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Simulating the technical factors of Precast Concrete Production

G Long, University of Nottingham (gavin.long@nottingham.ac.uk)
Dr K Elliott, University of Nottingham (kim.elliott@nottingham.ac.uk)
Dr M Mawdesley, University of Nottingham (michael.mawdesley@nottingham.ac.uk)
Prof N Dawood, CCIR, University of Teesside (n.n.dawood@tees.ac.uk)
J Dean, CCIR, University of Teesside (j.dean@tees.ac.uk)
Dr R Ahmed, CCIR, University of Teesside (r.ahmed@tees.ac.uk)

Abstract

The use of precast concrete in construction provides an example of successfully employing off-site manufacturing in the industry. The UK construction industry aspires to increase its use of off-site manufacture in line with the findings of industrial reviews (Egan and Latham reports). Innovation in the precast concrete industry is limited by the risks associated with change. There is scope for simulation to provide a tool for reducing these risks and enabling greater innovation and use of precast concrete.

The Enterprise Simulation for Precast Concrete Operations (ESPCO) project intends to address this limitation by developing a virtual precast concrete manufacturing facility. ESPCO will adopt a flight simulator or sandbox approach to simulation allowing the user free rein in modelling a specific facility in detail or examining the effect of changing a single element of production such as plant equipment or materials.

This paper describes work on development of a simulation of precast concrete production from a technical perspective. The simulation focuses on concrete as a material, modelling its constituents and the production processes that affect its properties. In addition to modelling current practice, the simulation aims to enable the input of novel materials or processes and examine their impact on the concrete produced

Findings from the research undertaken in the production of a prototype technical simulation are described. The integration between the technical and operational simulations being developed is also detailed. Preliminary work moving from a prototype to a full simulation of precast concrete production is discussed.

Keywords: Virtual simulated construction sites, Integration of products, processes, life cycle support and information, Off-site manufacturing and preassembly

Background

Industrial Context

This paper reports on the results of a prototype simulation model development for Enterprise Simulation for Precast Operations (ESPCO). The ESPCO project has been funded for the UK precast industry by the British Department of Trade and Industry under technology their initiative program. The University of Nottingham (UoN) and the University of Teesside (UoT) are acting as academic partners; industrial collaborators include AMEC, Tarmac, and Aggregate Industries; the project is being led by the British Precast Concrete Federation.
The ESPCO project aims to provide a flight-simulator-like tool to precast concrete companies. It should encapsulate technical and operational aspects of precast concrete production to help them study cost and

schedule tradeoffs and identify effects of different concrete mix designs on the production process. The project has been divided into two areas: technical simulation and operational simulation of precast production operations. The University of Nottingham (UoN) is responsible for the technical simulation of precast concrete production operations and University of Teesside (UoT) is responsible for operational simulation. A prototype of operational aspects of precast concrete production has been developed by UoT and is described in a separate report by UoT. The two models will be integrated to form the flight simulator for the precast concrete industry.

This report presents a review of the activities undertaken in ESPCO at UoN. A review of the work carried out at the UoT can be found in Dawood et al (2007).

The precast concrete industry in the UK is far from homogeneous. It consists of a variety of companies ranging from small to large. The products can be classified in several ways such as Manufacture for Stock or Manufacture to order; or Structural components or non-structural components.

The methods of manufacture employed also vary and include wet casting, dry casting and spinning. Despite all these variations, the process used is significantly the same at the macro level and consists of the following steps: Production of concrete, Preparation of moulds, placing of concrete, Curing of concrete, Removal of moulds, and Transfer to storage. In addition the process for the manufacture of some units has reinforcement and prestressing steps.

Problem

Much of the precast production process is affected by the design of the concrete mix irrespective of the precasting method used or the product being made. Examples of the effects are shown in table 1.

This paper describes the development of a prototype model of the design of mixes and production of batches of the mixes. It provides the data for the process model and data to allow the combined model to evaluate the mix. This data is in terms of important measures and includes, the rate of strength gain, the workability, the curing methods allowed and their effects on the strength gain, the mixing time the actual quantities produced. Future work will investigate the provision of safety and sustainability related information for a more holistic evaluation of a mix and the process.

The prototype will act as proof of concept for the final technical model and the overall simulation model. It will allow users to investigate new constituent materials and mixes and their effects on both the batches produced and, through the process model, on the process. It also include the effects of uncertainties inherent in the individual material properties the behaviour of the materials when they are combined into a mix and the amounts of each material in any given batch of the concrete

Process step	Effect of mix design
Concrete production	Cost of raw materials
Placing of concrete	Workability of the mix is affected. This in turn affects the amount of vibration required, the quality of the finished item (in terms of voids), and how long is required for the placing process. These all affect the cost of production. In addition, the mix design will affect the maximum amount of time that is available for placing after the mixing. If this is too short, material may have to be discarded.
Curing of the units	The mix may determine the curing methods that can be used and the rate of strength gain. This in turn will determine the amount of time which must be allowed for curing.
Removal of / from moulds	The mix design will affect the rate of strength gain and hence the time before stripping is possible. It may also affect the methods that can be applied including the lifting equipment that can be used or are required.

Table 1: Illustrations of effects of mix design on process steps

The method chosen for designing the mix for the prototype model is that developed by the Building Research Establishment (BRE, 1988) and often referred to outside the UK as the British Method. This was selected as it is the most commonly used by the industrial partners at present. As more detail and accuracy becomes necessary, this choice may be re-examined. Other potential methods for concrete mixture examined range from the complex theoretical models based on particle interactions and requiring detailed material information (De Larrard, 1999; Dewar, 1999; Wong, 2005) to less complex methods based on experimental results such as the one chosen or Shacklock (Shacklock, 1974).

Learning Objectives:

- How a simulation model of the behaviour of a concrete mix can be developed
- How such a simulation model can be used to predict the values of parameters which will affect the precasting process
- How such a simulation model can be used to provide input to a process simulation model
- How such a model can be used to improve a concrete mix in terms of cost, strength, environmental impact and safety.
- How such a model can be used as a method of knowledge elicitation
- How uncertainty in the material properties can be incorporated into such a simulation model

Approach

A five-step approach as shown in figure 2 was adopted for this work. This paper covers the first two ste

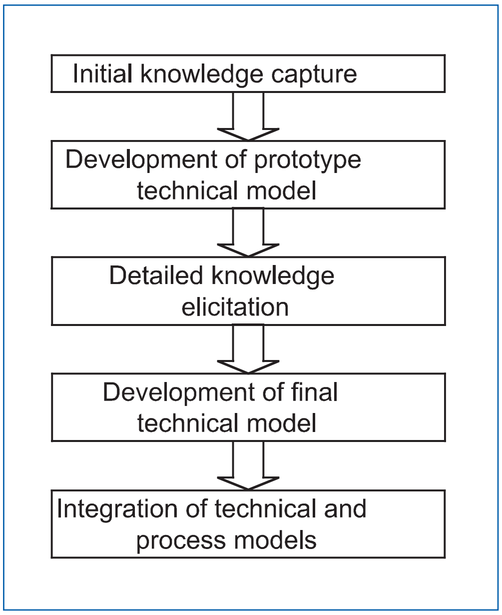


Figure 2: The outline development process

Initial Knowledge Capture

The main source of the information required for this phase was the industrial partners. Their practical knowledge was used to extend the information available from the literature and from academic sources. Several important points arose during the phase. Firstly, it became obvious that industry treated much of the required information as commercially sensitive. For example, the detailed effects of admixtures and additives were often not divulged. This is surprising because the manufacturers often want the properties of their products to be known and treat them as selling points. It is understandable however, that they would want to maintain strict control of their product information.

Secondly, and related to the first point, the products range provided by the material manufacturers changes rapidly. This is particularly true of admixtures. This sensitivity and rapid changes meant that the design of the simulation had to incorporate general materials but allow users to add their own specific materials and define exactly their effects when added to mixes.

A third point which affected the design of the simulation model was how much of the information existed only in the form of graphs and not in terms of equations. An example of this is the strength gains over time. Curve fitting could be used to produce equations but there would be no real scientific reason behind the resultant equations and it was decided, therefore, to use the graphs as these were what is used in practice.

The graphs of strength gain that are available are usually related to in-situ placed concrete and not to concrete used for precasting. In precasting, the behaviour of the concrete during the first few hours after mixing is important since it must gain sufficient strength rapidly to enable the precast unit to be moved and the mould reused. In general concrete, the first few hours are relatively unimportant since the moulds will normally not be stripped for over a day. This sparsity of data could affect the accuracy of the model and some experimentation might be required if further data cannot be found.

A final point which arose from this phase of the work is that many of the interactions of the parameters are very non-linear. A specific example of this is the effects of combining Ordinary Portland Cement (OPC) and cement replacement products (CRPs) (such as blast furnace slag, fuel ash or silica fume) in various proportions. There is not a linear relationship between the strength and the proportion of OPC. Indeed, there is no easily apparent relationship. This has meant that the prototype model has been designed so that the user has to specify any combination of a two materials as a third, new material representing a blend of the OPC and CRP.

Prototype Model Development

The model was developed around the concept that all concrete was made up of a maximum of four types of material: Binders, Bulkers, Water and Admixtures. More detailed descriptions of these types of materials and their effects on a concrete are given in a number of the sources given in this paper's references such as Neville, Powers or Dewar (Neville, 1995; Powers, 1968; Dewar, 1992). For a more detailed examination of the science and chemistry of concrete admixtures Rizom (Rizom & Mailvaganam, 1999), amongst others, provides a good background. Due to the variety of type, action and evolution of admixtures, these materials were particularly difficult to model in terms of a prototype

A 'Binder' is the material, such as OPC, Rapid Hardening Portland Cement (RHPC) or a blend of these with CRPs which binds all the materials together. It is the main active ingredient of the concrete.

A 'Bulker' is a material which gives the final product its volume. Typical bulkers are the coarse and fine aggregates.

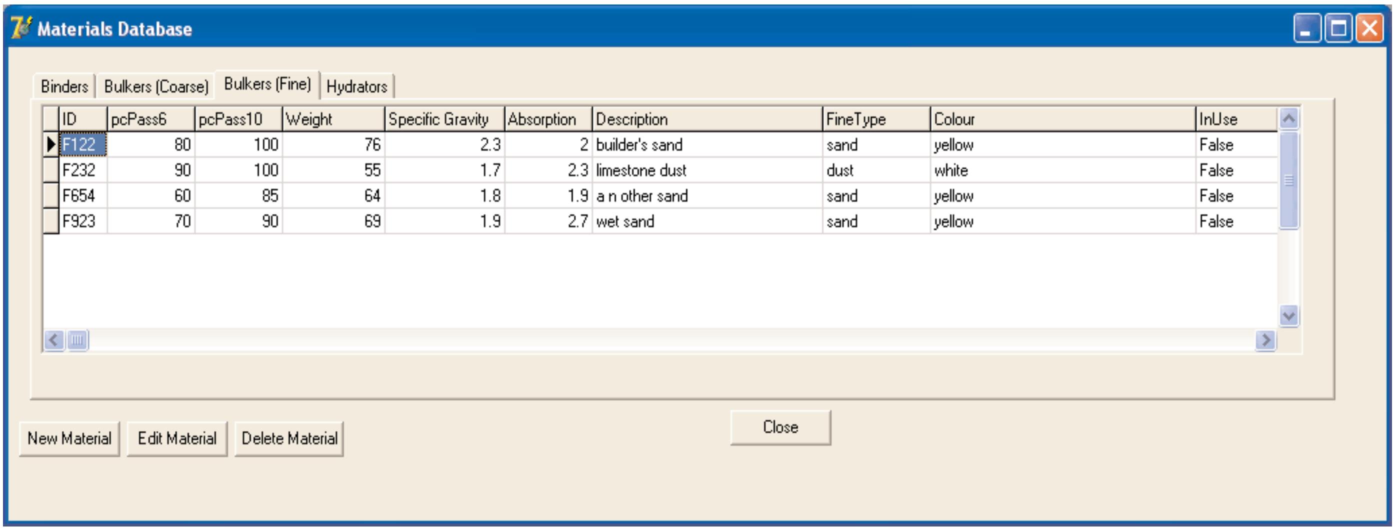
'Water' is the material required by the binder to enable it to gain strength. In all situations encountered so far in the project this is ordinary water although the model would allow any other to be used.

An 'Admixture' is anything added to the mix to alter the behaviour of the mix in respect of the major measures considered. Typically, an admixture would change the workability or final strength of a mix.

Several different development tools were examined before the final choice was made. Simulation packages such as ARENA were eventually rejected because of the nature of the problem and it was decided to use a high-level language development environment. Visual Studio and Delphi were investigated and Delphi selected for personal preference. An Access database is used to pass information between the process and technical models and to store the information about the materials.

Analysis

The technical simulation model is called from the main menu/hub of the overall system. This hub enables access to the various modules that make up ESPCO and is intended to represent an overview of a precasting facility. Key information is displayed here detailing current production options and recent production history.



ID	pcPass6	pcPass10	Weight	Specific Gravity	Absorption	Description	FineType	Colour	InUse
F122	80	100	76	2.3	2	builder's sand	sand	yellow	False
F232	90	100	55	1.7	2.3	limestone dust	dust	white	False
F654	60	85	64	1.8	1.9	a n other sand	sand	yellow	False
F923	70	90	69	1.9	2.7	wet sand	sand	yellow	False

Figure 3: Materials Database

Figure 3 shows details for typical materials stored in the system database. The screen can be used to browse through materials and select materials for editing, deletion or inclusion in the mix design module. Selecting a material is done by setting the "InUse" field to true. Materials are classified by type (i.e. binders, coarse bulkers, fine bulkers, admixtures, etc).

Figure 4 shows the screen used to input data for a material such as a binder (example shown above), bulker (coarse and fine) or other concrete constituent. Data consists of a variety of types and includes the ability for the user to input tabular information via a graphical interface. The example shown illustrates how the package has been designed to allow a user to input graph-based data which is commonly the only type available. In this case hydration profile(s) for a binder are input by positioning the y-values on the graph to indicate strength values at fixed time intervals (x-values)

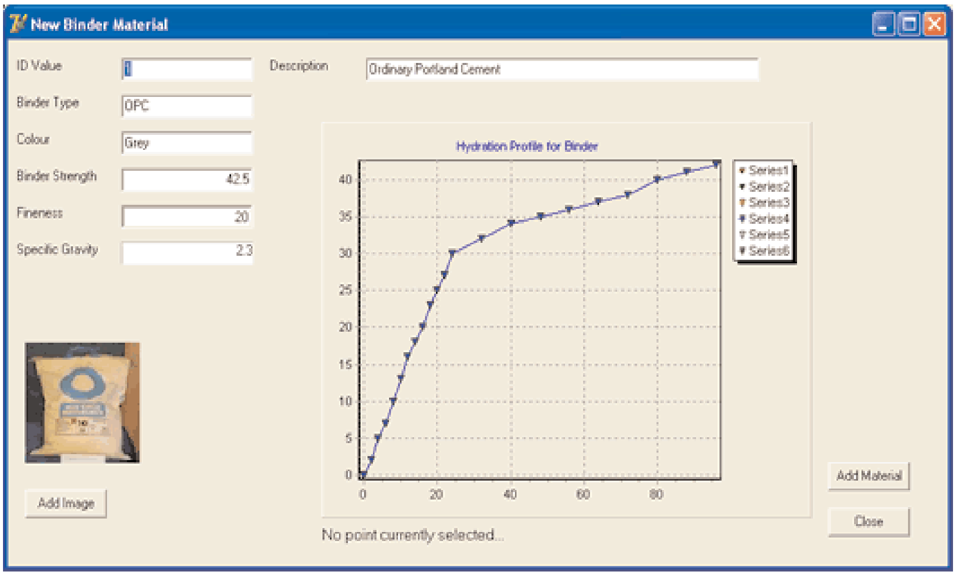


Figure 4: Add new material screen.

Figure 5 shows a screen which displays details of mix designs and concrete batches created from those mixes. The user can see extra data specific to the selected mix or batch if necessary and can use this module to open the mix designer module (see figure 8) for creating or editing concrete mixes.

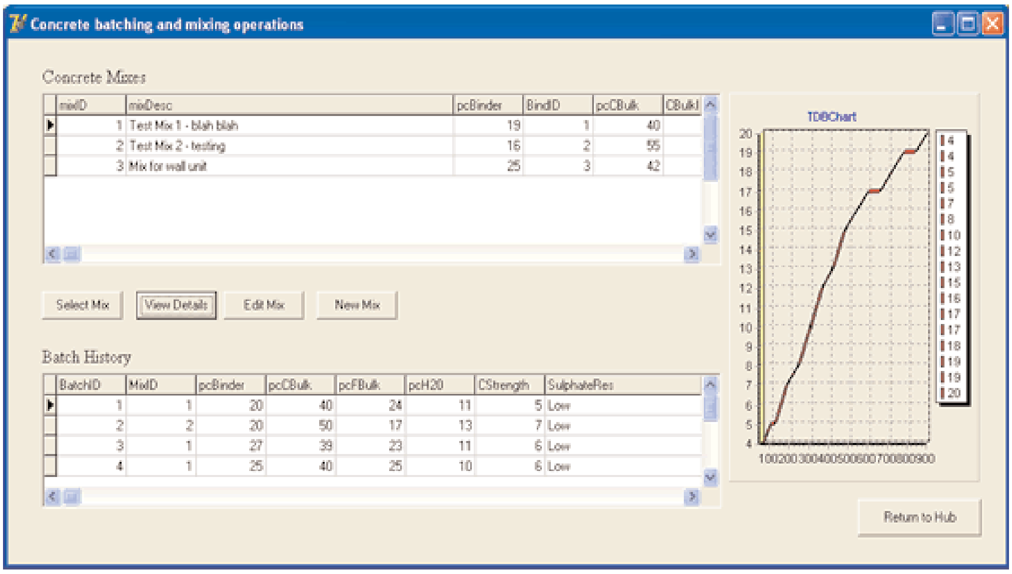


Figure 5: Mix and Batch Book

Figure 6 shows a screen-dump from the 'Product Catalogue'. This contains information for finished products which the precasting company makes. It is useful to have this information for the technical model as some mixes might not be suitable for some products. For example, a mix with a low workability might not be suitable for a wall panel if it is cast vertically but would be suitable if it were cast horizontally. The database works in a similar fashion to the materials database but displays product data relevant to the ESPCO system. A user can view, edit, browse or add products used in the simulation. Additional data for a selected product is shown in the lower area of the form.

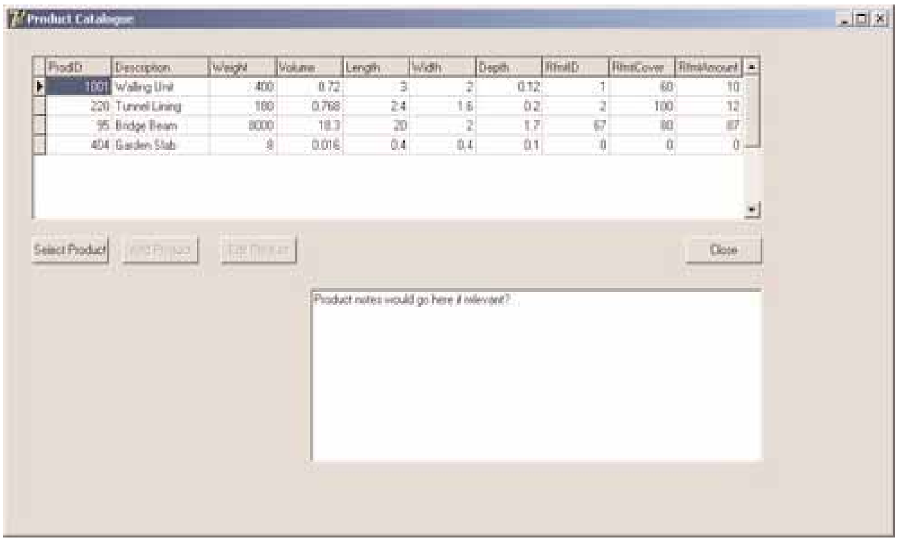


Figure 6: Product Catalogue.

Figure 7 shows a screen dump from the mix designer. This is the main element of the technical simulation. Previous screens exist for the administration, data entry or navigation in the system. The mix designer consists of a number of sub-windows that perform specific functions:

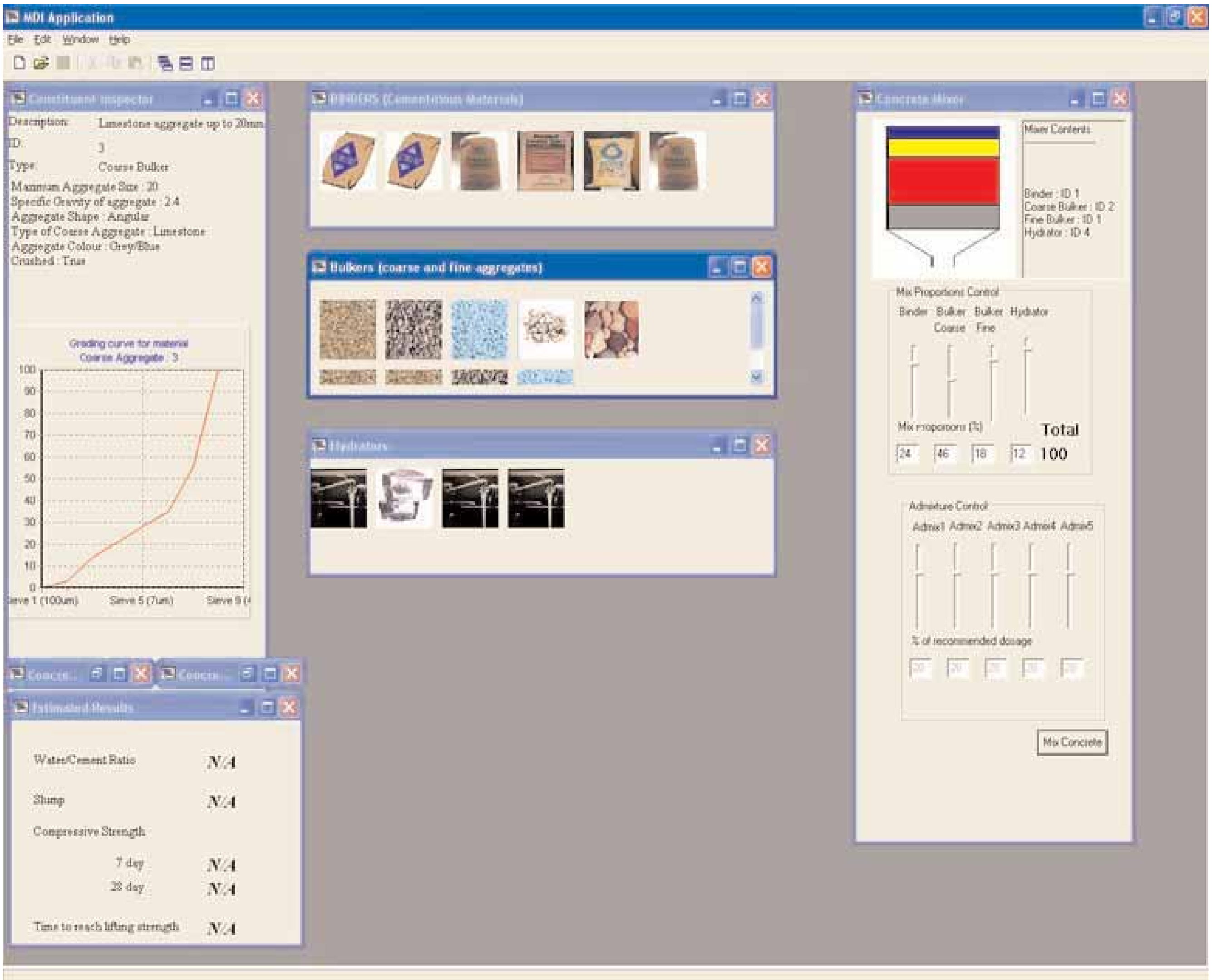


Figure 7: Mix Designer.

- Object Inspector – displays data for the item (material) currently selected (if any) in the mix designer.
- Mixer Window – Used to combine the selected elements and set the relative proportions of each element in the mix design.
- Estimate Window – gives an estimate of the likely concrete specification once a viable mix has been produced in the mixer window. This window only provides a limited subset of concrete properties such as strength, workability, etc.
- Binder/Bulker/Hydrator/Admixture windows – These windows contain the relevant concrete constituents identified for use in the mixer in the materials database. Each constituent is represented by an icon which can be dragged into the mixer image in the mixer window for addition to a mix. When an icon is selected the data for that item is displayed in the object inspector window

Results and Business Impacts

The prototype simulation has been completed. It can produce mixes and batches from any materials that the user wishes to specify. The specification is not a simple matter of naming a material. It is necessary to give its properties and the effects it has on all the major parameters when combined with other materials.
Figure 8 shows a screen-dump of the results of the main mix design interface. This is displayed when the users have selected the materials and proportions to use. It shows the main results of the technical simulation. It can be seen that it includes, for example, the curing profile is performed and the mix data window will be displayed with the results of this processing.

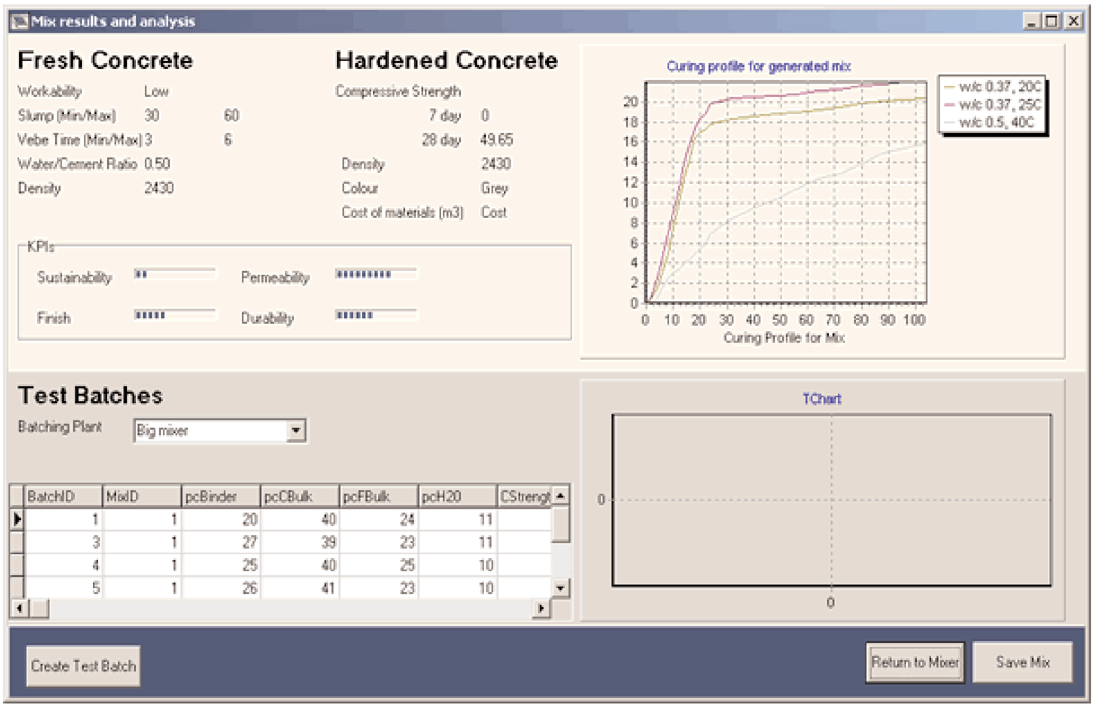


Figure 8: Mix Data window

It contains the properties of a concrete that are determined through the mix design method chosen and produces an estimated curing profile for the mixture. Some relative measures of key performance indicators such as sustainability and finish are given along with calculated figures such as strength, cost and workability. The user can also produce test batches using a specified batching plant and mixer to examine the potential variability of concrete produced using the specified mixture under those conditions. Figure shows the simulated output including hydration profiles for two different test mixtures.

Key Findings

A summary of the major findings of the work described are listed below.

Business Impacts

The simulation models (technical and operational) will be able to provide the precast industry with tools to forecast production schedules using different concrete mix and manufacturing methods. The models will be able to predict the effect of new materials, mix designs and production technologies before major investment by a precast company. The ability to model Heath and Safety factors (such as Noise, vibration and Dust) in a precasting factory is of a great interest for the industry and will be included in the models.

Conclusions

This paper reports on the results of a prototype simulation model development for Enterprise Simulation for Precast Operations (ESPCO). The ESPCO project aims to provide a flight simulator like tool for the precaster industry. It will encapsulate technical and operational aspects of precast concrete production to help them study cost and schedule tradeoffs and identify effects of different concrete mix designs on production process. The paper introduced the concept of the modelling of the technical aspects of precasting. It has illustrated some of the problems encountered and solutions proposed.

Key Lessons Learned

- An holistic approach to precasting process is needed to optimise production plans and thus factory operation
- The approach should include materials, mix design and process aspects
- Modelling material behaviour is a complex issue.

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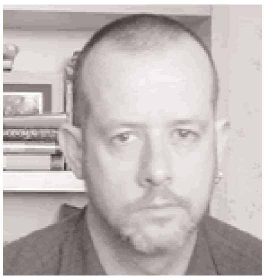

Gavin Long has been a research associate at Nottingham University for the last 6 years. He has worked on a number of projects during this time including the development of games and simulations for teaching construction management, a method for visual inspection of flood defence infrastructure and a tool for assessing the potential for use of modular building service units in large buildings. His main area of research is in the use of simulations and games for teaching and training.

Dr Mawdesley has an extensive background in the development and use of simulations in the construction industry. He has developed a number of simulations during his academic career both for use in the teaching of undergraduates and for practical use in industry. His research interests cover many aspects of construction management including project management, planning and control and the use of AI techniques to improve the management of construction projects.

Dr. Kim S Elliott (BTech, PhD, MICE, CEng) is Senior Lecturer in the School of Civil Engineering, University of Nottingham. He has published 110 journal and conference papers on the structural and material behaviour of precast and prestressed concrete structures, twice winning the Henry Adams Award from the IStructE. He has authored 4 books, Precast Frame Buildings Design Guide (1992), Multi-Storey Precast Concrete Frame Structures (1996), Precast Concrete Structures (2002) and Precast Concrete in Mixed Construction (2002). He has lectured on this subject is 15 countries worldwide and at 25 universities in UK. Dr Elliott is a member of the FIB Commission on Prefabrication, and was Chairman of the European research project COST C1 on Semi-Rigid Connection in Precast Concrete Structures

Nashwan Dawood is a Professor of construction management and IT. Currently director of CCIR at Teesside and have spent many years as an academic and researcher within the field of project and construction management and the application of IT in the construction and precast processes. This has ranged across a number of research topics including Information Technologies and Systems (4D,VR,Integrated databases), risk management, intelligent decision support systems, cost forecasting and control and business processes. This has resulted in over 140 published papers in refereed international journal and conferences, and research grants totalling about £1,800,000 in cash and £600,000 in kind.

Rizwan Ahmed is a Research Fellow in process modelling and simulation at CCIR, University of Teesside. He is currently working on the ESPCO project funded by the DTI and teaching project management to engineering students. He obtained his PhD in process modelling and simulation from University of Hertfordshire, UK in 2006. Where he proposed and evaluated an empirically formulated framework for process modelling and simulation. He has presented at various high profile conference in simulation. He holds a first degree in computer science and MSc. in Software Engineering.

J.T. Dean an electrical engineer with experience at board level in process industries and an MSc on Operational Management, Member-Institute of operations Management, Member-chartered Management Institute. Specialising in Automation change management in the Precast Industry over eight years prior to 2006. Currently engaged in developing IT projects and supervising PhD student at the University of Teesside.