USING DECADES OF DATA TO RETHINK PROPORTIONING AND OPTIMISATION OF FRC MIXES: THE OPTIFRC PROJECT

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ABSTRACT

Fibres enhance the mechanical properties of concrete, but residual flexural strength parameters present significant variability. The proportioning and optimisation of FRC should integrate fresh and hardened state properties as well as their variability, and this is the urgent challenge addressed by this project funded by the ACI Foundation. It follows a meta-analytical, multivariate approach, based on the creation of an exhaustive database with information on hundreds of FRC mixes compiled from papers published over two decades and adopting a data analytics perspective. First, the relationships between the relative amounts of the mix constituents, fibre geometry and dosage are modelled. Then, the strong correlations between residual flexural strength parameters, limit of proportionality, and compressive strength are exploited to develop efficient predictive tools. The final outcome will be a software package called "OptiFRC". This will integrate capabilities to access the database compiled, to visualise and utilise the models for the optimisation of FRC mix proportionings, and to calibrate and use the derived quality control charts. This paper presents an overview of the project, reports on its progress to date and summarises the ongoing developments and anticipated impact.

KEYWORDS: characterisation, optimisation, proportioning, residual flexural strength, variability.

1. INTRODUCTION

Fibre reinforced concrete (FRC) is, by definition, any concrete made primarily of hydraulic cements, aggregates, and discrete reinforcing fibres [1]. Fibres enhance numerous mechanical properties of concrete, particularly tensile, flexural strength and toughness in the cracked state. The use of FRC has evolved from the small scale to the larger scale of routine production and field applications, with tens of millions of cubic yards produced every year [2]. However, the perception that fibres can be treated as an add-on to conventional concrete mixes is still prevalent amongst practitioners. For example, ACI 544.3R-08 [3] stated that, when fibres are incorporated to the mix, "some mixture adjustments may be required", or "more paste may be needed to provide better workability". This last statement also puts the focus on fresh state performance and its importance when proportioning FRC mixes. These aspects can no longer be addressed relying only on simple adjustments, considering the family of special concretes that has developed around FRC. Fresh state performance is crucial to fibre-reinforced self-compacting concrete (FRSCC) [4] or ultra-high performance fibre-reinforced concrete (UHPFRC) [5].

Their relevance and increasing prevalence in industry requires that the proportioning of FRC mixes is regarded as a multi-objective optimisation problem, integrating all dimensions shown in Figure 1.

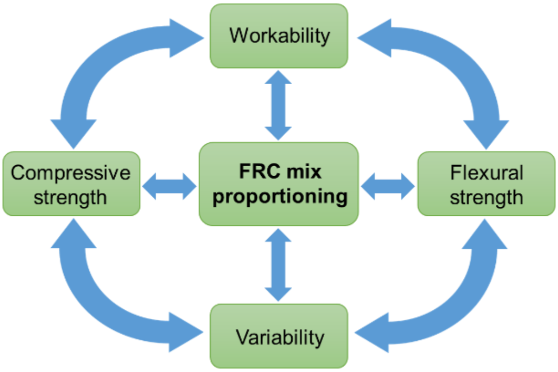

Figure 1. FRC proportioning redefined as a multi-objective optimisation problem.

In terms of hardened state performance, the consideration of fibres as reinforcement is now embedded in the ACI 318 code, and their structural contribution is accounted for in design equations [6]. However, the mechanical properties of FRC, particularly the residual flexural strength parameters, present considerable variability [7]. This is highly relevant, as these parameters are the basis of FRC characterisation and specification. Figure 2 shows the flexural test set-up configurations according to standards EN 14651:2005 [8] and ASTM C1609/1609M [9], and an example of stress-strain curve, where the limit of proportionality and the residual flexural strength parameters are defined.

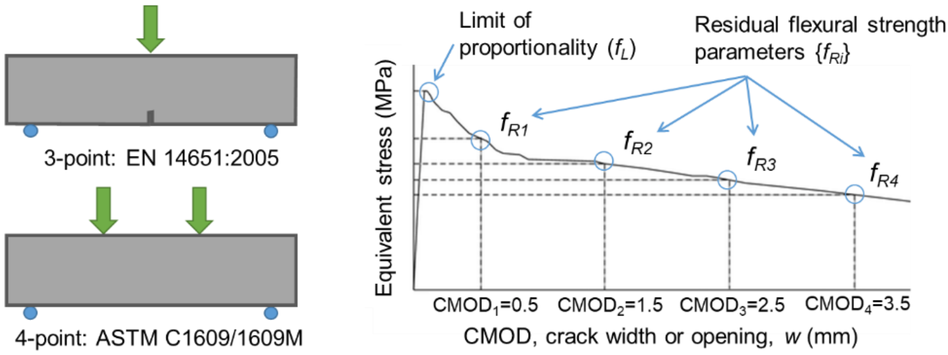

Figure 2. Characterisation of the flexural behaviour of FRC.

The residual flexural strength parameters (f_{R1}, f_{R2}, f_{R3}, f_{R4}), limit of proportionality (f_L) and compressive strength (f_c) present strong correlations between them and are mutually interdependent. Treating these parameters as if they were independent variables means that part of the information obtained from characterisation tests is confounded with noise or experimental error. However, their variability and sensitivity to changes in the mix design have been analysed very rarely, and only for specific fibres in specific mixes, in separate studies. Bearing in mind that the prediction and systematic control of variability is key to the effective quality control of FRC production, a meta-analysis of the variability of FRC mechanical properties was urgently needed.

2. OVERVIEW OF THE PROJECT

2.1. Main objectives

With the aim of addressing the aforementioned challenges, the project "Optimization of Fiber-Reinforced Concrete using Data Mining", funded by the Concrete Research Council through the ACI Foundation, has the following objectives:

- To compile, pre-process, and publish an exhaustive database with mix proportionings and experimental results of FRC mixes available in literature.
- To analyse the properties of FRC as a multivariate phenomenon, using data mining techniques.
- To develop predictive models, based on the database compiled, that provide accurate estimates of the residual flexural strength parameters of FRC and their variability.
- To implement the outcomes from the above in a software (OptiFRC) that assists in the visualisation and interpretation of the database and the predictive models developed.

2.2. Methodology and work programme

An overall view of the methodology followed in this project is summarised in the flowchart shown in Figure 3. It is based on the methodological framework previously applied by the author to the meta-analysis of self-compacting concrete mixes [10, 11].

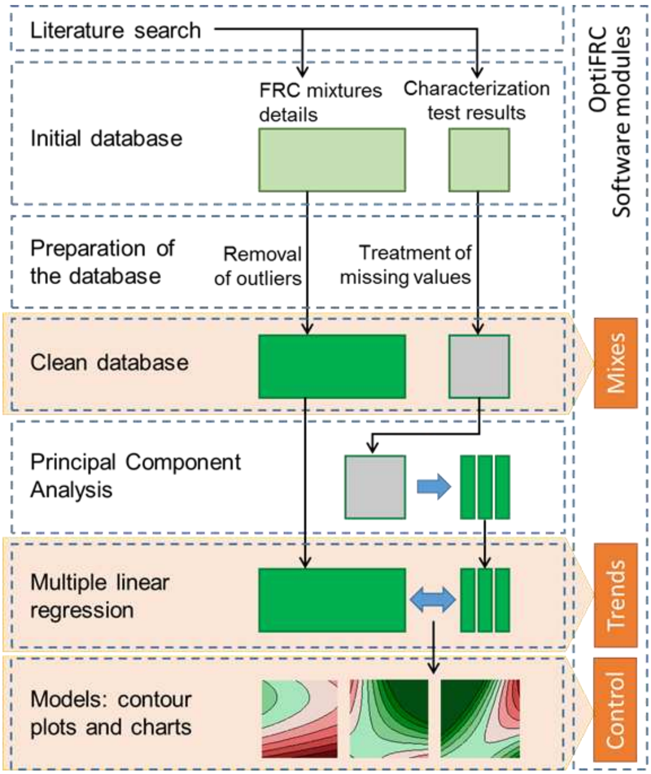

Figure 3. Overview of the methodology and correspondence with OptiFRC modules.

2.2.1. Construction of the database

Detailed information on different FRC mix proportionings and their characterisation tests results has been extracted from previous literature and compiled in a database. The sources of information considered for this study are those papers published in ACI Structures, ACI Materials, and journals indexed in ScienceDirect® since 1999, resulting from the search with the terms “fiber-reinforced concrete” or “fibre-reinforced concrete”. The database is prepared in mineable format and consists of two datasets in row-to-row correspondence: one with the FRC mix proportionings, and another with the characterisation tests results. The first dataset comprises the relative amounts of the mix constituents (in kg/m^3), maximum aggregate size (in mm), fibres aspect ratio and length (in mm), and fibre material. The second dataset includes values for the slump and average compressive strength at 28 days, in addition to f_L, f_{R1}, f_{R2}, f_{R3}, and f_{R4}. To ensure sufficient statistical power for the subsequent analysis, the database size was defined to include between 500 and 3,000 complete cases [12].

2.2.2. Meta-analysis of FRC mix designs

The objective of this meta-analysis is to model the relationships between the relative amounts of the constituents of FRC mixes and to quantify their variation with respect to the type of fibres used, their geometry and dosage. Data mining techniques have been used to carry out a thorough analysis of the latent structure of correlations, namely: multiple linear regression, surface response methodology, and the fitting of conditional probability distributions [13]. Initially the analysis has been segmented by fibre type, and this paper presents the most salient aspects of the preliminary analysis of the database of steel FRC (SFRC). This will be followed by a global analysis of the entire dataset without disaggregation by fibre types, which is work in progress at the moment of writing this paper.

2.2.3. Meta-analysis of FRC residual flexural capacity

The structure of correlations and association patterns between the residual flexural strength parameters (f_{R1}, f_{R2}, f_{R3}, and f_{R4}), limit of proportionality (f_L) and compressive strength (f_c) will be analysed by means of dimension reduction techniques [14] to compress the information represented by these six interdependent variables into a reduced set of independent factors. Multiple linear regression and analysis of variance will then be applied to find equations to relate them to the FRC mix proportioning, not only in terms of average values but also to estimate their variability and sensitivity to changes.

2.2.4. Development of multivariate quality control charts and the OptiFRC software

The models obtained as outlined in the previous section and the corresponding probability distributions will be used to define quality control charts that can be used in the monitoring of continuous production of FRC mixes. In addition to univariate tools based on Shewhart charts, CUSUM and EWMA, new multivariate charts based on Hotelling’s T2 statistic [15] will be derived. All these outcomes will be implemented in a standalone software package that can be used to access the database compiled, to visualise and utilise the models for the optimisation of FRC mix proportionings, and to use the corresponding quality control charts. It will consist of three modules: Mixes, Trends, and Control. The correspondence of these modules with the outcomes of the different stages of the work programme is also shown in Figure 3.

3. META-ANALYSIS OF SFRC MIXES

At the time of preparation of this paper, the SFRC database consisted of 770 different cases, each case corresponding to a different SFRC mix with detailed information of their proportioning and the characterisation tests results. They have been extracted from more than 100 papers published between the years 2000 and 2019. The following sections present an overview of their analysis.

3.1. Binder type and content

The piechart, histogram and box-and-whisker plot shown in Figure 4 present an at-a-glance description of the binder type and contents in SFRC mixes. In almost 42% of the cases, the original sources did not report the type of cement. However, in 94% of the cases for which this information was available, the cement type was either CEM I or CEM II, and CEM I in particular was the most prevalent.

In Figure 4 (right), it can be observed that there were two distinct frequency distributions of binder contents, and therefore two sub-populations could be defined in terms of the total binder content. In 90% of the cases, the binder content was not higher than 710 kg/m^3, and the median was 450 kg/m^3. The first value can be regarded as the maximum, whilst the median can be considered as a typical, representative value, as it corresponds to the value below which 50% of the cases are found.

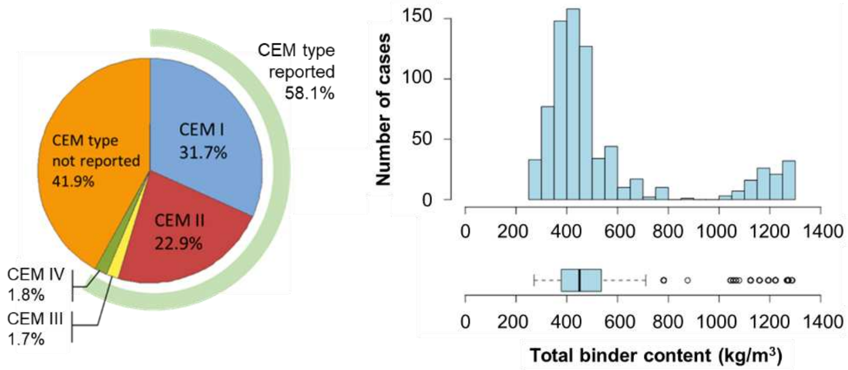

Figure 4. Overview of the binder composition and distribution of total binder content values.

In terms of the binder composition, 47.3% of the cases in the database incorporated supplementary cementitious materials (SCMs) in addition to cement. Figure 5 shows the histograms and box-and-whisker plots for the cement content (left) and the SCMs content (right). For the cement content, the median was 400 kg/m^3, and in 90% of the cases it was not higher than 660 kg/m^3. Regarding the SCMs content, in 90% of the cases it was not higher than 230 kg/m^3. However, SCMs contents higher than 100 kg/m^3 were associated with cement contents higher than 660 kg/m^3.

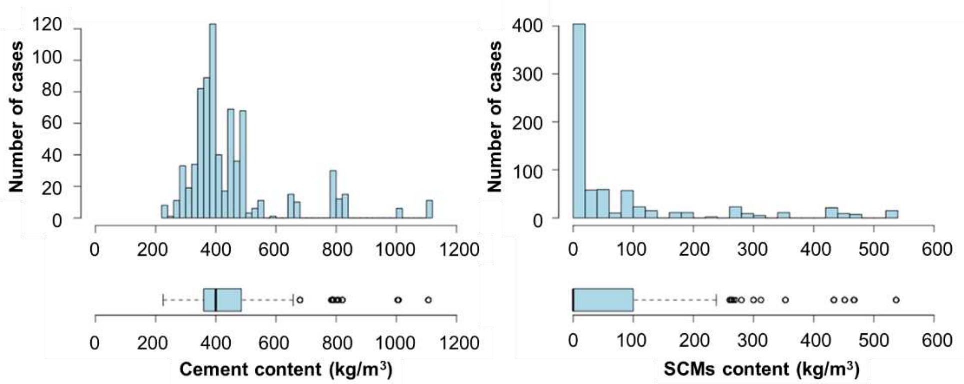

Figure 5. Distribution of cement and SCMs contents.

3.2. Fibres and aggregates

The histogram corresponding to the fibres volume fraction, in percentage, is shown in Figure 6 (above). In 75% of the cases, the fibres volume fraction was not higher than 1%, and in 90% of the cases it was lower than 1.6%. When the fibre content was higher than this, in the majority of cases it ranged between 1.8% and 2%, very rarely exceeding this last value. In terms of the fibre dimensions, the aspect ratio ranged between 45 and 80 in 90% of the cases in the database (data not shown).

An interesting correlation between the grading of the aggregates and the fibres content was observed. The contour plot in Figure 6 (below) shows how the relationship between the gravel-to-sand ratio and the total aggregates content changes for increasing fibre contents. Cases with moderate fibre contents, that is, below 0.75% in volume, were associated with gravel-to-sand ratios between 1.5 and 2 but were not limited to any particular range of aggregate contents. However, increasing fibre contents were linked with a decrease in both the gravel-to-sand ratio and the total aggregates content. This can be attributed to the fact that the introduction of higher fibre contents requires the mix design to be substantially more cohesive and to have a higher relative volume of paste.

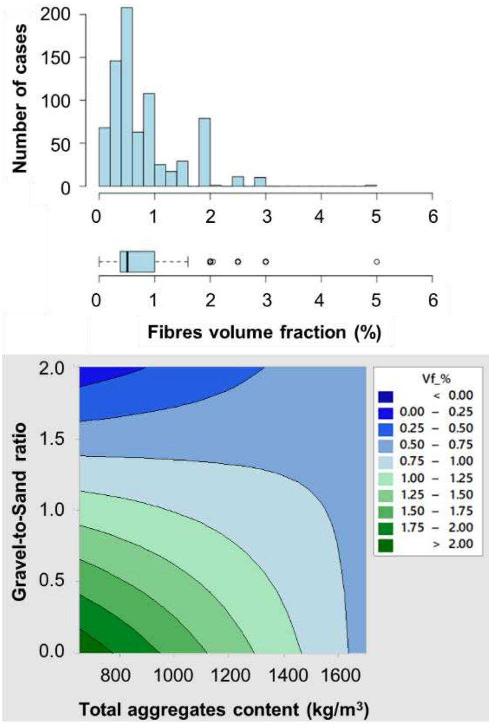

Figure 6. Distribution of fibre contents and their relationship to aggregates content and grading.

3.3. Compressive strength and limit of proportionality

The SFRC database represents a wide spectrum of mixes in terms of their average compressive strength at 28 days, as the histogram in Figure 7 (left) shows. Similarly to what was observed in relation to the total binder content, there are two distinct clusters in terms of compressive strength. The main cluster represented 90% of the cases in the database and comprised mixes with compressive strength not higher than 110 MPa, well distributed around a median of 55 MPa.

In terms of the limit of proportionality, all the cases in the database conformed to the same frequency distribution, as the histogram in Figure 7 (right) shows. The values of this parameter were below 10 MPa in most of the cases.

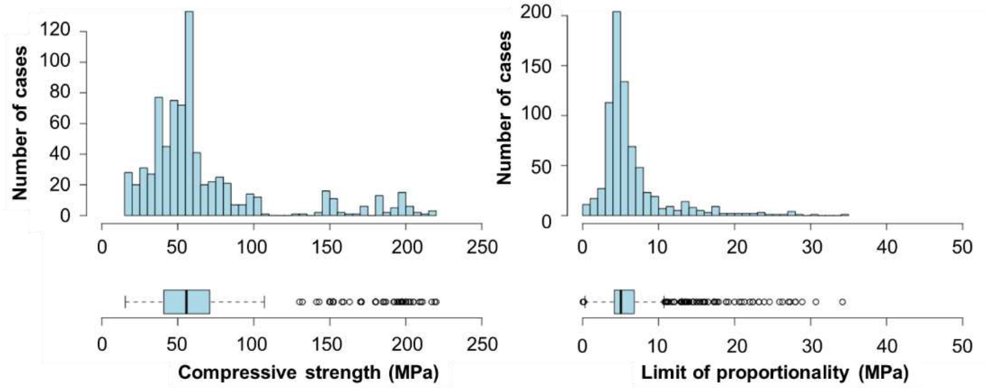

Figure 7. Distribution of compressive strength and limit of proportionality.

3.5. Residual flexural strength parameters

The residual flexural strength parameters were observed to follow very similar distributions, and only the histogram for f_{R1} values is shown in Figure 8. It can be seen that this histogram shows a distribution which is very similar to that observed for the limit of proportionality (Figure 7), the main difference being its range or width of the distribution, with 90% of the values below 15 MPa.

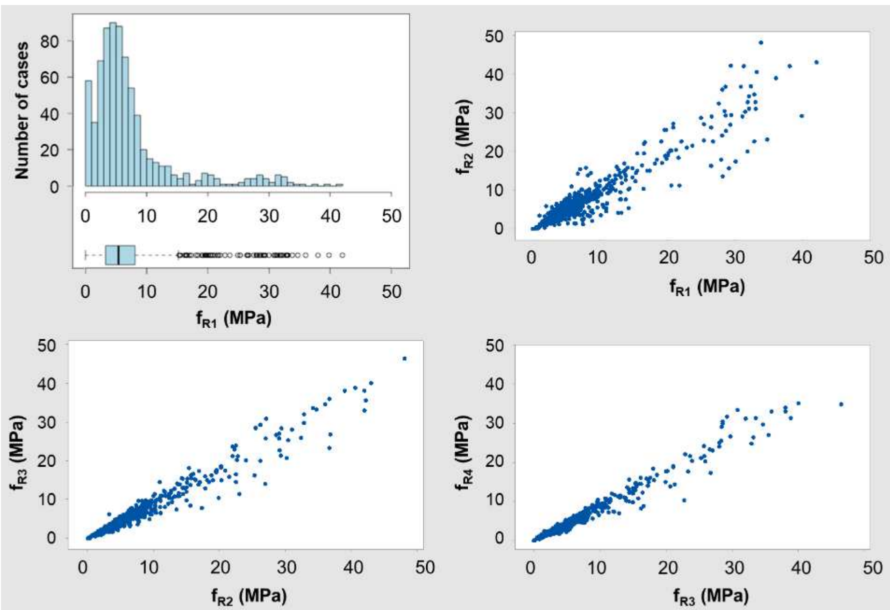

Figure 8. Distribution of f_{R1} values and bivariate scatterplots for f_{R1}, f_{R2}, f_{R3}, and f_{R4}.

More interesting are the bivariate linear correlations between f_{R1}, f_{R2}, f_{R3}, and f_{R4} and how clear they are. The scatterplots for f_{R2} versus f_{R1}, f_{R3} versus f_{R2}, and f_{R4} versus f_{R3} are shown in Figure 8. These plots confirm that, from a multivariate perspective, any of these parameters can be expressed as a direct function of the others.

As a preliminary analysis concerned with the sensitivity of these parameters with respect to the mix proportioning, a multivariate regression analysis was carried out for f_{R1}. The following variables were considered: cement, SCMs, sand and gravel contents in kg/m^3; cement-to-water and SCMs-to-water ratios; fibres volume fraction in percentage, fibre length in mm, and fibre aspect ratio. It is worth noting that not all the variables related to the mix proportioning were used in this regression analysis, as this was intended to be a simple, exploratory model. Despite that and the fact that the data come from many different sources, this analysis yielded a model with a high goodness of fit, the R-squared being 0.83.

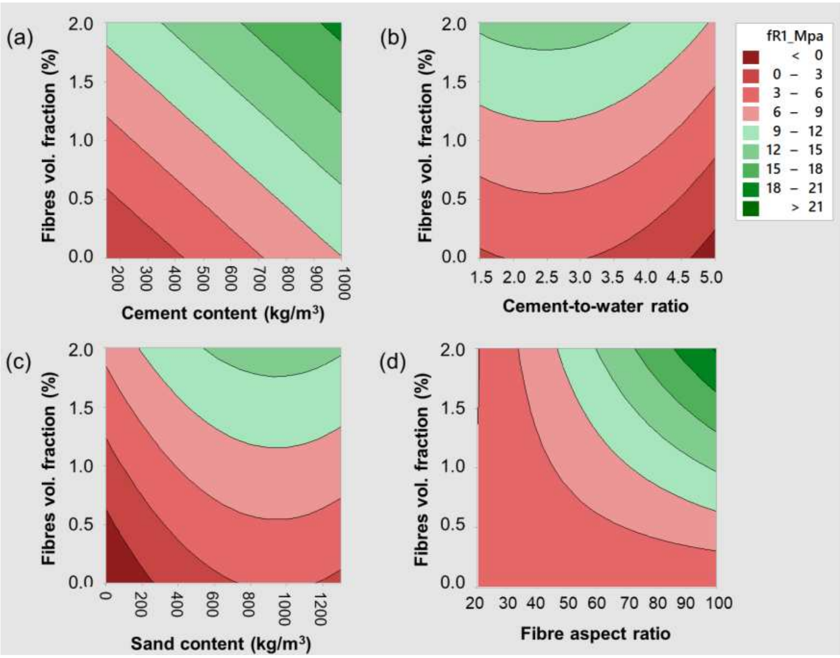

Figure 9. Contour plots for f_{R1} in SFRC mixes, based on a preliminary model.

Figure 9 shows some of the contour plots corresponding to the model obtained for f_{R1}, and in all cases the vertical axis represents the fibre volume fraction, in percentage. Figure 9(a) shows that residual flexural strength can be improved not only by increasing the dosage of steel fibres, but also by increasing the cement content. This model predicts that, on average, the effect of increasing the fibre volume fraction in 0.1% is equivalent to that of increasing the cement content in 50 kg/m^3, from the point of view of f_{R1} values.

The relationship between these parameters and water content is completed with the contour plot in Figure 9(b), which shows that the effect of any amount of steel fibres on f_{R1} is affected by the cement-to-water ratio of the mix. In fact, this model predicts that, on average, the cement-to-water ratio which can be considered optimal in enhancing the effect of fibres is 2.5, which is equivalent to a water-to-cement ratio of 0.40.

A similar observation can be made with respect to the sand content. According to the contour plot shown in Figure 9(c), this model predicts that, on average, sand contents close to 950 kg/m^3 are best in maximising the performance of fibres in terms of net increase in f_{R1} per unit volume of fibres. In fact, any of these contour plots can be used as double-entry graphs to obtain different pairs of values associated to the same predicted performance, as the contour lines correspond to constant f_{R1} values.

Finally, the effect of the fibres dimensions is partially explored through the interaction between aspect ratio and volume fraction, in Figure 9(d). This contour plot reflects the fact that residual flexural strength of SFRC can be improved by increasing either fibre content or aspect ratio, or a combination of both. The relationship between them is, however, not linear, and therefore different combinations of aspect ratio and volume fraction can be adequate depending on the f_{R1} value adopted as target.

Of course, the contour plots presented in Figure 9 are only partial examples of a preliminary model based on SFRC data, but they illustrate how the software tool resulting from the OptiFRC project will present the information and predictive models for optimisation purposes.

4. SUMMARY AND CONCLUSIONS

This paper presents an overview of the ongoing project "Optimization of Fiber-Reinforced Concrete using Data Mining" and its progress to date. The most salient aspects can be summarised as follows:

- The main objectives of this ongoing research project are: to compile an exhaustive database of FRC mix proportionings and their properties; to analyse their variability using data mining techniques; to develop robust models for estimating the residual flexural strength; and to implement these developments in an optimisation tool (software OptiFRC).
- Detailed information on hundreds of FRC mixes has been compiled from papers published in indexed journals and conference proceedings published since 1999. The database contains: relative amounts of mix constituents, maximum aggregate size; fibres aspect ratio, length, material, and fibre content; slump and compressive strength; and f_L, f_{R1}, f_{R2}, f_{R3}, and f_{R4} values.
- A preliminary analysis has been carried out on a dataset of SFRC mixes consisting of 770 cases, extracted from more than 100 papers published over the last two decades. It was found that the fibre volume fraction was typically below 1%, and very rarely exceeded 1.6%.
- Cements type CEM I and CEM II were found to be the most common in SFRC mixes. In almost half of the cases compiled, SCMs were used. In 90% of the cases, the total binder and cement contents were below 710 kg/m^3 and 660 kg/m^3, respectively. In 50% of the cases, total binder and cement contents were not higher than 450 kg/m^3 and 400 kg/m^3, respectively.
- SFRC mixes with fibre contents up to 0.75% in volume were associated with gravel-to-sand ratios of 1.5 and above. Increasing fibre contents were linked with a decrease in both the gravel-to-sand ratio and the total aggregates content.
- Regarding the average compressive strength at 28 days, it was not higher than 55 MPa in 50% of cases, and values higher than 110 MPa corresponded to only 10% of the SFRC mixes compiled. All residual flexural strength parameters followed a lognormal distribution, and it was confirmed that the linear correlation between them was very strong.
- A preliminary analysis of the f_{R1} values with respect to the SFRC mix proportions revealed that, to optimise the efficiency of fibres in improving the residual flexural strength, a water-to-cement ratio of 0.40 and sand contents around 950 kg/m^3 were optimal.

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