Validation of EnergyPlus infiltration models for a case study in a high-rise residential building

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Abstract
There is a lack of studies on air leakage for buildings higher than 3 stories, and the infiltration models of EnergyPlus (FlowCoefficient and Effective-LeakageArea) were developed for low-rise residential buildings. This study aims to verify if these models are reliable for estimating the dynamic infiltration in an attic in a 7-story building. Tracer gas and blower door tests were carried out to find the ad-hoc coefficients of the models and to allow their empirical evaluation according to ASTM D5157 criteria in three different periods. Models with only in situ coefficients met the standard over all time periods, demonstrating accurate performance, consistency, and reliability in both equations. For the best model generated with tracer gas data, the R² and NMSE values are equal to 0.94 and 0.019. The model created with blower door test data and EnergyPlus default values presented 64% less accuracy than the best one, which could deliver misleading energy estimates. The results can help EnergyPlus users gain insight into these models’ performance in a high-rise building to improve their implementation decisions in building energy simulations.

Key innovations
• The application of two EnergyPlus infiltration models in a high-rise residential building;
• Effective translation of the tracer gas test data to the EnergyPlus infiltration models;
• The use of three different seasons to validate the models (summer 2021, winter 2022, and spring 2022), and
• The empirical evaluation of the infiltration models with the ASTM D5157 requirements comparing measured and predicted CO₂ concentrations.

Practical implications
• Performing a tracer gas test to find in situ coefficients for the infiltration models.
• Monitoring the thermal conditions of the test space to accurately calculate infiltration.
• Applying the EnergyPlus infiltration models to buildings higher than three stories with ad-hoc coefficients.

Introduction
Nowadays, there is a need of changing the energy system based on fossil fuels to one of zero or nearly zero carbon emissions by using renewable energies. To reach this goal, carbon reduction in the building sector has become essential, as the operation of buildings accounts for 30% of final energy consumption globally and 27% of total energy sector emissions (IEA, 2022). Therefore, there is a need for precise quantification and reduction of buildings loads, in new buildings and retrofit projects. One of the ways of doing this estimation is by using Digital Twins (Hou et al., 2020) that can have a building energy model (BEM) incorporated to do instantaneous energy simulations as it receives monitored data inputs by the building management system (BMS). However, BEMs can present a building energy performance gap (BEPG), which is the difference between simulated and measured data. Calibration methods were developed to reduce the BEPG, by inserting measured data into BEMs and resulting in more accurate highly-time energy estimates (Bandera & Ruiz, 2017; González et al., 2020).

Air leakage values are one of the most important data to be inserted in BEMs. Since 1979, air tightness has been seen as an indicator of building quality and energy performance. As Feijó-Muñoz et al. (2019) affirm, infiltration can cause building energy losses and be responsible for 2.43 to 16.44 kWh/m²·year of heating demand and 0.54 to 3.06 kWh/m²·year of cooling demand. Erroneous or wrong magnitude infiltration values inserted in BEMs can result in inaccurate energy estimation (Han et al., 2015).

Two in situ measurements can be carried out to calculate air leakage and reduce its uncertainty: a blower door test and a tracer gas test (ASHRAE, 2017). The first one gives an average infiltration value after pressurizing and
depressurizing the building at high indoor-outdoor pressure differences (e.g. 10 to 300 Pa) (Shrestha et al., 2019). On the other hand, de Gids et al. (2022) states that the tracer gas techniques determine infiltration without the necessity of knowing the airflow routes. This test consists of injecting a tracer gas (in this case, CO$_2$) into a test space at normal operating conditions (e.g. 4 Pa). It can be based on one of the methods: constant injection, constant concentration, and concentration decay. In the latter, it is possible to apply the decay equation (Eq. 1, Appendix A) (ASHRAE, 2017), and then, calculate infiltration.

Nevertheless, the process of translating the air leakage test data into a building energy model is not simple or direct, especially if the work is based on dynamic energy estimation. EnergyPlus (E+) (DoE, 2021) provides three infiltration models to calculate air leakage (Appendix B): ZoneInfiltration: DesignFlowRate, ZoneInfiltration: FlowCoefficient (Eq. 2, herein as IFC), and ZoneInfiltration: EffectiveLeakageArea (Eq. 3, hereafter ELA), the latter two were applied in this study.

Some studies present the application of IFC and/or ELA to model infiltration. Shrestha et al. (2019) use IFC with flow coefficient and pressure exponent values from the blower door test they have performed on 8 one-story test facilities. Then, they empirically compared the estimated air changes per hour (ACH) values to their tracer gas test results carried out at normal operating conditions. As a result, there was a better agreement between the estimated ACH values with tracer gas results when the parameters of the blower door test were found during the pressurization test. Another study applied both models combining coefficients from their blower door test or provided by the literature to a two-story flexible research platform. They stated that regression coefficients are not reliable to be applied to other conditions, i.e. another season with different climate conditions (Bae et al., 2021).

In the González et al. (2020) method of BEMs calibration, the ELA model is applied for two three-stories single-family houses, where the leakage area is dynamically adjusted based on outdoor conditions: wind speed and direction, and outdoor temperature. However, they did not validate the calculated leakage area and infiltration with real measurements. Despite the coefficient’s values, the measured data of weather conditions are also relevant to precisely estimate infiltration. As mentioned by Zheng et al. (2020), wind has a significant influence on the measurement uncertainty of building air tightness or infiltration rate, making it one of the primary contributing factors. Porsani & Bandera (2023) studied the performance of the three infiltration models of EnergyPlus when applied with five different types of wind data and regression coefficients. The study concluded that using the wind from the weather file to predict infiltration was not the most accurate option for their preliminary test case, which casts questions on the use of this wind in the calibration of BEMs without disaggregating the wind data. Another study defined five cases with different wind speed conditions to estimate air leakage for a residential building (Winkler et al., 2017).

They compared their results from the Air-FlowNetwork (AFN) model of EnergyPlus with CONTAM and building energy optimization results, but, they did not empirically evaluate them. In addition, EnergyPlus states that the local outdoor temperature and wind speed used in the infiltration models can be calculated as a function of the height of the zone centroid above ground.

Due to the considerable height of multi-family high-rise residential buildings, complex airflow occurs based on the external wind pressure and stack effect, which in consequence, leads to indoor air and environmental problems in the dwellings, unlike in low-rise and/or single-family houses (Bak et al., 2020). An accurate process to quantify and model infiltration is relevant in order to achieve precise indoor temperature and building energy estimations. McLeod et al. (2020) affirm that the mass transfer of heat from one zone to another is often overlooked. A flat in EnergyPlus was modeled using AFN models and defined different infiltration scenarios to understand the effect of infiltration/exfiltration pathways in the prediction of indoor temperatures. Simulation results were compared with empirical data and showed that the predicted indoor temperatures are highly sensitive to how the AFN is set. As well as Mcleod et al., Monari & Strachan (2017) defend that a sensitivity analysis should be conducted at a detailed level, to consider highly uncertain parameters (e.g. wind directions, airflow pathways, moisture flow, convective heat transfer, etc), especially when the objective is to carry out calibration and validation of building energy models.

Although the authors are aware that an accurate quantitative estimation of air leakage can be done with CONTAM and FLUENT, it can be a cumbersome process when coupling them with EnergyPlus. Some of the challenges that may appear when combining these software are: difficulty in ensuring synchronization between the time steps from both software, which requires careful coordination and data exchange; increase in computational loads compared to running each tool independently, and demanding validation and calibration with required field data to compare and fine-tune the coupled models Dols et al. (2016). Also, we are focused on the building’s thermal balance and use EnergyPlus to analyze it. Therefore, we want to simplify the input of building infiltration models for EnergyPlus users as we are.

In this study, we tried to facilitate the translation process between the field measurements and the two EnergyPlus infiltration models, in order to verify if they are reliable for estimating the dynamic infiltration of a unit in a high-rise residential building. For this purpose, we decided to assess the model’s performance with in situ coefficients and combine them with off-the-shelf values. To design the tracer gas experiment, the authors investigated some previous studies (Cui et al., 2015; Li et al., 2014), and the blower door was carried out by a professional. All experimental, quantitative, and primary data were collected in situ and were managed in a spreadsheet program. The authors proved the robustness of the in situ
coefficients in other seasons and, then avoided coincidences in the results.

The models were validated according to the requirements of the American Society for Testing Material (ASTM) D5157: Standard Guide for Statistical Evaluation of Indoor Air Quality (IAQ) Model IAQ (2019). This standard is usually applied to IAQ models, by comparing the measurement and prediction of the contaminant (Pourkiaei & Romain, 2022; Emmerich et al., 2004), and evaluating it according to three statistical instruments for assessing agreement between prediction and measurements. In this study, we are applying it analogically to the CO2 concentrations, and considering that the decay curve is a function of infiltration, we are able to assess the infiltration models by the standard criteria. According to the ASTM Standard D5157, a major prerequisite for model evaluation is the independence of the data to construct and evaluate the model. This condition was met in this study because we used the summer period for training and the other two (winter and spring) for checking.

Methods

Tracer gas test

The tracer gas test was performed in the living room of an attic of a 7-story residential building in Pamplona, Spain. This space was selected, due to four main reasons: 1) we had access to monitoring it and permission to carry out in situ tests, 2) it is a real space, that has its imperfections in the thermal envelope, and three exterior façades exposed to weather conditions, only the east side adjoins the building’s vertical circulation lobby, 3) it is located in the top of a high-rise building, which has surrounding buildings from 25 m, 27 m, and 55 m, approximately, from the southeast, west, and northwest façade, respectively, and 4) it was unoccupied during the on-site experiments. As it is stated in the cadaster of the Government of Navarre, the building was built in 1992, and according to the Spanish building code from that time, it has façade insulation. The test consisted of injecting CO2 with a fire extinguisher. Only the uniform mixture of CO2 was considered in the calculations, then the first 40 minutes of the concentrations peaks were not included. This procedure allows us to find the most proper coefficients for the test space, as well as to empirically validate the models. It followed the ASTM Standard E741 test method (ASTM, 2017; Sherman, 1990). The decay method was calculated based on the multi-point approach, to smooth the measurement errors in comparison to the two-point method (Cui et al., 2015). Figure 2 indicates the main steps and sub-steps carried out during the research.

Blower door test

A blower door test (herein as BWD) was also performed in the test space, to have ad-hoc coefficients. The test was made according to ISO9972 requirements (ISO, 2015), with HVAC off, closed openings, and interior doors sealed off. During the experiment, the room was pressurized and depressurized with an indoor-outdoor pressure difference of 50 Pa.

Monitored data

The dataset included a total of 48,439 time-steps of indoor and outdoor air temperature (°C), indoor and outdoor CO2 concentrations (ppm), and wind speed (m/s) at 1-minute intervals (see Figure 3). The indoor air temperature sensors were installed at two different heights (0.80 m and 1.75 m, approximately equal to two-thirds of the floor-to-ceiling height) for gathering diverse data regarding temperature stratification. The wind speed sensor was positioned to collect data from the main directions of the site: north and northwest, according to the weather data analysis in the Climate Consultant software. The monitored data were divided into three different seasons and periods:

- P_1_T: training, 9 summer days from June 20th to July 2nd, 2021;
- P_2_C: checking 01, 11 winter days from December 10th to January 9th, 2022;
- P_3_C: checking 02, 11 spring days from March 24th to April 24th, 2022.

The rationale behind CO2 sensor placements was to gather as much diverse data as we could with respect to gas homogeneity in the room. Also, two types of sensors with the same precision of ±5% were installed: two Delta OHM HD37VBTv.1 and three EXTECH CO210. To calculate infiltration, we used the mean data from the two Delta OHM sensors, because these sensors are connected to the HOBO monitoring system of the room and enable effective data management. Table 1 shows the technical specifications of the sensors.
The uncertainty of the measurements was carried out to verify if the data was proper to generate the models. As it can be seen in Table 2, \( P_{1\_T} \) equals 70% of the highest \( \sigma \) values, which validates its application as the training period.

### Table 2: Mean (\( \mu \)) and standard deviation (\( \sigma \)) values of each measured data for each period.

<table>
<thead>
<tr>
<th>Data</th>
<th>Sensor</th>
<th>Model</th>
<th>P₁₄ T</th>
<th>P₂₄ C</th>
<th>P₃₄ C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>DELTA</td>
<td>OHM HD37V</td>
<td>613.75</td>
<td>561.14</td>
<td>629.78</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BTV.1 ppm</td>
<td>316.80</td>
<td>378.57</td>
<td>278.47</td>
</tr>
<tr>
<td>CO₂</td>
<td>EXTECH</td>
<td>CO210 ppm</td>
<td>4.80</td>
<td>13.08</td>
<td>11.26</td>
</tr>
<tr>
<td>Temp</td>
<td>HOBO</td>
<td>ZW-006 ºC</td>
<td>10.29</td>
<td>3.17</td>
<td>3.85</td>
</tr>
<tr>
<td>WS</td>
<td>AHLBORN</td>
<td>FVA 615-2 m/s</td>
<td>0.18</td>
<td>0.13</td>
<td>0.13</td>
</tr>
</tbody>
</table>

### Coefficients of the equations

Off-the-shelf coefficients. EnergyPlus (\( E^* \)) provides predefined coefficients values for equations 2 and 3. ASHRAE (2017) determines some values for stack (\( C_s \)) and wind (\( C_w \)) coefficients, and shelter factor (\( s \)) according to the number of stories of the building; if it has a crawlspace or basement with or without a flue, and the sheltered class. For this case study, we selected the maximum of stories available (three), as there are no values for a space of seven stories; a crawlspace with no flue, and a shelter class of 3. Despite the coefficient’s names being similar for both equations, they are not interchangeable. In situ coefficients. To find site-specific coefficients for both equations, we carried out mathematical regressions (herein as REG) of the coefficients where the objective function was to minimize the mean absolute error (MAE) between the predicted and measured CO₂ concentrations. Infiltration values calculated by IFC and ELA were inserted in the decay equation that results in the predicted CO₂ concentration. This iterative process is made until the MAE is minimized for all the decay days of the training period. During model fitting, there was no restriction on the range of the coefficients, with the exception of n value, which was constrained to be between 0.60 and 0.70, according to DoE (2021) recommendation. In addition, results of the BWD can be applied to the equations as coefficients, two to IFC (n value of 0.704 and \( c \) value of 0.00788 at depressurization mode), and one to ELA (\( A_L \) of 75.60 cm² at 4 Pa). Tables 3 and 4 present all models with the source of their coefficients.

### Models validation

As mentioned in the Introduction section, the models were validated according to the requirements of the American Society for Testing Material (ASTM) D5157: Standard Guide for Statistical Evaluation of Indoor Air Quality (IAQ) Model IAQ (2019). Table 5 shows the statistical values that should be complied.

### Results and discussion

It is noteworthy that the results and in situ coefficients presented in Tables 6 and 7 are specific to this test case, with no intention of extrapolating them to other spaces with the same characteristics.
Table 6: IFC coefficients. (In bold those provided by EnergyPlus).

<table>
<thead>
<tr>
<th>Model</th>
<th>IFC coefficients</th>
<th>c</th>
<th>s</th>
<th>C_T</th>
<th>C_W</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. REG</td>
<td>9.9E-03</td>
<td>1.29</td>
<td>0.038</td>
<td>0.344</td>
<td>0.600</td>
<td></td>
</tr>
<tr>
<td>2. REG + E^-</td>
<td>0.00500</td>
<td>0.70</td>
<td>0.098</td>
<td>0.151</td>
<td>0.600</td>
<td></td>
</tr>
<tr>
<td>3. BWD + REG</td>
<td>0.00788</td>
<td>1.26</td>
<td>0.041</td>
<td>0.382</td>
<td>0.704</td>
<td></td>
</tr>
<tr>
<td>4. BWD + E^-</td>
<td>0.00788</td>
<td>0.70</td>
<td>0.098</td>
<td>0.151</td>
<td>0.704</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: ELA coefficients. (In bold those provided by EnergyPlus).

<table>
<thead>
<tr>
<th>Model</th>
<th>ELA coefficients</th>
<th>A_L</th>
<th>C_s</th>
<th>C_s_s</th>
<th>C_w</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. REG</td>
<td>104.46</td>
<td>0.00002</td>
<td>0.00197</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. REG + E^-</td>
<td>27.31</td>
<td>0.00004</td>
<td>0.00027</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. BWD + REG</td>
<td>75.60</td>
<td>0.00003</td>
<td>0.00377</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. BWD + E^-</td>
<td>75.60</td>
<td>0.00004</td>
<td>0.00027</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As mentioned above, the models should comply with ASTM Standard D5157 criteria in training and checking periods. Tables 8 and 9 show that the only ones that meet this requirement are the first (“REG”) and third (“BWD+REG”) IFC and ELA models, even though the in situ tests were carried out during different indoor-outdoor pressures. In the ELA model “BWD+REG”, the A_L value is set at 4 Pa, which represents a normal pressure condition that may be the same as during the tracer gas test. This may justify why this model’s results are accurate. The precise performance of these models in all periods reveals robustness and reliability in both equations and in the site-specific coefficients.

In contrast, the other four models in IFC and ELA (“REG+E^-” and “BWD+E^-”) did not approve the standard requirements, because the site-specific coefficients were combined with coefficients found for spaces until 3-stories. As expected, the model “BWD+E^-” is less accurate in predicting dynamic infiltration in both equations. Although this model has values found at normal conditions in the ELA, it presents the highest NMSE value of 2.735 and the lowest R^2 value of 0.60. On the other hand, it is remarkable that the second ELA model (“REG+E^-”) almost complied with the standard criteria, which validates the methodology of finding coefficients proper for the room. Despite the fact the regression tries to compensate for the other EnergyPlus coefficients, it is clear that it only succeeds when combined with proper site-specific values.

The comparison between measured (in black) and predicted CO2 concentrations of the eight models are illustrated in Figures 4, 5, 6, 7, 8, and 9, where is evident their performance. Regardless of the fact we are testing the models in three different periods, all models show a pattern of behavior. In all of them, we can see that IFC and ELA models can be properly applied to predict air leakage in this test case in a high-rise residential building when using in situ coefficients. The IFC and ELA “REG” models fit the measured CO2 curve over the training period, thereby rendering it unable to see the green curve in the graphs.

If the best models are those with regression coefficients, then a blower door test is not needed for estimating dynamic infiltration for this case study. Ultimately, if we did not have the possibility to carry out a tracer gas test and have monitored data, the blower door test would be required to combine its results with EnergyPlus coefficients to generate the infiltration models. In terms of calibrating BEMs and doing time-dependent building energy simulations, it is crucial to take into account the potential inaccuracy of air leakage predictions. In this particular case study, the estimated infiltration can be up to 64% less accurate, which can lead to erroneous energy estimates.

Limitations

One of the main limitations of this study is that it was only applied to a single zone in the apartment in a high-rise building. The requirement to carry out a tracer gas test in an unoccupied space to have values of infiltration might not be feasible for complex multi-story buildings, as it was for the test case of this study.

Future work

Further research into different methods for finding ad-hoc coefficients is needed to improve the cost-effectiveness of the process applied in this study. In addition, the in situ coefficients are easily inserted into EnergyPlus, and the next step would be to see if they improve the quality of the calibration process of BEMs. The following flowchart (Figure 10) outlines how would be the next steps in the model calibration based on the translation of field measurements to the coefficients and exponents required by the EnergyPlus infiltration equations.
Conclusion

This research has shown that the FlowCoefficient and EffectiveLeakageArea equations are suitable to be applied to predict dynamic infiltration for this case study in the attic of a high-rise building. The models showed steadiness across all periods. Site-specific coefficients found by tracer gas tests presented the best results, according to the ASTM Standard D5157 and, therefore, they are required to obtain more accurate infiltration values. The IFC model with regression coefficients showed the best results, with 0.94 of $R^2$ and 0.019 of NMSE in the training period. On the other hand, the combination of blower door results with off-the-shelf coefficients of EnergyPlus represents 64% less accuracy of $R^2$. Although the results as discrete values cannot be extrapolated to other spaces with the same properties and in buildings higher than three stories, the trend of the best models should be the same when the methods of this study are applied to other test cases. Further work should be done to verify this assumption.

Acknowledgment

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Appendix A. Decay equation

\[
C_p = (\bar{C}_o - \bar{C}_{bg})e^{-lt}
\]  

(1)

$C_p$ = predicted CO2 concentration at time, $t$; $\bar{C}_o$ = average of observed indoor CO2 concentration in the space; $\bar{C}_{bg}$ = daily average of measured outdoor CO2 concentration in the air; $t$ = time, s; and $l$ = infiltration of each time-step.

Appendix B. EnergyPlus Infiltration Models

The ZoneInfiltration:FlowCoefficient (IFC) is appropriate for smaller, residential-type buildings, and can be expressed as:

\[
I = (F_{schedule})(cC_s\Delta T_n)^2 + (cC_w(s \times WS)^2n)^2
\]  

(2)

$F_{schedule}$ is a value from a user-defined schedule; $c$ is the flow coefficient in $m^3/(sPa^n)$; $C_s$ is the coefficient for stack-induced infiltration in (Pa/K)$^n$; $\Delta T$ is the absolute difference in temperature between the average dry bulb of the zone and the average outdoor dry bulb; $n$ is the pressure exponent; $C_w$ is the coefficient for wind-induced infiltration in (Pas²/m²)$^n$; $s$ is the shelter factor, and $WS$ is the local wind speed.

The ZoneInfiltration:EffectiveLeakageArea (ELA) is based on ASTM Standard E779 effective leakage area calculation (ASTM, 2019) and its equation is as follows:
\[ I = (F_{\text{schedule}})A_1 \cdot 1000 \sqrt{C_e \Delta T + C_w (WS)^2} \]  

(3)

\( F_{\text{schedule}} \) is a value from a user-defined schedule; \( A_1 \) is the effective air leakage area in \( \text{cm}^2 \) that corresponds to a 4 Pa pressure differential; \( C_e \) is the coefficient for stack-induced infiltration in \( \text{L/(s}\cdot\text{m}^2) \); \( \Delta T \) is the absolute difference in temperature between the average dry bulb of the zone and the average outdoor dry bulb; \( C_w \) is the coefficient for wind-induced infiltration in \( \text{L/(s}\cdot\text{m}^2) \cdot \text{cm}\right(\text{K}) \); and \( WS \) is the local wind speed.

### Table 8: IFC models results according to the ASTM Standard D5157. (In red color the values that do not meet the standard.)

<table>
<thead>
<tr>
<th>Model</th>
<th>Period</th>
<th>( C_e ) (ppm)</th>
<th>( C_p ) (ppm)</th>
<th>R²</th>
<th>m</th>
<th>b</th>
<th>b/( C_e ) (%)</th>
<th>NMSE</th>
<th>FB</th>
<th>FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. REG</td>
<td>P 1 T</td>
<td>613.87</td>
<td>636.91</td>
<td>0.94</td>
<td>1.05</td>
<td>-4.96</td>
<td>-0.81</td>
<td>0.019</td>
<td>0.037</td>
<td>0.149</td>
</tr>
<tr>
<td></td>
<td>P 2 C</td>
<td>559.27</td>
<td>382.23</td>
<td>0.96</td>
<td>1.00</td>
<td>-179.76</td>
<td>-32.14</td>
<td>0.177</td>
<td>-0.376</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td>P 3 C</td>
<td>627.72</td>
<td>577.88</td>
<td>0.94</td>
<td>1.09</td>
<td>-107.86</td>
<td>-17.18</td>
<td>0.026</td>
<td>-0.083</td>
<td>0.121</td>
</tr>
<tr>
<td>2. REG + E⁺</td>
<td>P 1 T</td>
<td>613.87</td>
<td>657.95</td>
<td>0.72</td>
<td>0.81</td>
<td>163.71</td>
<td>26.67</td>
<td>0.077</td>
<td>0.069</td>
<td>-0.100</td>
</tr>
<tr>
<td></td>
<td>P 2 C</td>
<td>559.27</td>
<td>305.98</td>
<td>0.91</td>
<td>0.94</td>
<td>-219.32</td>
<td>-39.22</td>
<td>0.452</td>
<td>-0.585</td>
<td>-0.014</td>
</tr>
<tr>
<td></td>
<td>P 3 C</td>
<td>627.72</td>
<td>511.22</td>
<td>0.89</td>
<td>1.11</td>
<td>-182.63</td>
<td>-29.09</td>
<td>0.079</td>
<td>-0.205</td>
<td>0.156</td>
</tr>
<tr>
<td>3. BWD + REG</td>
<td>P 1 T</td>
<td>613.87</td>
<td>637.24</td>
<td>0.94</td>
<td>1.05</td>
<td>-7.86</td>
<td>-1.28</td>
<td>0.021</td>
<td>0.037</td>
<td>0.164</td>
</tr>
<tr>
<td></td>
<td>P 2 C</td>
<td>559.27</td>
<td>398.97</td>
<td>0.96</td>
<td>1.00</td>
<td>-160.78</td>
<td>-28.75</td>
<td>0.139</td>
<td>-0.335</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td>P 3 C</td>
<td>627.72</td>
<td>551.07</td>
<td>0.93</td>
<td>1.11</td>
<td>-142.57</td>
<td>-22.71</td>
<td>0.040</td>
<td>-0.130</td>
<td>0.136</td>
</tr>
<tr>
<td>4. BWD + E⁺</td>
<td>P 1 T</td>
<td>613.87</td>
<td>438.62</td>
<td>0.64</td>
<td>0.86</td>
<td>-86.69</td>
<td>-14.12</td>
<td>0.276</td>
<td>-0.333</td>
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<tr>
<td></td>
<td>P 2 C</td>
<td>559.27</td>
<td>174.57</td>
<td>0.74</td>
<td>0.72</td>
<td>-226.69</td>
<td>-40.53</td>
<td>1.895</td>
<td>-1.048</td>
<td>-0.181</td>
</tr>
<tr>
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<td>P 3 C</td>
<td>627.72</td>
<td>286.59</td>
<td>0.76</td>
<td>1.01</td>
<td>-346.58</td>
<td>-55.21</td>
<td>0.785</td>
<td>-0.746</td>
<td>0.147</td>
</tr>
</tbody>
</table>

### Table 9: ELA models results according to the ASTM Standard D5157. (In red color the values that do not meet the standard.)

<table>
<thead>
<tr>
<th>Model</th>
<th>Period</th>
<th>( C_e ) (ppm)</th>
<th>( C_p ) (ppm)</th>
<th>R²</th>
<th>m</th>
<th>b</th>
<th>b/( C_e ) (%)</th>
<th>NMSE</th>
<th>FB</th>
<th>FS</th>
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<tbody>
<tr>
<td>1. REG</td>
<td>P 1 T</td>
<td>613.87</td>
<td>638.29</td>
<td>0.94</td>
<td>1.03</td>
<td>8.64</td>
<td>1.41</td>
<td>0.018</td>
<td>0.039</td>
<td>0.111</td>
</tr>
<tr>
<td></td>
<td>P 2 C</td>
<td>559.27</td>
<td>470.40</td>
<td>0.99</td>
<td>1.03</td>
<td>-106.68</td>
<td>-19.07</td>
<td>0.038</td>
<td>-0.173</td>
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<tr>
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<td>627.72</td>
<td>601.13</td>
<td>0.94</td>
<td>1.08</td>
<td>-75.83</td>
<td>-12.08</td>
<td>0.019</td>
<td>-0.043</td>
<td>0.109</td>
</tr>
<tr>
<td>2. REG + E⁺</td>
<td>P 1 T</td>
<td>613.87</td>
<td>665.26</td>
<td>0.72</td>
<td>0.80</td>
<td>176.98</td>
<td>28.83</td>
<td>0.077</td>
<td>0.080</td>
<td>-0.129</td>
</tr>
<tr>
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<td>P 2 C</td>
<td>559.27</td>
<td>390.62</td>
<td>0.96</td>
<td>1.00</td>
<td>-166.81</td>
<td>-29.83</td>
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<td>1.10</td>
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<td>0.053</td>
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<tr>
<td>3. BWD + REG</td>
<td>P 1 T</td>
<td>613.87</td>
<td>638.28</td>
<td>0.94</td>
<td>1.03</td>
<td>8.61</td>
<td>1.40</td>
<td>0.018</td>
<td>0.039</td>
<td>0.111</td>
</tr>
<tr>
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<td>P 2 C</td>
<td>559.27</td>
<td>470.39</td>
<td>0.99</td>
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<td>-106.68</td>
<td>-19.07</td>
<td>0.038</td>
<td>-0.173</td>
<td>0.038</td>
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<tr>
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<td>P 3 C</td>
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<td>601.13</td>
<td>0.94</td>
<td>1.08</td>
<td>-75.84</td>
<td>-12.08</td>
<td>0.019</td>
<td>-0.043</td>
<td>0.109</td>
</tr>
<tr>
<td>4. BWD + E⁺</td>
<td>P 1 T</td>
<td>613.87</td>
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<td>0.60</td>
<td>0.81</td>
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<td>-0.612</td>
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<td>0.64</td>
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<tr>
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<td>P 3 C</td>
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<td>-55.34</td>
<td>1.278</td>
<td>-0.923</td>
<td>0.097</td>
</tr>
</tbody>
</table>

### References


technical note 70-40 years to build tight and ventilate right: From infiltration to smart ventilation.


