HETT[22] – A COMSOL® App to Accurately Simulate, Plan and Monitor Concrete Castings

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Abstract

Concrete, as the world's most widely used construction material, presents significant environmental benefits and cost-saving opportunities when chosen thoughtfully for specific applications. The early-stage behavior of concrete is profoundly influenced by factors like temperature, wind conditions, construction techniques, and dimensions, requiring contractors to make informed decisions regarding concrete selection and hardening methods. Heidelberg Materials has long provided customers with finite element-based software solutions based on the maturity method to predict heat generation and strength development in concrete. However, it became evident that the existing software was becoming outdated and in need of a comprehensive update, incorporating new functionalities and features. This led to the development of the new software, HETT[22], which was created entirely on the COMSOL® platform. HETT[22] utilizes the Application Builder, complemented by method code written in the Java® programming language, to offer an intuitive interface with comprehensive functionality. The application is transformed into a stand-alone compiled application using COMSOL Compiler™, enabling any contractor to leverage the power of COMSOL Multiphysics®.

HETT[22] includes a diverse selection of pre-defined construction cases, covering various structural elements such as walls, floors, slabs, and columns. The software empowers users to manually input ambient temperature and wind conditions, whether as constant values or interpolation tables derived from weather forecasts. Furthermore, HETT[22] incorporates an automated boundary condition setup that seamlessly integrates weather forecasts from smhi.se and yr.no via JSON document retrieval. To enhance precision and validation, HETT[22] supports the import of sensor data measurements from construction sites, enabling a direct comparison between simulated outcomes and real-world observations.

Key features of this application encompass an installer for deployment, an integrated check-for-updates mechanism, and passcode system granting users access to specific functionalities. Additionally, HETT[22] provides an extensive material library and user-defined libraries, multi-language support, and the flexibility to choose between light and dark themes. To safeguard proprietary information while enabling the integration of materials from various vendors, the application employs encrypted concrete libraries, ensuring data security.

HETT[22] represents a significant leap forward in optimizing concrete construction processes, offering advanced modeling capabilities, real-world data integration, and user-friendly customization options, thereby enhancing productivity, quality, environmental sustainability, and overall performance in the construction industry.

Keywords: Concrete, Maturity Method, Simulation App, Application Builder, COMSOL Compiler.

Introduction

Concrete stands as the world's most extensively utilized building material [1]. Substantial savings and reductions in environmental impact can be achieved by selecting the most appropriate concrete for specific conditions. The early-age performance of concrete hinges significantly upon variables such as temperature, wind conditions, construction type, and dimensions. Considering these important factors, contractors must choose the concrete type carefully. This involves the selection of construction methods and optimal building materials. This is where a specialized software tool is required to provide early support to contractors in planning and monitoring the construction. Heidelberg Materials, a global leader in building materials, has been serving customers in Sweden and Norway for over three decades, offering software based on the finite element method to predict heat generation and strength development during the concrete hardening process. Accurate early strength information is vital in ensuring proper formwork removal and preventing premature exposure to sub-zero temperatures. Consequently, calculations facilitated by such software play a pivotal role. However, it became evident that the existing software was becoming outdated and required a comprehensive overhaul, incorporating new functionalities and features. As a result, Deflexional was commissioned to undertake the development of a new version of this software, named HETT[22], leveraging the versatile capabilities of the COMSOL® software tools.

The Maturity Method

The maturity method is a technique employed in the construction industry to predict the development of concrete strength over time. Concrete gains strength as it cures, and this process is highly temperature dependent. The method is founded on the principle that the rate of concrete strength gain is directly influenced by the temperature history it undergoes during hardening.

Mathematical modeling in this method is based on the discoveries of the chemist Svante Arrhenius, a Swedish Nobel Prize winner in 1903, who introduced the Arrhenius Equation, incorporating the concept of activation energy. Utilizing the Arrhenius Equation, the so-called equivalent time, and thus, the concrete maturity can be determined during the concrete hardening process. The equivalent time is a calculated value that represents the total amount of time at a standard reference temperature that is equivalent to the actual time-temperature history experienced by the concrete [2] [3].

The maturity method is implemented in a COMSOL® model using the *Heat Transfer in Solids* physics interface to simulate the heat transfer. The equivalent time is calculated with the *Domain ODEs and DAEs* physics interface and the calculated concrete strength is based on the equivalent time.

The Graphical User Interface

The application comes equipped with a range of pre-defined construction scenarios, covering various constructions including walls, floors, slabs, columns, and the ability to import measurements from sensors.
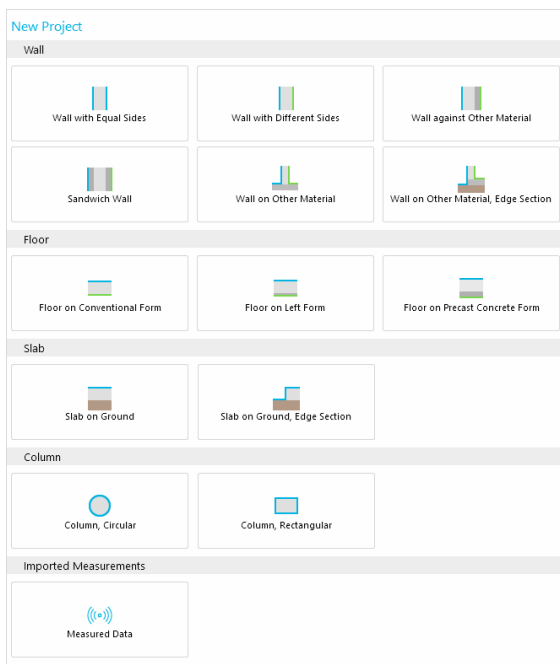

Figure 1. When launching the app, the user can choose from various construction cases.

Except for the *Measured Data* case, which uses 1D, all simulations are conducted in 2D. Once a case has been selected, the user interface and options are tailored to the specific scenario.

The primary components of the graphical user interface include a navigation menu on the left, a settings window corresponding to the selected option in the navigation menu, graphics on the right, and a ribbon menu at the top.
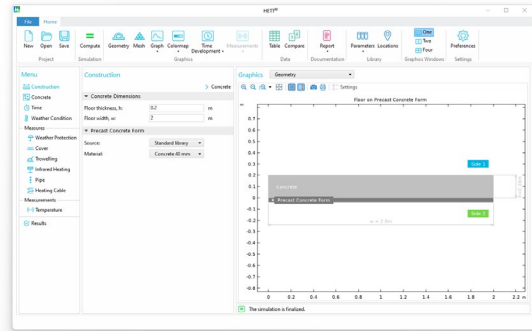

Figure 2. The graphical user interface for the "Floor on Precast Concrete Form" case.

Navigation Menu

For all 2D cases, the navigation menu contains the following options:

- *Construction:* Dimensions and materials.
- *Concrete*: Concrete quality, cement type and amount, and additional binder.
- *Time*: Simulation time, casting start time, and advanced time settings for solver.
- *Weather condition*: Temperature and wind conditions that can be constant, varying, or based on weather forecast data. Different sides may have different conditions.
- *Weather Protection*: Increased temperature with optional wind settings.
- *Pipe*: Dimension, position, material, temperature, and on/off conditions.
- *Heating Cable*: Position, power, and on/off conditions.
- *Temperature*: Import concrete sensor data or ambient temperature for comparison with simulations.
- *Results*: Output data such as strength and temperature. Potential warnings and notifications.

All walls and columns have the option to remove the form shortly after casting. You can specify either a specific time or a concrete strength for form removal. In the latter option, the time for form removal is automatically calculated. Additionally, insulation can be added after form removal. When it comes to floors and slabs, there is a particular interest in protecting the concrete from cold weather and freezing, which can be achieved by adding a cover or using infrared heating. Additionally, surface troweling options can be entered.
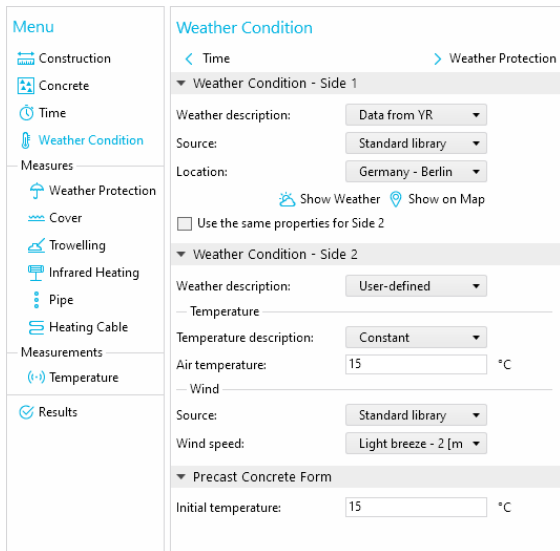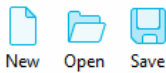
Figure 3. The navigation menu for the case, Floor on Precast Concrete Form, and the settings for the weather condition.

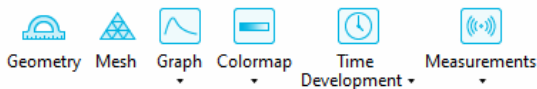## Ribbon Menu

The ribbon menu is divided into several sections:

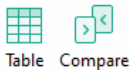- *Project*: Create a new project, save, and open.

  New Open Save

- *Simulation*: Compute the results.

  Compute

- *Graphics*: Options to visualize geometry, mesh, graphs, 2D plots, and 3D plots.

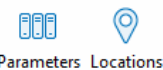 Geometry Mesh Graph Colormap Time Development Measurements

- *Data*: Simulation results as numerical data.

  Table Compare

- *Documentation*: Simulation reports in Microsoft® Word® and Microsoft® PowerPoint® formats.

  Report

- *Library*: Standard libraries and user libraries for locations and materials such as forms and insulation.

  Parameters Locations

- *Graphics Windows*: Number of concurrent graphics windows.

  One
  Two
  Four

- *Settings*: User preferences such as language and automatic software update settings.

  Preferences

Exploring and Understanding

To clarify the process by which users interact with HETT[22] to make informed decisions regarding concrete selection and appropriate construction measures to achieve specific objectives, an illustrative example is presented. It involves the casting of a wall onto a concrete floor, a scenario situated in Luleå, located in Northern Sweden, where a significant portion of the mathematical models originated.

The initial step involves the selection of the construction case, with *Wall on Other Material* chosen as the specific case in this instance. The geometry is visualized in the graphics, and it contains four different sides representing the ambient conditions, conventional forms on both sides of the wall, and the material below the concrete.
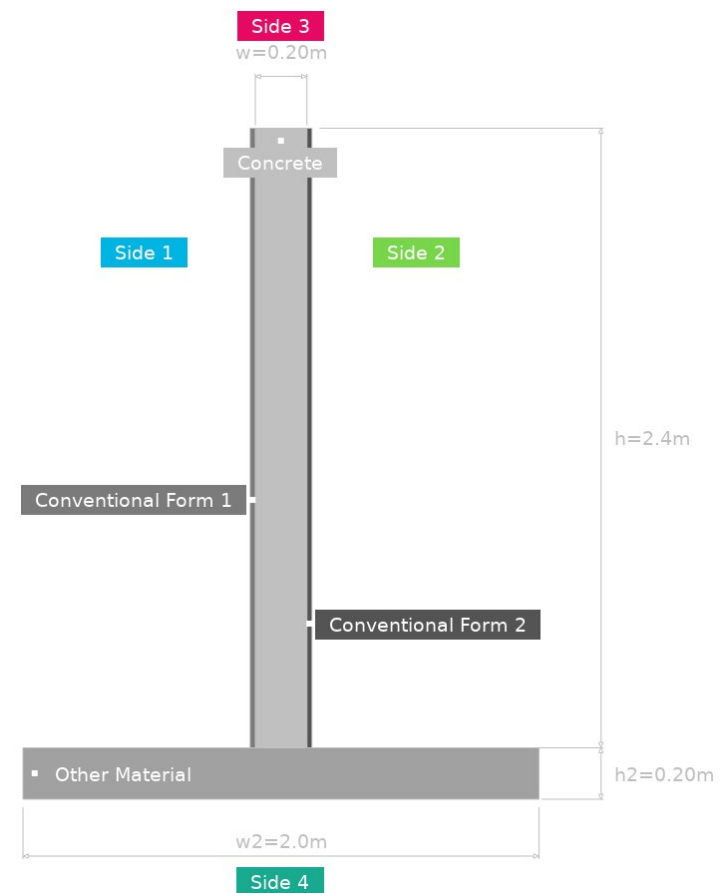
Figure 4. The construction drawing is presented with dimensions, colors and text and it is created with the COMSOL® postprocessing tools.

The user proceeds to define the dimensions and materials, while also specifying that the form should be removed after an 18-hour hardening period.

Figure 5. Settings for the selected construction are displayed, with all dimensions also visualized in the graphics.

Initially, the concrete quality, C25/30, is chosen. Subsequently, the casting temperature is set to 15°C, and the start time is scheduled for September 14th, 2023, at 08:00, one day after the simulation was performed. Automatic retrieval of forecasted weather conditions from yr.no is facilitated by inputting the construction site's longitude and latitude.

Figure 6. In this specific construction case, all four sides have the same properties. To obtain temperature and wind conditions, latitude and longitude coordinates are provided. Data is automatically downloaded from yr.no and transformed into boundary conditions. Locations can be easily saved for future use.

After the solution has been calculated, users gain access to a variety of plots in 1D, 2D, and 3D

formats. The temperature-versus-time plot clearly displays temperature profiles for both the air and the concrete.
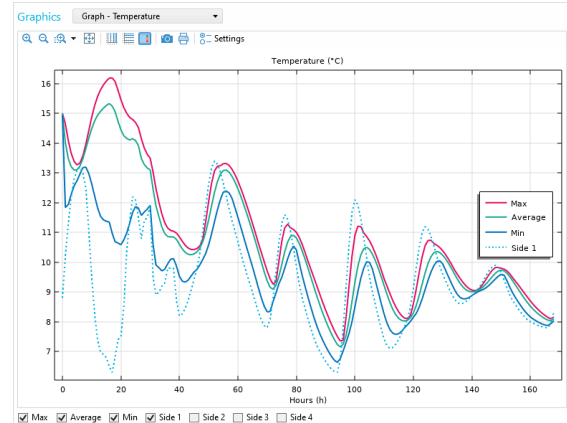

Figure 7: Temperature-versus-time is visualized in the graphics for the casting. The dotted line represents the ambient temperature, while the solid lines represent the temperature within the cast concrete.

Regrettably, the user receives a notification indicating that the strength of the concrete is insufficient to facilitate the removal of the form after the stipulated 18-hour period. Consequently, additional tests are warranted to identify an optimal configuration. The next test involves switching to concrete quality C30/37, even though it comes at a higher cost and carries increased environmental impact. Upon running the simulation, the user will ascertain that there are no hindrances to remove the form after 18 hours. However, in the endeavor to reduce CO_2 emissions, a binder combination with 20% slag is chosen. Yet, even with these adjustments, upon computing the solution with the revised settings, the user once again receives a notification, indicating that the concrete's strength remains insufficient for form removal.
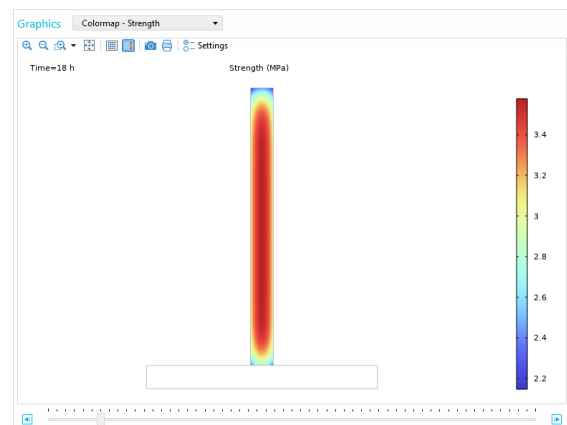

Figure 8: The strength at 18 hours is insufficient to support form removal under the forecasted weather conditions and with the selected low-carbon concrete.

Another way to rapidly increase the strength of the concrete is to elevate the temperature. One approach to achieve this is by incorporating insulation into the formwork, where transitioning

from an uninsulated steel form to a Plywood form with 30 mm XPS foam presents a viable and straightforward option. Upon re-computation, the user will receive no warnings, affirming the safety of form removal after 18 hours, given the specific concrete choice, construction parameters, and anticipated weather conditions.
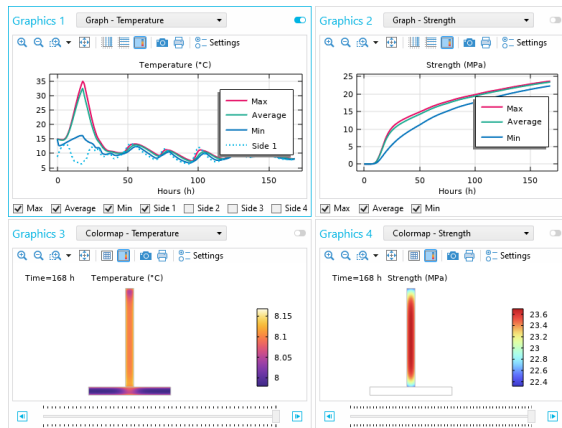

Figure 9: The results for the selected setup, with multiple windows displaying temperature and concrete strength.

The Underlying COMSOL® Model

The 2D model geometry is dynamically generated by using methods in the Application Builder based on the selected construction case by the app user. The model uses the *Heat Transfer in Solids* physics interface to simulate the heat transfer. The boundary conditions are set to *Heat Flux*, and in certain scenarios *Thin Layer*. The heat flux boundary conditions are time dependent, and both the heat transfer coefficient and the external temperature may change over time. To increase convergence and simulation time, most of the construction cases use the *Events* physics interface. This feature efficiently manages dynamic changes in the model such as formwork removal, cover additions, or the activation/deactivation of heating cables or pipes. The *Heat Source* is partly based on the equivalent time which is calculated with the *Domain ODEs and DAEs* physics interface which is also used to calculate the equivalent time and concrete strength.

The mesh is automatically adjusted for the specific construction cases and can be a mix of triangular elements and mapped meshes. Boundary layer meshing ensures that temperature gradients are resolved close to important areas. The discretization is set to quadratic lagrange for the *Heat Transfer in Solids* physics interface.

The solver uses MUMPS and the time stepping method is set to BDF with strict steps taken by the solver. Further settings can also be controlled directly from the app.

A second *2D Component* without any physics is also added. It is used to visualize the construction drawing with dimensions, colors, and textual elements.

Application Features

The development of HETT[22] has been a substantial undertaking, and the software encompasses functionalities that are likely unique and have not been previously implemented using the COMSOL® Application Builder.

Weather Forecasts to Boundary Conditions

The way concrete matures is highly dependent on the concrete temperature and thus on the surrounding air temperature and wind speed. To improve the prediction of near-future conditions, HETT[22] can automatically download weather forecasts from smhi.se [4] and yr.no [5] through JSON document retrieval. The data is then transformed into the appropriate boundary conditions. Users can either choose a city from the standard library or manually enter the latitude and longitude for the construction site. Forecasts from smhi.se are available exclusively in Sweden, while yr.no supports locations worldwide.

Sensor Data Import

For improved accuracy and validation, HETT[22] enables users to import sensor data measurements from construction sites, facilitating a direct comparison between simulated results and real-world observations. The software supports multiple sensor data formats and importing data from a Microsoft® Excel® file is straightforward. Sensors can be placed both in the air and inside the concrete. If a temperature sensor is situated inside the concrete, a 1D simulation will convert the temperature data to strength, allowing for comparison with the results generated by the 2D simulation.

Comprehensive Material Library

HETT[22] features an extensive library of construction materials. Rather than manually inputting thermal conductivity, density, or heat capacity for specific materials, users can conveniently select materials from combo-boxes, streamlining the modeling process. Besides the pre-installed standard library, users have the option to expand their library for easy access to material data. Furthermore, the software allows for the creation of a library for construction site locations.

Regional Support

At the current stage, most of the users are in Sweden and Norway. As a result, supported languages include Swedish, Norwegian, and English. The translations are integrated as an Excel file, making it easy to add additional languages in the future. Furthermore, apart from language support, it's worth noting that the background equations differ somewhat for the two concrete libraries currently supported in HETT[22].

Imported Concrete Libraries

Concrete producers have the option to include their concrete data in *Imported Concrete Libraries* that can be shared with customers. To guarantee data security, these libraries are encrypted.
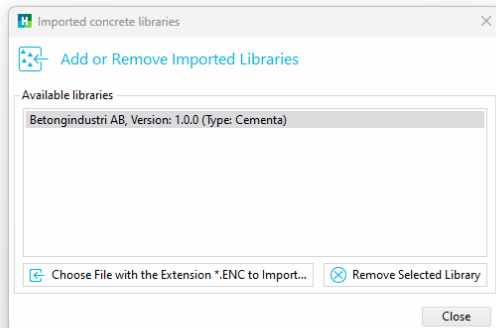

Figure 10. Encrypted concrete libraries from other vendors can easily be imported.

Access to Specific Functionality

A specific portion of the software is allocated for advanced users and researchers. To access this section, a passcode is necessary, and this passcode is tied to the MAC address of the user's computer. HETT[22] will automatically identify the MAC address of the user's computer, simplifying the process of sending this information to Heidelberg Materials before obtaining the passcode.

Check For Updates

As HETT[22] continually evolves with new features, an automatic update-check system is in place. When a new version is released, users will receive notifications each time they launch the previous version.

HETT[22] Installer

The user will download an installation file created with Inno Setup [6]. Upon completing the installation, HETT[22] is readily accessible from the Windows Start menu. If COMSOL Runtime™ is not already installed, it will be automatically downloaded.

Visual Preferences

HETT[22] offers the option to choose between light and dark themes to match their individual visual preferences. Users can also select the number of graphics windows to simultaneously visualize multiple post-processing results.
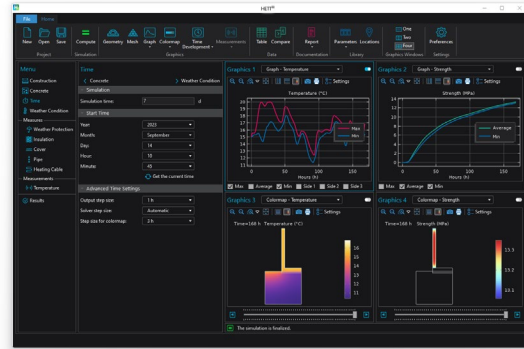

Figure 11. The user can select to run the user interface in dark theme in addition to the default light theme.

Conclusions

Concrete, the most widely used building material, holds immense potential for cost savings and environmental impact reduction when chosen wisely for specific conditions. The early-age performance of concrete is intricately linked to variables like temperature, wind, construction methods, and dimensions. It is imperative for contractors to make informed decisions regarding concrete selection, where the aid of specialized software is indispensable.

Heidelberg Materials, a renowned player in the building materials industry, has been providing software solutions based on the finite element method for over three decades. This software required a comprehensive upgrade to meet evolving needs. Deflexional was tasked with developing a new version, HETT[22], leveraging the versatile COMSOL® software tools.

HETT[22] represents a cutting-edge solution for optimizing concrete construction processes, offering advanced modeling capabilities, integration with real-world data, and user-friendly customization options. Its development marks a significant step in enhancing the construction industry's productivity, quality, environmental impact, and overall performance.

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