors.

5 CONCLUSIONS

This paper reported a correlation between laboratory expansion tests using AW-CPT and field expansion of concrete and a prediction method of ASR expansion at ambient environments. The following conclusions can be drawn on the basis of this study:

(1) AW-CPT, which can avoid alkali leaching and drying, gave larger expansion sustained over long term than the conventional CPT. This tendency is well consistent with the results of monitoring of field-exposed concrete block.

(2) On the basis of expansion model and its temperature-dependency calibrated by AW-CPT results, a predictive methodology was proposed. The predicted result by AW-CPT agreed with the expansion of field-exposed concrete block whereas the one by conventional CPT did not.

(3) Meteorological conditions, namely temperature and especially precipitations, have a strong impact on ASR expansion so that special care has to be taken when implementing the field exposure test result of a certain site to other places where the meteorological conditions are different.

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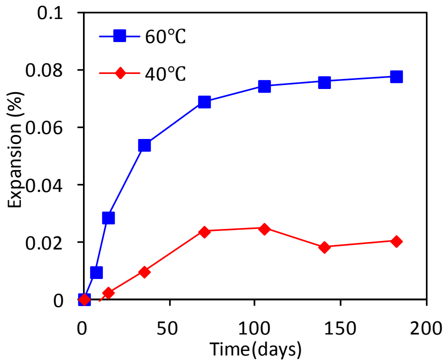


FIGURE 1: Expansion behaviour of concrete as measured by conventional CPT (specimens stored in a sealed humid container without wrapping).

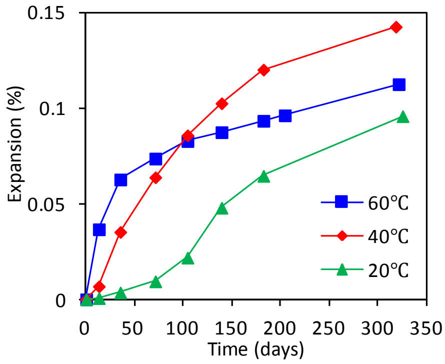


FIGURE 2: Expansion behaviour of concrete by AW-CPT (specimens stored in a humid container with wrapping by alkaline-wet cloth and plastic films).

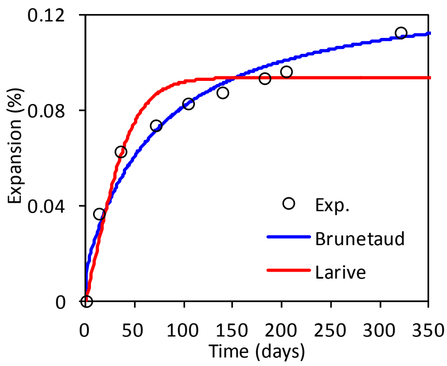


FIGURE 3: Fitted results by Equations (1) and (2).

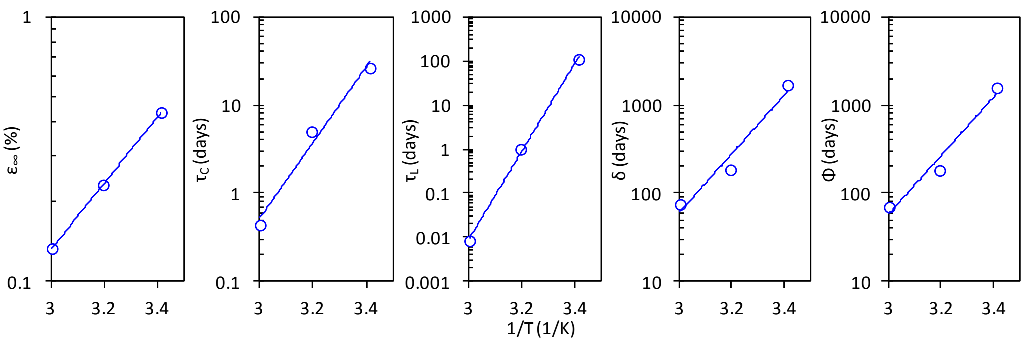
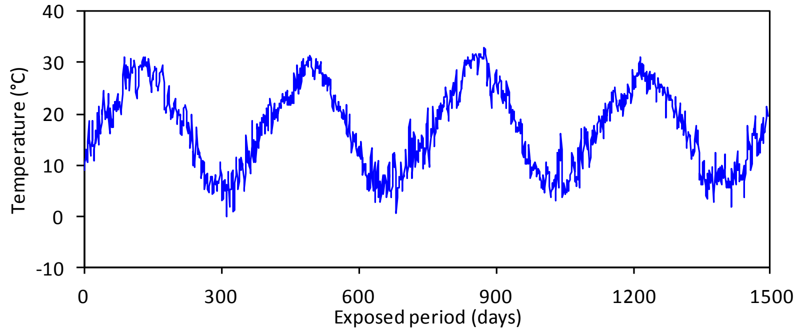
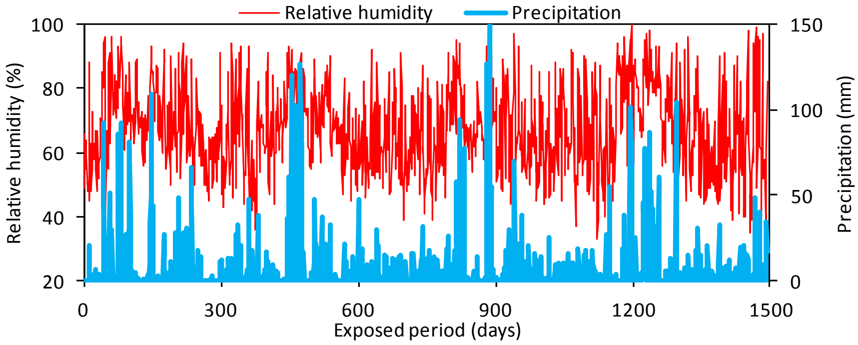


FIGURE 4: Temperature dependency of each parameter of Equation (2).



(a) Temperature



(a) Relative humidity and water precipitation

FIGURE 5: Meteorological conditions of exposure site.

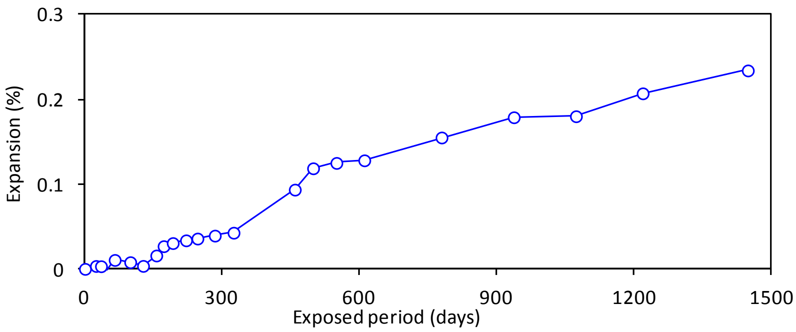


FIGURE 6: Expansion behaviour of concrete block exposed to the field.

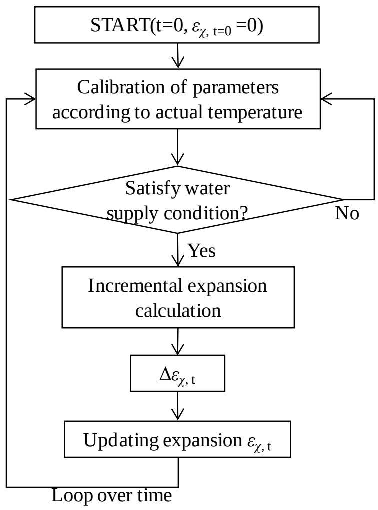


FIGURE 7: Calculation procedure.

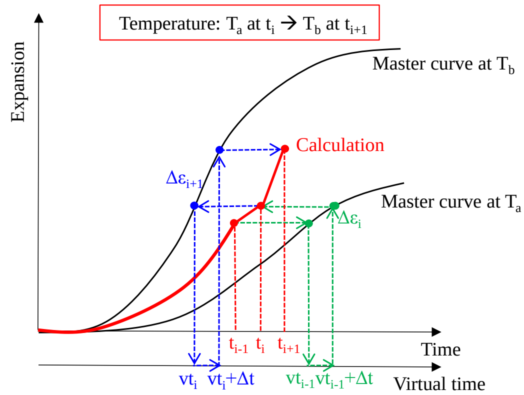


FIGURE 8: Schematic image of calculating incremental expansion at each time step.

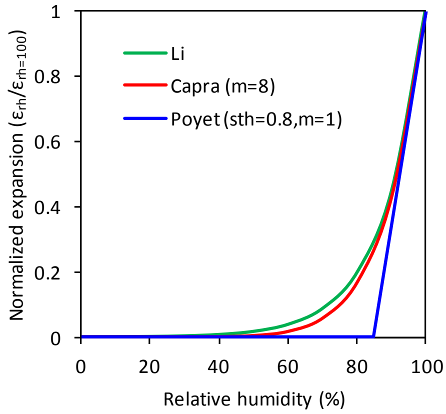
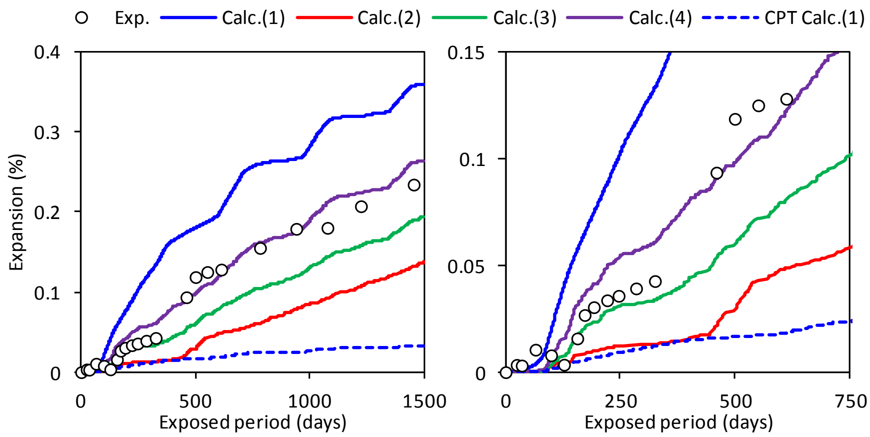


FIGURE 9: Relative humidity and normalized expansion.



(a) Overall results (0-1500 days)

(b) Magnified up to 750 days

FIGURE 10: Calculated results.