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The Power of Statistical Learning Applied to the Proportioning of Fiber-Reinfoced Concrete

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Introduction

OVERVIEW OF THE PRESENTATION

Introduction

Modelling the mix proportioning variables

Modelling the residual flexural strength

Closing remarks

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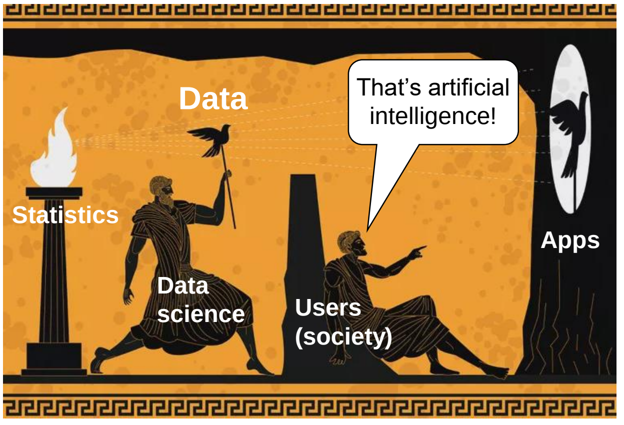
Statistical learning?

Plenty of terms, plenty of overlap:

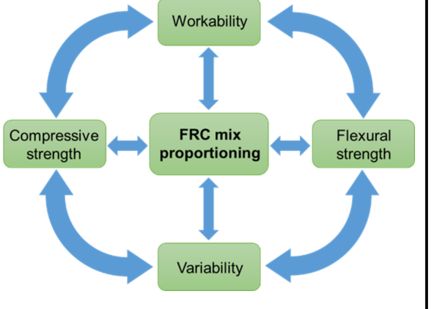
data science, data analytics, big data, data mining, multivariate analysis, machine learning, artificial intelligence…

Plato's allegory of the cave (ca. 2,400 years old):



Optimization of FRC mixes

- **Project "Optimization of Fiber-Reinforced Concrete using Data Mining" funded by CRC / ACI Foundation.**
- Articulating principle: proportioning FRC mixes as a multiobjective optimization problem.
- Implications:
  - Workability and variability are not 'associates': they are 'partners'.
  - Shift to a **multivariate perspective**, taking advantage of correlations.
  - Variability is not a problem but a source of information → **data mining**.



- Objectives:
  - Exhaustive database with mix proportionings and characterization results from papers.
  - Predictive models for residual flexural strength parameters and their variability.
  - Statistical analysis of all four dimensions above by means of multivariate techniques.
  - Software 'OptiFRC' for visualization and interpretation of database and utilization of the predictive models for mix optimization.

Optimization of FRC mixes

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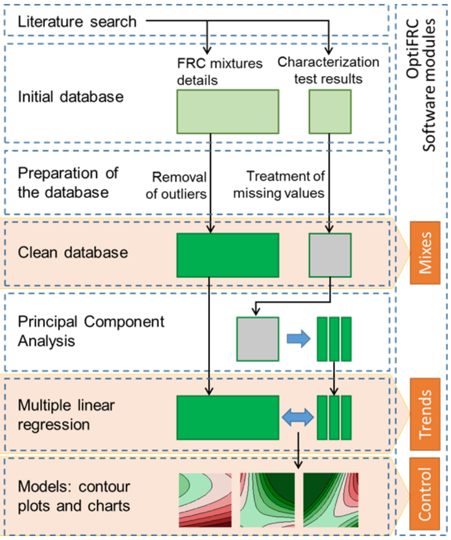
OUTLINE OF THE PROJECT

1. Literature search and descriptive analysis.
2. Development of database of FRC mixes and characterization test results.
3. Meta-analysis of FRC proportionings.
4. Meta-analysis of FRC residual flexural capacity.
5. Development of multivariate quality control charts.
6. Development of software OptiFRC.



The database

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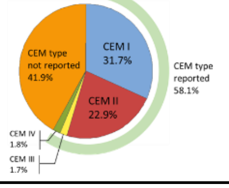
Data structure (variables in the database):

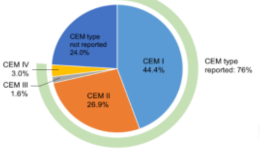
```
Cement_kgm3        Retarder_kgm3          Slump_mm
Water_kgm3         AirEntrainer_kgm3      SlumpSpread_mm
Binder_Kgm3        HRWR_kgm3              SlumpFlowTable_mm
SCMs_kgm3          VMA_kgm3               Age_days
LSP_kgm3                                  CompStrength_Mpa
GGBS_kgm3          Vf_%                   TestType
SF_kgm3            FibreLength_mm         LOP_MPa
PFA_kgm3           FibreDiameter_mm       fR1_Mpa
Sand_kgm3          FibreAspectRatio       fR2_MPa
Gravel_kgm3        FibreStrength_Mpa      fR3_MPa
MaxAggSize_mm      FibreContent_kgm3      fR4_MPa
```

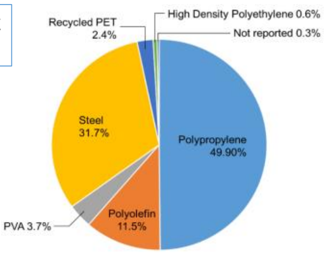
Mix proportioning variables | ***Properties***

Steel FRC dataset
766 cases



Synthetic FRC dataset
1053 cases





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Modelling the relationships between mix proportioning variables

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Overview

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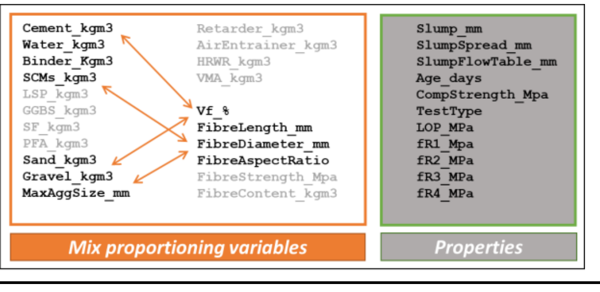
RELATIONSHIPS BETWEEN PROPORTIONING VARIABLES

- Focus: relationships that exist between FRC mixtures in terms of the ***relative amounts*** of their constituents and their ***main descriptors***.

Contents of cement, sand, etc (kg/m^3)
Fiber volume fraction (%)

Maximum aggregate size (mm)
Fiber material (steel, PP, etc)
Fiber length (mm)
Fiber aspect ratio

- Objectives:
  - Analysis: to visualize and understrand trends in one variable when others change.
  - **Modelling: quantification of mix proportioning variables as a function of others**.
- Method: multiple linear regression.



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  Maximum aggregate size (mm)
  Fiber material (steel, PP, etc)
  Fiber length (mm)
  Fiber aspect ratio

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REGRESSION MODELS: SPECIFICATION

- Alternative definitions trialled for different variables, including for example:
  - Total binder = cement + SCMs, total aggregates = fine + coarse aggregate
  - Ratios: water/cement, water/binder, fine/coarse aggr. ratio.
  - Fiber contents in kg/m^3 instead of volume fraction and fiber material
- Model specification selected based on: **goodness of fit** (i.e. accuracy of resulting equations), **interpretability**, and **robustness** of the models.

Coarse/fine aggr. ratio

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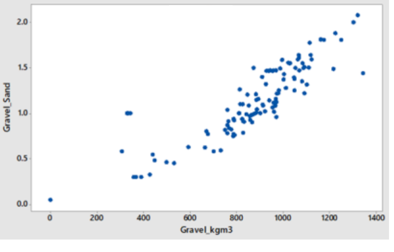
JUSTIFICATION

- Practical first approximation as descriptor of aggregates grading.
- ~ Cohesiveness of the mix → informative in relation to fresh state performance.

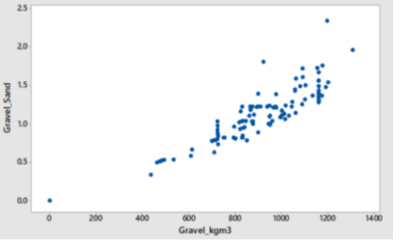
STATISTICAL MODELLING

- Good correlation with coarse aggregate content in both datasets:

Steel FRC dataset



Synthetic FRC dataset



Coarse/fine aggr. ratio

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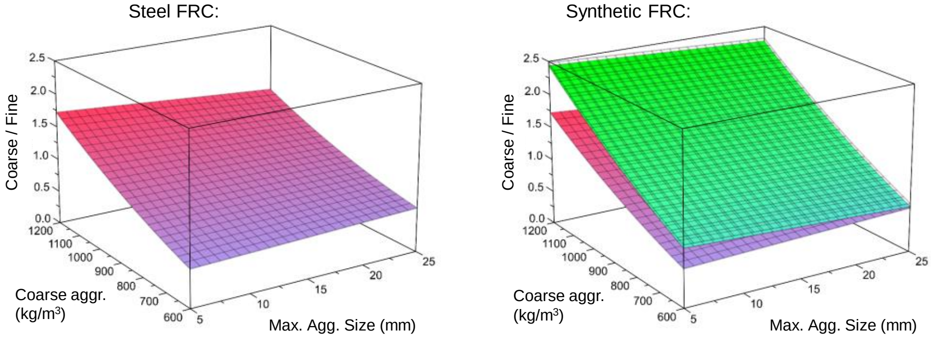
STATISTICAL MODELLING

- In addition to the **coarse aggregate content**, the **max. aggregate size** and **fiber material** also have a statistically significant impact on coarse/fine aggr. ratio.
- Simple equations with very high goodness of fit (R^2 = 0.92 and 0.87).

Steel FRC: Synthetic FRC:



Coarse aggregate content

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JUSTIFICATION

- Together with the coarse/fine aggr. ratio, it is representative of the volume of aggregates.
- Why not fine aggregate, or total aggregates?
  - Models for coarse aggregate proved more robust: goodness of fit, simple specification.
  - Interactions with max.agg.size and fiber length were most clear (interpretability) when the model was based on coarse aggregate content.

STATISTICAL MODELLING

- Equations obtained (R^2 = 0.76 and 0.61):
  - Coarse aggr. content as a function of maximum aggregate size, fiber volume fraction, fiber length and aspect ratio.
  - Fitted coefficients are different for steel FRC and synthetic FRC.
  - Statistically significant interactions between fiber volume fraction, length and aspect ratio, and maximum aggregate size.

Coarse aggr. content in SFRC

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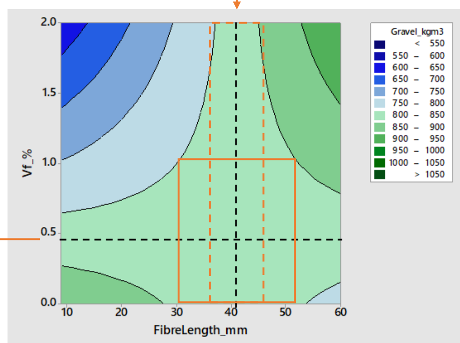
COARSE AGGREGATE CONTENT, STEEL FIBER LENGTH AND DOSAGE

- For low to medium fiber dosages (up to 0.4-0.7%), the coarse aggregate content is not remarkably sensitive to changes in fiber length and generally within 800-850 kg/m^3.
- For high to very high fiber dosages (>1%), coarse aggregate contents are generally within 800-850 kg/m^3 as long as the fiber length is between 35 and 45 mm.
- That is also the case for fiber dosages up to 1%, for fiber lengths between 30 and 50 mm.

$$\frac{\partial G}{\partial V_f} = 0 \;\rightarrow l_f = 35 - 45$$

$$\frac{\partial G}{\partial l_f} = 0 \;\rightarrow V_f = 0.4\% - 0.7\%$$



Coarse aggr. content in SFRC

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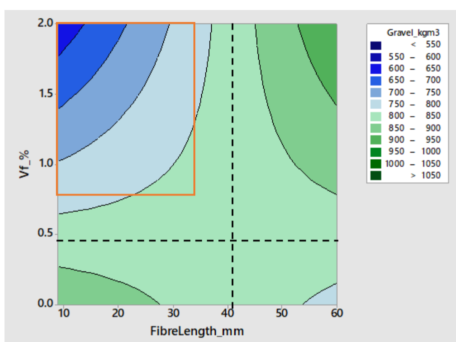
- That is also the case for fiber dosages up to 1%, for fiber lengths between 30 and 50 mm.

- Short fibers (~30 mm and shorter) in moderate to high dosages are generally associated with lower coarse aggregate contents → mixtures with more sand and paste to be more cohesive.



Binder content

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JUSTIFICATION

- It is representative of the finer constituents of the mixture.
- Why not cement and SCMs separately? Some reasons:
  - The water-to-binder ratio is a defining parameter of the mixture.
  - The model for total binder turned out to be the most robust: goodness of fit, simple specification.

STATISTICAL MODELLING

- The equations obtained showed very good fit to data (R^2 = 0.90 and 0.84):
  - Binder content as a function of fine and coarse aggregate contents, and maximum aggregate size.
  - Quadratic effects and statistically significant interactions between these terms.

- *Why are the fibers dimensions and their dosage not in the equations? Don't they have an 'effect' on the binder content in a FRC mixture?*

Three equations, one model

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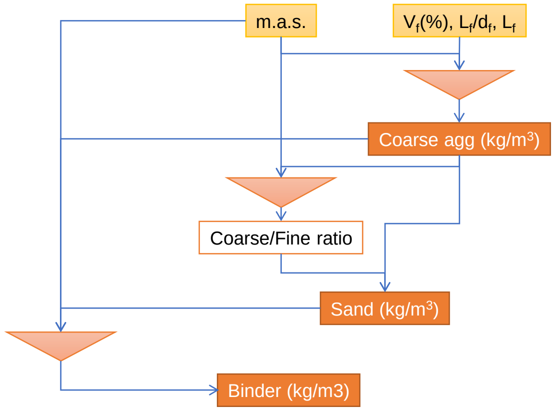
A DATA-DRIVEN PROPORTIONING METHOD

- Why are the fibers dimensions and their dosage not in the equations? Don't they have an 'effect' on the binder content in a FRC mixture?

- By organising the equations in sequence, a sort of FRC mix proportioning method begins to emerge:



Three equations, one model

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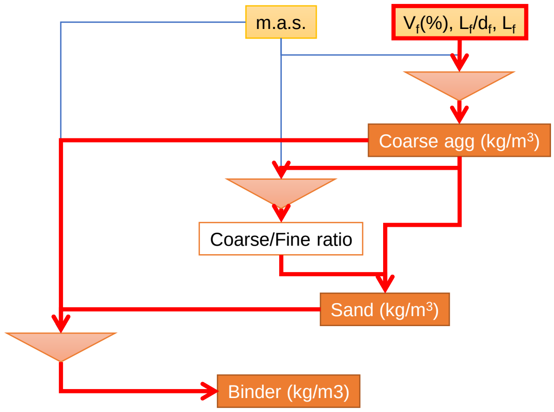
A Data-Driven Proportioning Method

- Why are the fibers dimensions and their dosage not in the equations? Don't they have an 'effect' on the binder content in a FRC mixture?

Yes, because they influence the aggregate contents!

- By organising the equations in sequence, a sort of FRC mix proportioning method begins to emerge:



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Residual flexural strength parameters as a function of mix proportions

Overview of the presentation

- ✓ Introduction
- ✓ Modelling the mix proportioning variables
- Modelling the residual flexural strength
- Closing remarks

Overview

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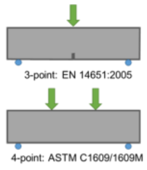
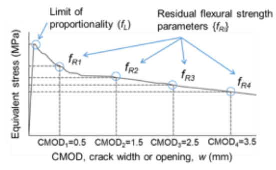
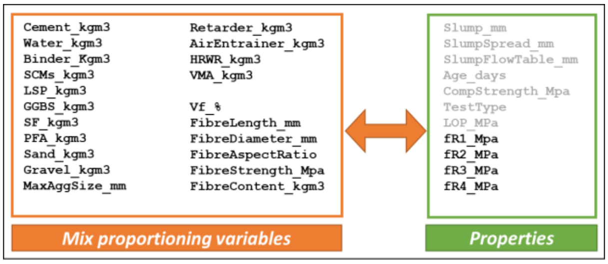
Modelling Residual Flexural Strength

- Focus: relationships that exist between f_{R1}, f_{R2}, f_{R3} and f_{R4} and the FRC mix proportioning variables.





- Method: multiple linear regression for each residual flexural strength parameter.
- Objectives:
  - Analysis: visualising and understranding trends, with a particular focus on statistically significant ***interactions***.
  - Modelling: f_{Ri} estimates as a function of mix proportioning.



Overview

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Modelling Residual Flexural Strength

- Focus: relationships that exist between f_{R1}, f_{R2}, f_{R3} and f_{R4} and the FRC mix proportioning variables.
- Method: multiple linear regression for each residual flexural strength parameter.
- Objectives:
  - Analysis: visualising and understranding trends, with a particular focus on statistically significant ***interactions***.
  - Modelling: f_{Ri} estimates as a function of mix proportioning.

Specification of the Models

- Several alternative specifications were trialled.
- **What I was trying to achieve when developing the models**:
  - Compromise between goodness of fit (R^2) and degrees of freedom (number of terms).
  - Same model structure (i.e. format of the equation) for the four residual parameters.
  - Same model structure for steel and synthetic datasets (different coefficients).
- Good performance of models obtained: R^2 values between 0.75 and 0.85.

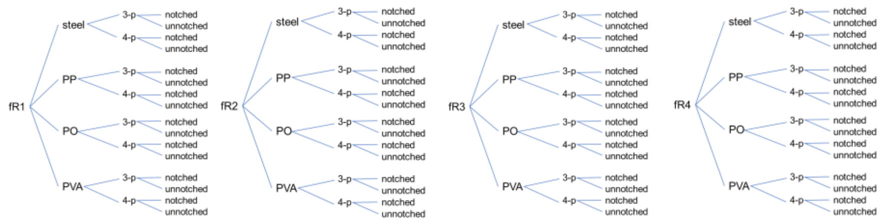
Modelling

Modelling Residual Flexural Strength

- General equation of the model obtained:

$$f_{R,i} = k_0 + k_1 \frac{\boldsymbol{G}}{\boldsymbol{S}} + (a_0 + a_1 MAS)\, \boldsymbol{L_f} + \left(b_0 + b_1 CEM + b_2 HRWR + b_3 \lambda_f + b_4 L_f\right) \boldsymbol{V_f}$$
$$+\, k_2\, \boldsymbol{SCMs} + k_3\, \boldsymbol{HRWR} + k_6 \boldsymbol{CEM} + (c_1\, CEM + c_2\, SCMs + c_3\, G/S)\, \boldsymbol{AGGR}$$

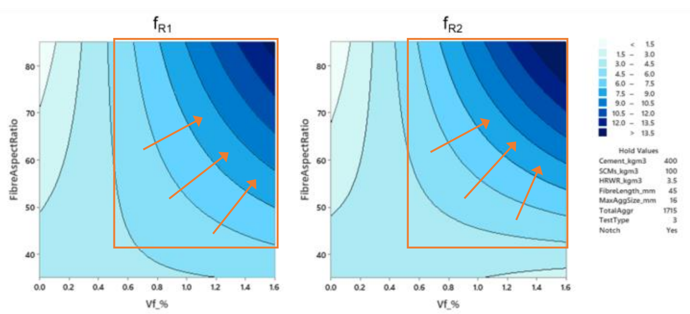
- Coefficients take different values for each residual flexural strength parameter.
- Coefficient k_0 depends on test configuration (3- or 4-point) and specimen (notched or not).
- All other coefficients (colored in red) depend on the fiber material.
- The equation above is in fact a compact representation of dozens of equations:



- It makes interpretation and understanding easier, and is the result of trying to find a common model specification that fits well the values of all four parameters.

Fiber aspect ratio (SFRC)

- Increasing the aspect ratio has a clear positive impact on residual flexural strength for moderate to high fiber contents.



Fiber aspect ratio (SFRC)

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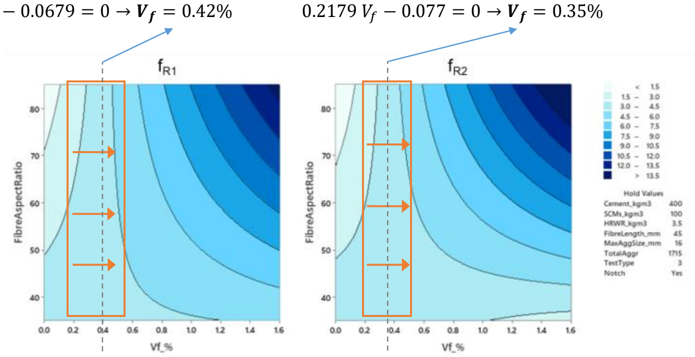
- Increasing the aspect ratio has a clear positive impact on residual flexural strength for moderate to high fiber contents.
- Changing the aspect ratio does not affect f_{R1} or f_{R2} when the fiber content is 0.3%-0.4%.

$0.1616\, V_f - 0.0679 = 0 \rightarrow \boldsymbol{V_f} = 0.42\%$

$0.2179\, V_f - 0.077 = 0 \rightarrow \boldsymbol{V_f} = 0.35\%$



Fiber aspect ratio (SFRC)

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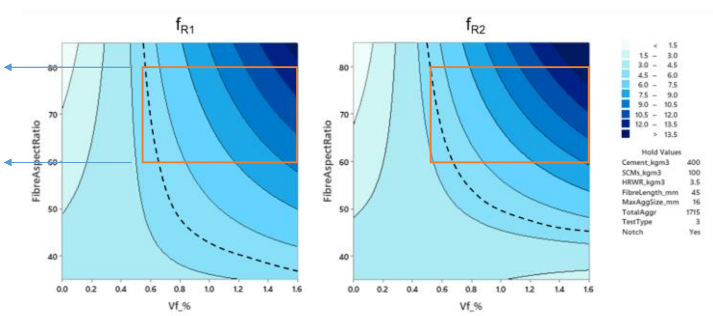
- Increasing the aspect ratio has a clear positive impact on residual flexural strength for moderate to high fiber contents.
- Changing the aspect ratio does not affect f_{R1} or f_{R2} when the fiber content is 0.3%-0.4%.

- Do we need high fiber dosages to get better-than-average performance? No.
  - With aspect ratios between 60 and 80, fiber contents in the region of 0.6%-0.8% are generally enough to get better-than-average residual flexural strength.
  - Minimum fiber contents to get better than average performance as a function of the fiber aspect ratio can be obtained:

$\lambda_f = 80 \rightarrow V_f \geq 0.56\%$

$\lambda_f = 60 \rightarrow V_f \geq 0.69\%$



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Closing remarks

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Statistical Learning

- Equations / software 'learn' from the data, but the treatment and modelling of data is a fantastic resource to help us learn and better understand the material.

Database and Mix Proportionings

- A database of almost 2,000 cases has already been compiled, 'cleaned' and analysed.
- The regression models obtained to describe the correlations between mix proportioning parameters are robust and show good fit with data. They are:
  - Useful to obtain reliable estimates of the contents of different constituents.
  - A powerful tool to better understand the interplay of the different parameters.
- The three semi-empirical equations represent a data-based mix proportioning rationale for guiding design of FRC mixes.

Residual Flexural Strength Model

- A unified predictive model has been obtained for all four residual flexural strength parameters in steel and synthetic FRC mixes.
- This model shows good fit with data and captures the effect of the most significant interactions between fiber content, size of fibers and aggregates, and the contents of all constituents.

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The Power of Statistical Learning Applied to the Proportioning of Fibre-Reinforced Concrete Mixes

Thank you

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