Study regarding the optimization of the mechanical behaviour of glass fibre reinforced concrete

E. MARIN, M. BARBUTA, L. CIOBANU, S. D. IONESI, I. CIOARA, C. DUMITRAS
Technical University"Gheorghe Asachi" of Iasi, Romania

The use of fibre reinforced concrete is well documented and the advantages of such materials in civil engineering refer to improved mechanical strength, improved concrete ductility and increased durability. The literature presents numerous studies concerning the subject. Some of them reveal the ecological trend of replacing cement with waste by-products such as silica, fly ash and slag. In this context it is of interest to study how the fibre reinforcement contributes to the mechanical behaviour of these recyclable composites. It is also important to see how the fibre characteristics affect the mechanical properties of the concrete. The paper presents an optimization study that considers the fibre length and the fibre percentage in the mix as independent variables. The output variable is the flexural strength. The experiment was carried out according to the experimental matrix and the data was processed using DOE++. A mathematical model for the flexural strength was obtained based on the ANOVA analysis. The model was validated. The response surfaces indicate that the optimum areas (maximum flexural strength) correspond to the maximum values of the input variables. The position of the area of maximum in the response surfaces indicate that the output variable can be further increased. Due to processing problems related especially with the percentage of fibres in the mix, only the fibre length was increased, while maintaining the fibre percentage to 1%. The results confirm the improvement of the flexural strength over the limit suggested by the experimental matrix.

1. Introduction

The use of glass as reinforcement material for concrete started in the 1960s. Researches up to date showed that the reinforcement of concrete with fibres leads to the absorption of the internal strains caused by the local variation in temperature, the drying and the initial contractions of the concrete element [6, 9, 10, and 11].

In Romania, the study of the fibre reinforced concrete is well developed by the civil engineering specialists, as it was recognised as an efficient way of improving mechanical behaviour.

The glass fibre reinforced concrete has numerous applications, such as: ornamental structures, wells, decorative elements, prefabricated panels, façade elements, domes, prefabricated elements, etc.

Further researches on the fibre reinforced concrete refer not only to the improvement of static strength, but also to the control of the cracking process, the improvement of concrete ductility, energy absorption characteristics and resistance to impact and to temperature variations [5, 7, 8]. Currently, the R&D trend is the production of concrete with elements that partially replace the cement, such as fly ash and slag. Such materials satisfy the increasing need for environment protection by adopting the so called no waste technologies [12, 13, 15, and 16]. Mineral components such as silica, slag and fly ash are commonly used as additives or cement replacements. They increase the density of the composite, reduce its porosity and improve the durability of the element. The partial replacement of the Portland cement was initiated in the 1960s and in the following decades [12, 13, 14, 15, and 16]. It cuts down the production costs and also the level of pollution caused by its processing

Almost all studies in the literature concerning this subject are not considering the possibilities offered by the fibre characteristics and the influence these characteristics can present on the concrete composites. Glass fibres (filaments) are not introduced as such in the composite. They are obtained by cutting glass yarns to preset length and therefore the properties of these yarns are very important as well as the knowledge of how the yarn segments are distributed within the concrete composite.

The paper has two objectives: the characterisation of the influence of the glass fibres in a composite with concrete with fly ash matrix and the optimization of the characteristics of these fibres – fibre length and fibre percentage in the mix – so that the material reaches the maximum its mechanical behaviour. The paper considers the flexural strength as the output variable reflecting the mechanical behaviour. It shows a part of a larger research that includes other mechanical properties of the glass fibre reinforced concrete materials.

2. Materials and methods

2.1. Experimental matrix

In order to solve the problem considered for the study – optimization of the use of glass fibres in composites with concrete and fly ash matrix – the advantages and disadvantages of the existing methods for the experiment design were reviewed. The nature of the problem lead to the selection of a central composite design that allows the identification of the optimum areas by generating response surfaces using the experimental data. This type of

experiment guaranties the precision of the results and the validity of the conclusions drawn from these results.

The experiment has two input variables: the fibre length (x1) and the percentage of glass fibre in the mix (x2). These variables were identified as significant to the mechanical strength of reinforced concrete. The output variable is the flexural strength of the concrete composite. In this experiment the optimum areas for the output variable correspond to the maximization of the flexural strength.

The coded and natural values for the input variables in the experiment are presented in Table 1.

Table 1. Coded and natural values for the input variables

No.	Variables	Coded variable	-1.414	-1	0	1	1.414
1.	Fibre length [mm]	x_1	**Natural variable**	5	10	20	30	35
2.	Fibre percentage [%]	x_2		0.25	0.5	1	1.5	1.75

The variation of each variable was carefully considered; the selection of the variation interval is based on the review of literature and on practical experience in producing concrete mixes. Table 2 presents the resulting

experimental matrix. According to this matrix, a number of 13 runs are carried out randomly, on samples of glass fibre reinforced concrete, with different combinations of fibre length and fibre percentage in the mix.

Table 2 Experimental matrix

Run	Input variables				Mass of cut fibre [g]
	Coded variables		Natural variables		
	x_1	x_2	Fibre length [mm]	Fibre percentage [%]	
1	-1	-1	10	0.5	319
2	-1	+1	10	1.5	956
3	+1	-1	30	0.5	319
4	+1	+1	30	1.5	956
5	+1.414	0	35	1	637
6	-1.414	0	5	1	637
7	0	+1.414	20	1.75	1116
8	0	-1.414	20	0.25	159
9	0	0	20	1	637
10	0	0	20	1	637
11	0	0	20	1	637
12	0	0	20	1	637
13	0	0	20	1	637

2.2. Characterisation of the glass fibres

The study was carried out using glass fibres rovings, linear density 2400 tex. The yarns were tested to determine their tensile behaviour, the experimental data being

presented in Table 3. The tests were carried out on a SATRA STM 466 testing machine, according to ASTM D2256 [3]. For the calculus of the Young's modulus and strength, the cross section of the glass roving was considered to be rectangular.

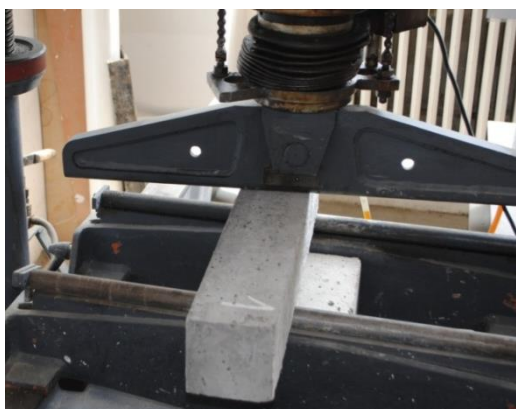*Table 3. Mechanical characteristics of the glass roving.*

Yarn	Breaking force [N]	Breaking elongation [%]	Young's modulus [N/mm^2]	Strength [N/mm^2]
Glass 2400 tex	704.1	3.02	16058.61	201.17

The glass rovings were cut to the specified dimensions, according to the experimental matrix. The corresponding values of the mass of the cut fibres were calculated based on the mass of the testing samples and the value of the second variable (x_2).

The introduction of the fibres in the mix made for the concrete with fly ash created some problems related to processing. These problems referred to the phenomena of fibre floating (when mixing), fibre clogging and fibre snagging (in the concrete composite) [2]. These problems affected the uniformity of the fibre distribution in the concrete samples and measures were taken to eliminate them, by modifying the mixing process.

2.3 Testing of the glass reinforced concrete samples

The tests were conducted according to SR EN 12390-4: 2005 [4], on 550x50x50 mm prisms of glass fibre reinforced concrete. The samples were tested using a hydraulic press. The force required for complete breaking was measured. Fig. 1 shows how the samples were tested and their aspect after breaking.

a) while testing

b) after testing

Fig. 1. Testing for flexural strength.

The test results showed that the presence of glass fibres improves the way the reinforced concrete samples break. If for the samples of concrete the breaking is sudden (the so called catastrophic breaking), the reinforcement with glass fibres slows down the fracture process by generating cracks in the concrete before the destruction of the sample. These cracks determine a gradual breaking process, indicating an improved behaviour for the reinforced concrete element.

The analysis of the cross section of the samples of glass fibre reinforced concrete offered information on the degree of dispersion of the fibres in the concrete mix. The first observation is that the fibres are distributed uniformly and without preset directions in the matrix, as exemplified in Fig. 1.b.

Another observation is that the cut fibres do not lose their integrity, maintaining the initial bundle, even if concrete penetrates between individual fibres, as illustrated in Fig. 2. Therefore, the dimensions of bundle of fibres (reflected by the yarn/roving fineness) influence the distribution of the glass fibre in the concrete mix.
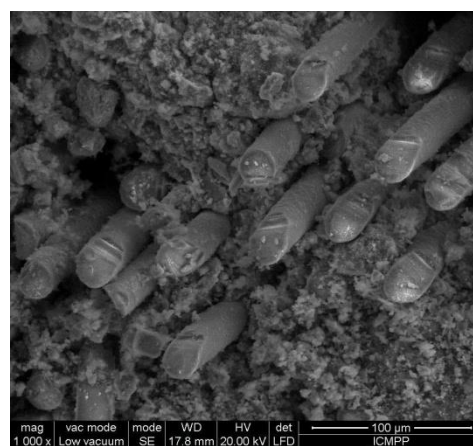

Fig. 2. Cross section of the concrete prism after testing.

3. Results and discussions

The experimental results regarding the flexural strength of the glass reinforced composites with concrete and fly ash matrix are presented in Table 4.

Table 4. The values of the flexural strength according to the experimental matrix.

	Variables		Flexural strength [N/mm^2]
	x_1	x_2	
1	-1	-1	3.54
2	-1	+1	3.36
3	+1	-1	2.74
4	+1	+1	4.18
5	+1.414	0	3.91
6	-1.414	0	3.98
7	0	+1.414	4.32
8	0	-1.414	3.89
9	0	0	3.95
10	0	0	4.12
11	0	0	3.92
12	0	0	3.97
13	0	0	3.93

3.1. Statistical processing of the experimental data

The statistical processing of the experimental data was carried out using DOE++ that allows the plotting of the 2D and 3D response surfaces and the determination of the areas of maximum for the output variable (flexural strength). The interactions of the two input variables were determined based on the extreme and average experimental values. The relevance of the model was considered for two levels of confidence - L1 (90%) and L2 (70%).

An ANOVA analysis was carried out using the experimental data. It shows that the linear and quadratic effects have a significant influence on the model for both levels of confidence. The regression equation giving the mathematical model for the flexural strength is:

$$Y = 3.932 + 0.2737x_1 + 0.5738x_2 - 0.1575x_1x_2 - 0.2954x_2^2 \qquad (1)$$

The response curves obtained for the output variable have as optimum value (the point of absolute maximum) the point corresponding to the coordinates: x1= 30 mm and x2 = 1.5% representing the highest values considered for both variables. In this case, the maximum corresponds to a combinations of factors considered in the experimental matrix. The flexural strength for this point is

4.18 N/mm^2, representing an increase of 33.3% in reference to the witness sample (concrete with fly ash).

The positions of the response curves in Fig. 3 suggest the importance of the second parameter – the percentage of fibres in the mix. This fact is also confirmed by the interactions matrix presented in Fig. 4. The matrix shows that the effect of the first independent variable (the length of the fibres) is not as strong as the effect of the second variable on the flexural strength.
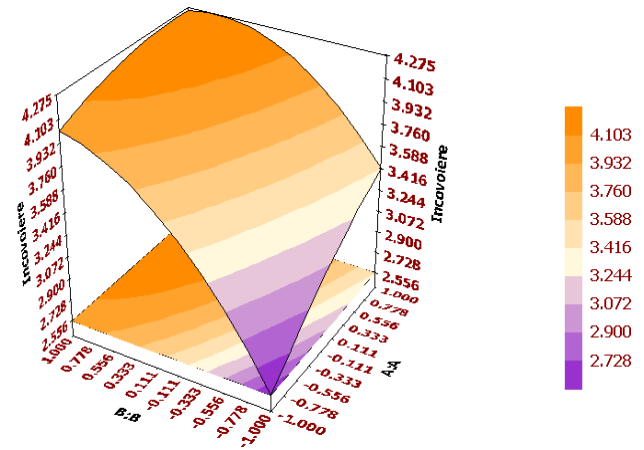

Fig. 3. 3D response surfaces for the flexural strength.
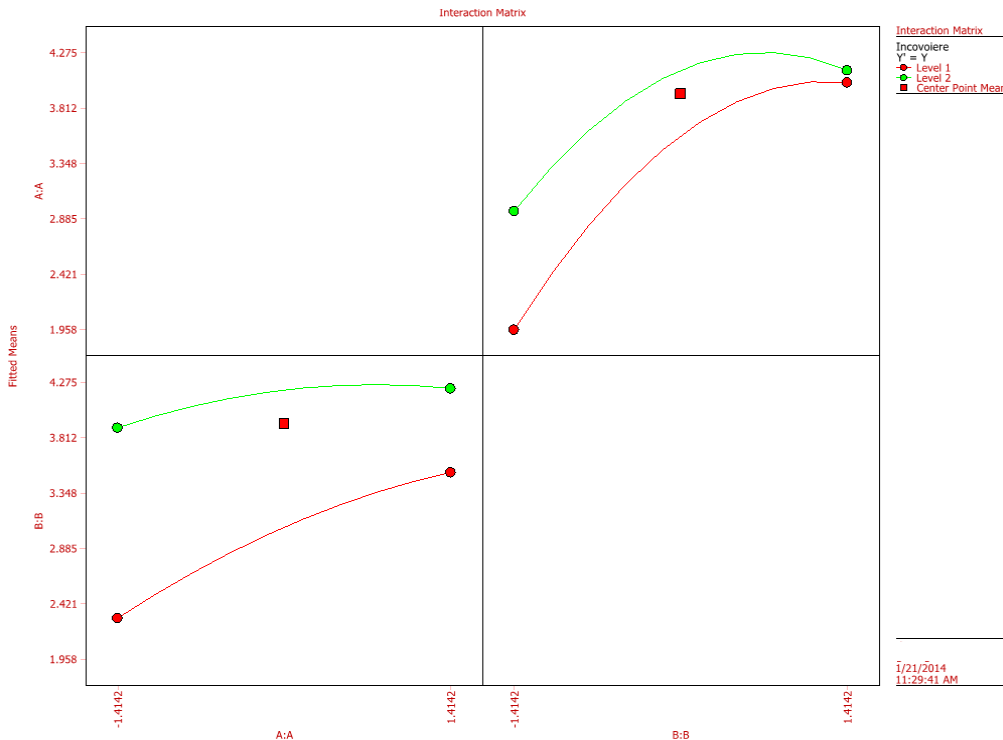

Fig. 4. Interactions of the experimental matrix.

The 2D response surface illustrated in Fig. 5 indicates more clear the position of the point of maximum. Furthermore, this graphic show that the plot area of

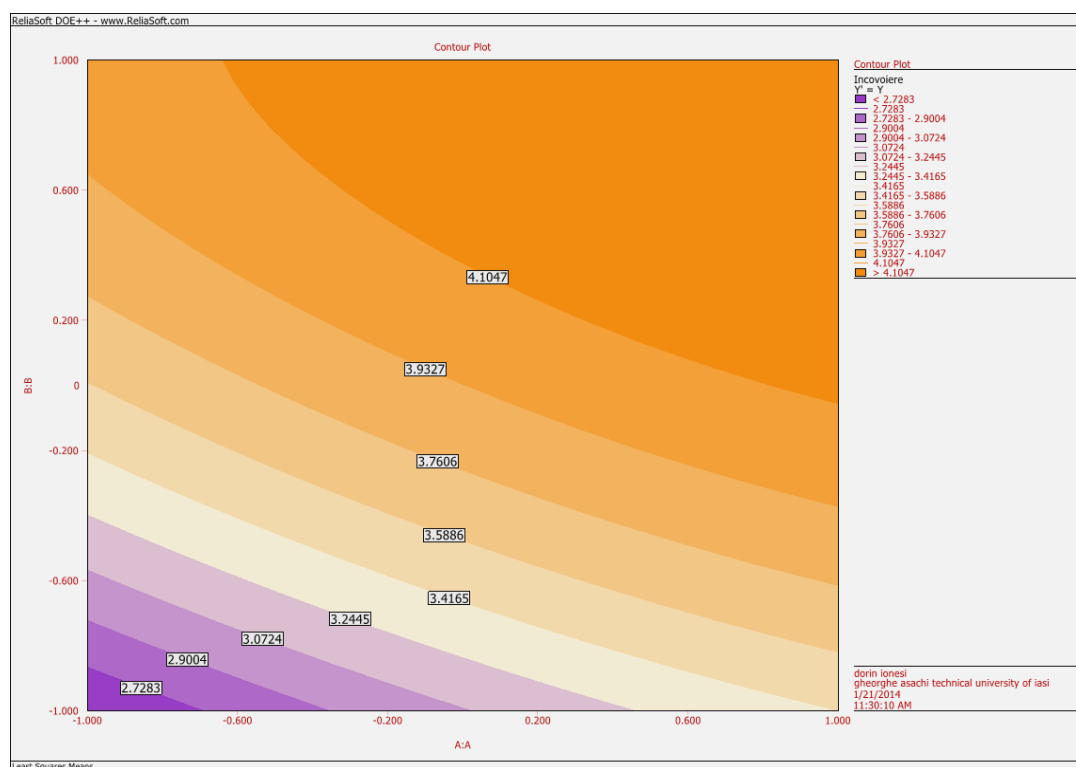maximum is not completely placed inside the surface defined by the experimental matrix.

Fig. 5. 2D response surfaces for the flexural strength.

Considering the influence of the length of the fibre on the flexural strength of the composite with concrete matrix, this can be seen for all values of the second variable (fibre percentage in the mix), but it grows for fibre percentages higher than 1%. The graphs suggest that an increase of the fibre length could be beneficial for the mechanical behaviour of the concrete elements (flexural strength).

For the lower fibre percentages (0.25% and 0.5%), the strength is decreased in reference to the witness - approx. 25% less for the concrete variant corresponding to Run 8 (x1 = 20 mm and x2 = 0.25%) and approx. 12% for the concrete variant corresponding to Run 1 (x1 = 10 mm and x2 = 0. 5%). It is interesting to emphasise that in the case of 0.5% fibre in the mix, when increasing the fibre length to x1 = 30 mm, the flexural strength improves in reference to the witness with approx. 15%.

Of course, the increase of the two variables must be considered taking into view the problems related to the processability of the concrete mix that were mentioned above [2]. This means that there will be certain limits to the fibre length and fibre percentage due to the difficulties related to the mixing of the glass fibres with the concrete.

It can be concluded that the flexural strength is controllable through a combination of both factors. The strength can be increased either by the use of higher length for the fibres and a lower percentage in the mix, or by maintaining lower values for the cut fibres (20 mm seems to be the inferior limit) and increasing the fibre percentage.

3.2. Validation of the mathematical model

The mathematical model resulting from the experimental data must be validated. As mentioned above, the point of maximum was determined for a pair of input variables from the experimental matrix, in natural values x1 = 30 mm and x2 = 1.5%. The experiment (run 4) was repeated and the experimental data obtained were similar to the calculated data.

Furthermore, the possibility of improving the flexural strength by increasing the fibre length over the range considered in the experimental matrix was studied. Other three length values for the cut glass fibres were used to determine the flexural strength, namely 45, 50 and 60 mm, while the percentage of fibres in the mix was kept at 1%. This way, the problems related to processability were eliminated. Table 5 shows the values obtained for the flexural strength in the case of the higher values for the fibre length.

Table 5. Flexural strength for the chosen fibre lengths.

Caracteristici fibră		Rezistența la încovoiere (N/mm^2)
Lungime de fibră (mm)	Procent de fibră (%)	
35	1	4.29
45	1	4.35
50	1	4.41
60	1	4.5

The experimental data confirms that the point of maximum in the experimental matrix was correctly

determined, but also that the flexural strength of the glass fibre reinforced concrete with fly ash can be further improved by using higher length for the cut fibres. The graph from Fig. 6 presents the variation of the flexural strength with the fibre length, considered for the extended interval, from 5 mm to 60 mm. For all values, the fibre percentage was maintained constant to 1%. For comparative purposes, the graph also shows the flexural strength of the witness - concrete with fly ash.
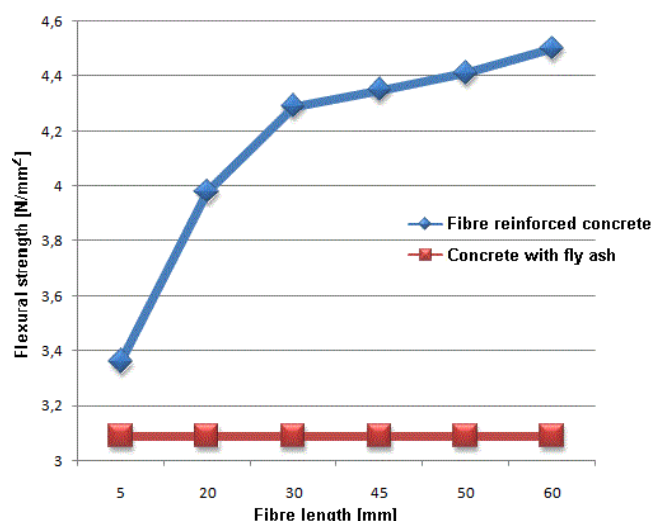

Fig. 6. Variation of flexural strength with the fibre length, for 1% percentage of glass fibre in the mix.

The flexural strength can be improved up to 50%. The possibility of increasing the fibre percentage must also be considered, but such high values for the fibre length presented the risk of processing problems that can affect the uniformity of the composite.

The graph also shows that the strength increases significantly in the range included in the experimental matrix (up to 35 mm). The increase of strength from 35 mm up to 60 mm fibre length is not as steeped and suggests that this length approaches the limit of its practical interval.

4. Conclusions

The paper presents the modelling of the mechanical behaviour of glass reinforced concrete with fly ash, in view of the recent researches for improving the strength of the building elements made with waste materials.

The paper aims at optimizing the characteristics of the glass fibres used in the concrete mix, considering the fibre length and the fibre percentage in the mix as the independent variables. An experimental matrix based on a composite experimental design was defined. The output variable is the flexural strength.

The experimental study allowed drawing practical conclusions on the way the glass fibres influence the processability of the composite with concrete and fly ash matrix. The observations made during processing confirmed the variation intervals chosen for the two variables. It was observed that a higher fibre percentage,

combined with higher fibre length caused problems regarding the distribution of the fibres in the composite and its strength.

The experimental data was processed and response surfaces were obtained. These surfaces indicate the followings:

• The optimum value (the point of maximum) is obtained for the maximum values of the input variables (code values x1 = +1 and x2 = +1)

• The second variable x2 (percentage of fibres in the mix) presents the strongest influence on the flexural strength; the influence of the first variable (fibre length) is more visible when the fibre percentage increases.

• For both variables, the lower part of their variation intervals are not improving the flexural strength. The strength is significantly improved starting with 20 mm length and 1% fibre in the mix.

The experiment was validated by testing in the point of maximum (that coincided with a run from the experimental matrix). The practical results confirmed the model. Furthermore, the position of the area of maximum shown by the response surfaces suggests that another increase in both variables can further improve the flexural strength of the concrete composite. Considering the processing problems encountered while producing the samples, it was preferred to increase the fibre length, while maintaining the fibre percentage to 1%, a value that ensured optimum processing. The experimental results confirm the improved flexural strength and suggest that a length of 60 mm approaches the limit to which the mechanical behaviour can be increased.

The tests also showed the importance of the yarn fineness on the distribution in the concrete mix and subsequently on its strength.

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*Correspondent author: dumitrascata@yahoo.com
lciobanu@easynet.ro