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EVALUATION OF THE BEHAVIOUR OF PRE-LOADED CONCRETE SPECIMENS CONTAINING POZZOLANS AND FIBRES

OCENA PONAŠANJA PREDOPTEREĆENIH BETONSKIH UZORAKA KOJI SADRŽE PUCOLAN I VLAKNA

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Ključne reči
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- čelična i staklena vlakna
- mehaničko ponašanje
- zeolit
- silikatna prašina

Abstract

One of the important criteria in the concrete structure design is to investigate the flexural behaviour of concretes. The flexural strength and fracture energy are the resulting parameters from the bending test of concrete samples. In order to investigate and improve the concrete specifications, two pozzolans and also two types of fibres have been used in concrete samples. The behavioural effect of each material (zeolite pozzolan and silica fume, steel fibres, and glass) and also their effect have been evaluated simultaneously. One of the new subjects over the last years regarding the concrete behaviour is to consider the preloading in fibre concretes in this study. The results demonstrate that increasing fibres in designs without pozzolan bring about different results. In these designs, increasing glass fibres did not significantly increase flexural strength, while increasing steel fibres increased flexural strength. Besides, in designs with combined preloading, the difference in results decrease by reducing 2 % of silica fume. Accordingly, it can be concluded that zeolite pozzolan plays a more active role in curing cracks for short periods. In assessing the fracture energy of samples, the samples containing 1 % steel fibres indicate greater fracture energy.

Izvod

Jedan od najvažnijih kriterijuma u projektovanju betonskih konstrukcija jeste istraživanje ponašanja betona pri savijanju. Savojna čvrstoća i energija loma su rezultujući parametri ispitivanja savijanjem betonskih uzoraka. Kako bismo istražili i poboljšali specifikacije betona, upotrebili smo dva pucolana i dva tipa vlakana u uzorcima betona. Efekti ponašanja svakog od materijala (pucolan zeolit i silikatna prašina, čelična i staklena vlakna), a takođe njihovi uticaji su procenjeni simultano. U radu se obrađuje jedna od novijih tema u nekoliko proteklih godina, koja se odnosi na ponašanje betona, tj. razmatranje predopterećenja u vlaknasto ojačanom betonu. Dobijaju se različiti rezultati dodavanjem vlakana bez pucolana. Kod ovakvih projekata, povećanje staklenih vlakana nije značajno povećalo savojnu čvrstoću, dok je povećanje čeličnih vlakana povećalo i savojnu čvrstoću. Osim toga, u izvedbama sa kombinovanjem predopterećenja, razlike u rezultatima se smanjuju, smanjenjem silikatne prašine za 2 %. Stoga se zaključuje da zeolit pucolan ima aktivniju ulogu u sanaciji prslina u kraćim periodima. Tokom procene energije loma kod uzoraka, uzorci sa sadržajem 1 % čeličnih vlakana pokazuju povećanje energije loma.

INTRODUCTION

By the advent of Portland cement after 170 years, nowadays, cement has been known as one of the most used building materials. Such being a case is due to its abundance, availability, relatively higher durability and the long-life property of reinforced concrete structures, resistance against fire, formability, higher compressive strength, and demands in constructing abundant concrete structures, e.g., buildings, bridges, tunnels, dams, wharves, roads, etc. /1-2/. The existence of intrinsic drawbacks in concrete, such as brittle fracture and non-ductility, have led the researchers to improve the behavioural properties of concrete using various fibres, increasing the concrete's weakness in brittle fracture and enhancing compressive strength. Using cement and fibre-reinforced concrete has become common in the last years. Reinforced concrete with glass fibres is used in prefabricated parts, panels, and decorative facades /3, 4/. By adding fibres to concrete, two main situations occur: parallel cracking with fibres or perpendicular cracking to it. In the case of the perpendicular cross of the fibres through the edges of cracks, the concrete's uniformity is sustained significantly by connecting the cracks via fibres /5/. The steel fibres have the most application in fibre-reinforced concrete preparation. These fibres are manufactured for the first time in 1962 in the USA. Compared to other fibres, these fibres have captured more interest among concrete researchers and executors due to increasing the resistance and the ductility of concrete, the variety in appearance to improve the mechanical and executive properties of the concretes, easy mixture with additives, higher durability, and easy formwork for concreting, /6/. Steel fibres have cross section shapes in different sizes. These fibres with circular cross-sections mostly have diameters of 0.25 to 0.8 mm. The most well-established steel fibres are those manufactured by Bekaert Factory in Belgium with Dramix commercial name. These fibres exist in a single and adherent form, where after contact with water, the fibres turn into a sole object and are orderly dispersed in parallel lines. The Duramax fibres have a curved end, providing a proper continuity between fibres and concrete. The Harex fibres are another type of machine steel fibres; its more typical type is of triangular cross-section including a flat surface with other rough surfaces. When the glass fibres are added to the concrete, using a proper plasticiser is inevitable due to reducing the performance of the fresh concrete. In this case, we can reach a proper mixture method. Besides, the existence of glass fibres and the tendency to adhere and being conglobated in the fresh concrete (the conglobation phenomenon in fibres) brings about the non-uniformity of fibre distribution; therefore, in order to overcome this obstacle, we should look for a solution. The diameter of special glass fibres is between 0.005 to 0.015 mm; when being connected to each other in producing elements with glass fibres, the diameter of these fibres reaches 0.013 to 1.3 mm /7/. Previous studies indicate that the polypropylene fibres decrease the compressive strength and increase flexural strength; in that case, the maximal resistance against concrete fracture is observed in polypropylene fibres. This situation indicates a lack of rupture in concrete. Another result obtained by their study is the reduction in compressive strength of concrete by the addition of polypropylene fibres. The compressive strength diagramme of concrete equipped with polypropylene fibres is ascending at 1 % fibres and descending at 1 to 6 % fibres. The maximum compressive strength is obtained at 1 % polypropylene fibres. Flexural strength of concrete increases by adding polypropylene, and maximum flexural strength is obtained at 6 % polypropylene fibres. Soroushian et al. /8/ investigate the expansion of cracks in normal concrete and concrete containing 3 % by volume polypropylene and steel fibres. They conclude that polypropylene and steel fibres could postpone the creation of cracks. The results of the investigation conducted by Corinaldesi and Moriconi indicate that steel fibres improve compressive and flexural strengths, increase elasticity modulus, and reduce shrinkage of concrete samples /9/. Chen and Lio conducted several studies on concrete with high strength and water to cement ratio of 0.33. They conclude that steel fibres increase compressive and tensile strength in this type of concrete /10/. The study conducted by Sivakumar and Santhanam on steel fibres in concrete with high strength indicate the improvement of compressive, flexural, and tensile strengths and also increase in elasticity modulus in this type of concrete /11/.

EXPERIMENTAL STUDY

The concrete samples tested in this study are composites including two types of fibres and pozzolans.

The employed gravel is of the river and round-edge type and is prepared as gravel 0-6 from the Pipe North factory, Iran. Specific bulk density of used gravel at the saturation condition with the dry surface is 2600 kg/m^3, its water absorption is 2.4 %, and fineness modulus is 2.75. Grading of used gravel is carried out according to ASTM C33 /12/ standard. Figure 1 demonstrates the grading of used gravel. The maximal size of sand grains is 12.5 mm, and the specific apparent density and water absorption are 1.5 %. Grading is carried out according to ASTM C33 /12/ standard. The grading diagramme of used sand is indicated in Fig. 2.

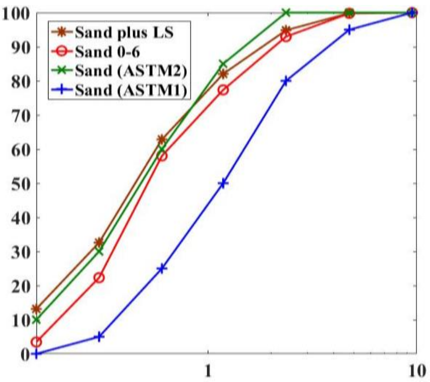

Figure 1. Grading diagramme of gravel according to ASTM C33 /12/.

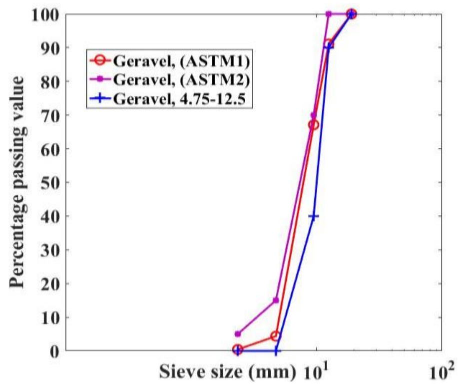

Figure 2. Grading diagramme of sand according to ASTM C33 /12/.

The fibres used in this investigation are two types of steel and glass. The employed micro-silica with a specific gravity of 2200 kg/m^3 is manufactured by Iran Ferrosilicon Co. This additive is dried without being dissolved in water and added to the concrete compound as a percentage of cement weight. Besides, two types of silica fume pozzolans with weight ratios of 0, 5, and 15 % and zeolite with a weight ratio of 0 and 10 % are employed as an alternative to a part of used cement. It should be noted that the ratio of water to all cementitious materials is 0.4.

In this study, to obtain favourable slump and better distribution of particles in the concrete compound, super concrete plasticiser based on polycarboxylate ether with commercial name of FARCO PLAST P10N produced by Shimisakhteman Co. Specifications of this superplasticiser are indicated in Table 1.

Table 1. Specifications of the lubricant used.

Technical specifications	
Chemical mixture	modified copolymers polycarboxylic acid
Ionic nature	anionic
Colour	dark green
Physical state	liquid
Specific gravity (kg/lit.)	1/2 /0 0.02 at 20 °C
Chloride (ppm[1])	maximum 500

[1]part per million

In this study, to investigate the impact of fibre variables and pozzolans solely and the effect of simultaneously using them on mechanical properties on concrete and flexural and compressive strength, 12 mixing designs consisting of different values of fibres and pozzolan materials are manufactured. Steel and glass fibres with 0, 5, and 10 % values are employed in manufacturing samples. Besides, pozzolan materials consisting of silica fume and zeolite with different values are employed as an alternative to a part of used cement and also cement type 2 with grades of 500 kg/m^3. The water to cement (w/c) ratio in all samples is considered constant and equal to 0.4. The mixing design pertinent to all manufactured samples is indicated in Table 2. Twenty-four hours after manufacture, samples are taken out from frames and are kept at water laboratory temperature 23 °C. Some of the flexural samples are loaded in order to investigate the impact of pre-loading on final performance at the 7-day age until respectively 80 and 100 % of the strength corresponding to the creation of cracks in the similar sample. The samples examined in this study are composites consisting of two types of steel and pozzolan fibres. The glass and steel fibres employed have solely unique properties and combining them will mitigate weaknesses and bring about positive outcomes. Besides, combining zeolite pozzolans and silica fume can be useful in improving the mechanical properties of concrete. The fineness of silica fume grains and high activity pozzolan activity compared to zeolite can be a suitable complement in mitigating weaknesses of zeolite and increasing the capacity of using pozzolan in concrete.

Table 2. Mixing design of all manufactured samples.

Number	Sample code	Silica fume %	Zeolite %	Steel fibre %	Glass fibre %
1	F00Z00S05G0	0	0	5	0
2	F00Z00S10G0	0	0	10	0
3	F00Z00S05G5	0	0	5	5
4	F15Z00S05G0	15	0	5	0
5	F15Z00S10G0	15	0	10	0
6	F15Z00S05G5	15	0	5	5
7	F00Z10S05G0	0	10	5	0
8	F00Z10S10G0	0	10	10	0
9	F00Z10S05G5	0	10	5	5
10	F05Z10S05G0	5	10	5	0
11	F05Z10S10G0	5	10	10	0
12	F05Z10S05G5	5	10	5	5
13	F00Z00S00G0	0	0	0	0

Figure 3. Samples of manufactured designs before framing.

DISCUSSION AND RESULT

This section examines the results obtained from performed experiments on hardened concrete samples. Flexural and compressive strength experiments are conducted to investigate the mechanical properties of concrete. Besides, due to simultaneously using different fibres and pozzolan, the manufactured concrete samples might have some unique properties that common and standard tests do not recognise. Accordingly, a special test is conducted in order to investigate the behaviour of these types of concretes, which have not been investigated widely so far. Pre-loading on samples until the cracking moment and close to rupture can be a solution to evaluate the performance of these concretes under critical conditions and after damages caused by an earthquake or other unexpected extreme loading. Given that compressive strength is one of the essential properties of manufactured concrete in classifications of international regulations, investigating it in manufactured concrete is taken into account. Compressive strength experiment at 28-day age of carried out on cubic samples of 100×100×100 mm^3. The obtained results are indicated in Fig. 4 and Table 3. In order to compare with other samples and more accurate evaluation in all graphs, control sample values are added.

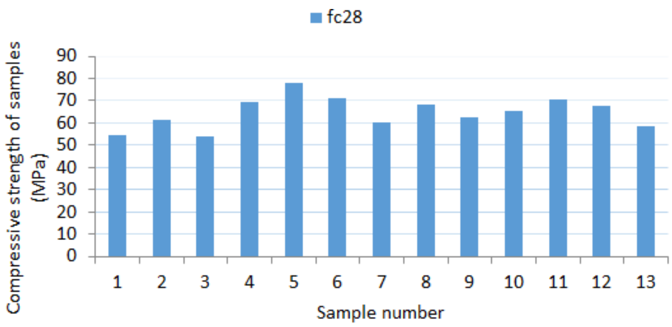

Figure 4. Diagramme of compressive strength at 28-day age samples.

Table 3. Compressive strength of different designs at 28-day age.

Number	Sample code	f_{c28} (MPa)
1	F00Z00S05G0	54.6
2	F00Z00S10G0	61.4
3	F00Z00S05G5	53.9
4	F15Z00S05G0	69.3
5	F15Z00S10G0	78.2
6	F15Z00S05G5	71
7	F00Z10S05G0	60.1
8	F00Z10S10G0	68.2
9	F00Z10S05G5	62.4
10	F05Z10S05G0	65.1
11	F05Z10S10G0	70.3
12	F05Z10S05G5	67.6
13	F00Z00S00G0	58.3

According to compressive strength results, the maximum compressive strength belongs to design 5 with 78.2 MPa, and the minimum value belongs to design 3 with 53.9 MPa. Designs number 5, 6, and 11 have the maximal compressive strength equal to 78.2, 71, and 70.3 MPa, respectively. All these designs contain steel and micro-silica fibres. Among all designs, design number 5 with maximal compressive strength contains maximal silica fume and steel fibres (15 % silica fume and 10 % steel fibres). In general, containing micro-silica and steel fibres increase compressive strength, /13/. Besides, designs 1, 3, and 7 have a minimum compressive strength equal to 54.6, 53.9, and 60.1 MPa, respectively. In general, it can be concluded that not using pozzolan, particularly micro-silica, also replacing glass fibres with steel fibres, reduces compressive strength.

As it is evident, the compressive strength rises as steel fibres increase in all designs, and compressive strength reduces by replacing glass fibres with steel fibres. In addition, all samples containing silica fume have greater compressive strength compared to samples containing zeolite. By comparing samples with combined fibres (samples 3, 6, 9, and 12), it can be seen that sample 6 (15 % silica fume, 5 % steel, and 5 % glass) lacking zeolite has maximum compressive strength. Furthermore, examining samples containing combined fibres indicates that pozzolan in design increases compressive strength, while micro-silica is more effective in this case compared to zeolite.

This experiment is carried out to determine the rupture modulus of concrete using the three-point method on samples at the ages of 7, 28, and 90-day. Results obtained from this experiment are indicated in Table 4 and Fig. 5.

Table 4. Values of flexural strength at ages of 7, 28, and 90-day.

Number	Sample code	7-day flex. strength	28-day flex. strength	90-day flex. strength
1	F00Z00S05G0	5.357	7.557	7.953
2	F00Z00S10G0	5.995	8.524	8.921
3	F00Z00S05G5	5.428	7.54	7.961
4	F15Z00S05G0	7.059	9.579	9.93
5	F15Z00S10G0	8.305	11.117	11.548
6	F15Z00S05G5	6.989	9.823	10.158
7	F00Z10S05G0	6.061	8.497	9.061
8	F00Z10S10G0	6.934	9.775	10.447
9	F00Z10S05G5	6.325	9.03	9.536
10	F05Z10S05G0	6.531	9.225	9.723
11	F05Z10S10G0	7.16	9.634	10.169
12	F05Z10S05G5	6.781	9.562	10.067
13	F00Z00S00G0	5.744	7.891	8.271

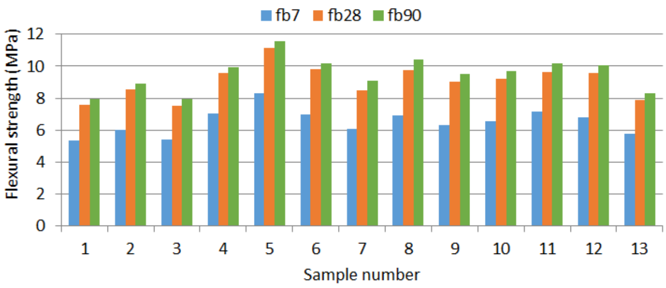

Figure 5. Diagramme of flexural strength at 7, 28, and 90-day ages.

According to the obtained results, sample 5 (15 % silica fume and 10 % steel fibres) has maximum flexural strength at different ages. Based on the results of compressive and flexural strength tests at the age of 7 days, sample no.5 without the presence of glass and zeolite fibres and the maximal selected percentages of silica foam and steel fibres, results in a higher ratio of compressive to flexural strength. Sample no.1, containing merely 5 % steel fibres, has the minimum flexural strength. In samples lacking pozzolan, increasing the content of steel fibres increases flexural strength, while increasing glass fibre does not significantly increase flexural strength. In samples containing pozzolan, similar to samples without pozzolan, increasing the steel fibres increases flexural strength. However, using glass fibres increases flexural strength, though insignificantly. Among designs containing combined fibres (steel and glass), design no.6 (15 % silica fume, 5 % steel fibres, and 5 % glass fibres) has the maximal flexural strength, and design no.3 lacking pozzolan (5 % steel and 5 % glass) has minimal flexural strength. By comparing designs 9 and 12, it can be seen that, in general, silica fume increases flexural strength. Examining the results indicates that maximum flexural strength rise from the age of 7 to 90 days belongs to sample no.8, consisting of 10 % zeolite and 10 % steel. Besides, the least increasing trend in flexural strength belongs to designs nos. 1, 2, and 3, all of which lack pozzolan.

Pre-loading on samples until the onset of cracking (100 %) and close to rupture (80 %) is carried out to examine the performance of concrete samples under critical conditions or after damages caused by unexpected extreme loads, such as an earthquake. Moreover, the flexural strength of pre-loaded 7-day samples after 28 days and comparing them with the 28-day flexural strength of samples are examined under normal conditions. Flexural strength of 28-day pre-loaded samples (at the age of 7-day) are indicated in Table 5 and Fig. 6. $f_{b7\text{-}80\text{-}28}$: 28-day flexural strength of pre-loaded samples close to rupture (80 %) at 7-day age. $f_{b7\text{-}100\text{-}28}$: 28-day flexural strength of pre-loaded samples until cracking (100 %) at the 7-day age.

Table 5. 28-day flexural strengths of non-loaded and pre-loaded samples at the age of 7-day.

Number	Sample code	f_{b28} (MPa)	$f_{b7\text{-}80\text{-}28}$ (MPa)	$f_{b7\text{-}100\text{-}28}$ (MPa)
1	F00Z00S05G0	7.557	7.423	5.973
2	F00Z00S10G0	8.524	8.373	6.525
3	F00Z00S05G5	7.54	7.398	5.507
4	F15Z00S05G0	9.579	9.539	7.471
5	F15Z00S10G0	11.117	11.272	7.925
6	F15Z00S05G5	9.823	9.637	7.143
7	F00Z10S05G0	8.497	8.535	6.352
8	F00Z10S10G0	9.775	9.951	6.905
9	F00Z10S05G5	9.03	9.066	7.038
10	F05Z10S05G0	9.225	9.16	7.031
11	F05Z10S10G0	9.634	9.733	7.584
12	F05Z10S05G5	9.562	9.595	7.606
13	F00Z00S00G0	7.891	7.683	5.810

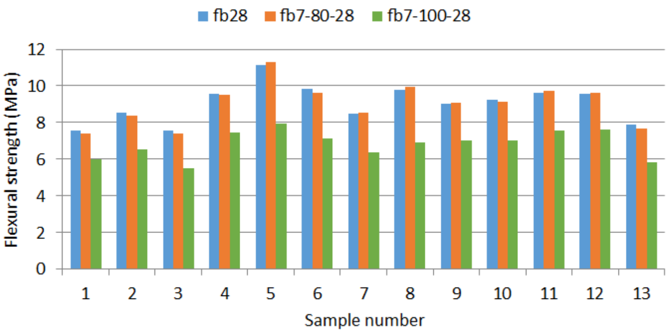

Figure 6. Flexural strengths of 7-day pre-loaded samples after 28 days.

Examination of the obtained results indicates that the maximal flexural strength among pre-loaded samples at both cases of 80 % (close to rupture) and 100 % (close to cracking) at 28-day age belongs to sample 5. Besides, examinations indicate that pre-loading at the 7-day age until cracking reduces the 28-day flexural strength by 20 to 30 %. The maximal reduction in pre-loaded flexural strength (100 %), respectively, belongs to sample 8 (10 % zeolite and 10 % steel fibres), sample 5 (15 % silica fume and 10 % steel fibres), and sample 6 (15 % silica fume, 5 % steel fibres, and 5 % glass fibres). In addition, investigating the 28-day flexural strength of pre-loaded samples (80 %) at the 7-day age indicates that in some cases, such as samples 5, 7, 8, 9, 11, and 12, the flexural strength of pre-loaded samples has been increased compared to 28-day flexural strength without pre-loading. In all of the samples containing combined fibres, it is observed that 28-day flexural strength after 100 % pre-loading at 7-day age decreases, while flexural strength of 80 % pre-loaded samples 3 and 6 (without zeolite) decreases and in samples 9 and 12 (containing zeolite) increases. In all samples lacking pozzolan and merely containing fibres, the 28-day flexural strength of 80 and 100 % pre-loaded samples decreases compared to flexural strength without pre-loading.

This section examines flexural strength at the age of 90 days for 100 and 80 % pre-loaded samples at the age of 7 days. The 90-day flexural strength (without pre-loading) under pre-loaded and normal conditions are indicated in Table 6 and Fig. 7. Examinations indicate that 90-day flexural strength of all samples under 80 and 100 % pre-loading decreases compared to flexural strength without pre-loading. This reduction in 100 % pre-loading is within the range of 10 to 22 % which has increased compared to the previous case (28-day strength). The maximum reduction in strength for the 100 and 80 % pre-loaded case belongs to sample no. 1 (containing only 5 % steel fibres) and sample no. 3 (containing 5 % steel fibres and 5 % glass fibres), respectively.

Table 6. 90-day flexural strength of samples with and without pre-loading at 7-day age.

Number	Sample code	f_{b90} (MPa)	$f_{b7\text{-}80\text{-}90}$ (MPa)	$f_{b7\text{-}100\text{-}90}$ (MPa)
1	F00Z00S05G0	7.953	7.853	6.142
2	F00Z00S10G0	8.921	8.813	7.042
3	F00Z00S05G5	7.961	7.851	6.241
4	F15Z00S05G0	9.93	9.864	7.946
5	F15Z00S10G0	11.548	11.485	9.732
6	F15Z00S05G5	10.158	10.014	8.553
7	F00Z10S05G0	9.061	8.924	7.305
8	F00Z10S10G0	10.447	10.445	8.416
9	F00Z10S05G5	9.536	9.406	8.105
10	F05Z10S05G0	9.723	9.586	8.284
11	F05Z10S10G0	10.169	10.037	9.089
12	F05Z10S05G5	10.067	10.003	8.926
13	F00Z00S00G0	8.271	7.638	6.315

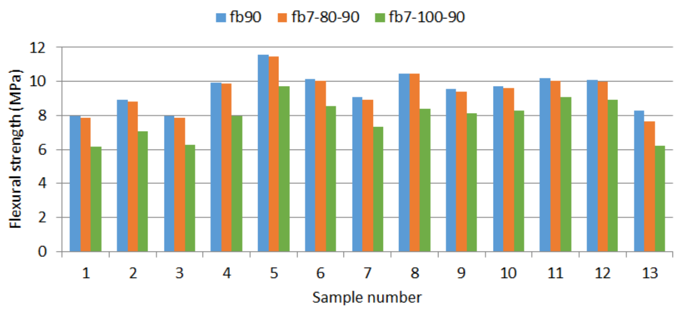

Figure 7. Flexural strength of 7-day pre-loaded samples after 90-day.

Examinations indicate that by increasing fibres, the flexural strength at the pre-loaded case decreases. Besides, replacing steel fibres with glass fibres in the design reduces flexural strength at the pre-loaded case relative to normal condition which is more significant in the 80 % pre-loaded case. Comparing and examining samples containing combined fibres indicate that maximum and minimum reduction in flexural strength due to pre-loading until the onset of cracking belongs to sample 3 (without pozzolan) with 22 % and sample 12 (containing both pozzolan zeolite and silica fume), respectively. In addition, in the 80 % pre-loading condition (close to rupture), maximal reduction among samples containing combined fibres belongs to sample 6 (containing silica fume, steel fibres, and glass fibres), and the minimal reduction belongs to sample 12 (containing both pozzolan zeolite and silica fume). $f_{b7\text{-}80\text{-}90}$: 90-day flexural strength of samples pre-loaded close to rupture (80 %) at the age of 7 days. $f_{b7\text{-}100\text{-}90}$: 90-day flexural strength of sampled pre-loaded until the cracking moment (100 %) at the age of 7 days.

The flexural strength of 90-day pre-loaded samples on day 28 is investigated in two states of 80 and 100 %. Obtained values are compared with the samples' flexural strength in the absence of pre-loading. Respective values to samples' 90-days flexural strength in the presence of pre-loading (on day 28) and the absence of pre-loading are demonstrated in Table 7 and Fig. 8.

Table 7. 90-day flexural strength of samples with and without pre-loading on day 28.

Number	Sample code	f_{b90} (MPa)	$f_{b28\text{-}80\text{-}90}$ (MPa)	$f_{b28\text{-}100\text{-}90}$ (MPa)
1	F00Z00S05G0	7.953	7.919	5.817
2	F00Z00S10G0	8.921	8.929	6.682
3	F00Z00S05G5	7.961	7.829	5.879
4	F15Z00S05G0	9.93	9.858	7.429
5	F15Z00S10G0	11.548	11.679	9.173
6	F15Z00S05G5	10.158	10.006	8.121
7	F00Z10S05G0	9.061	9.016	6.854
8	F00Z10S10G0	10.447	10.47	7.839
9	F00Z10S05G5	9.536	9.415	7.67
10	F05Z10S05G0	9.723	9.81	7.854
11	F05Z10S10G0	10.169	10.083	8.565
12	F05Z10S05G5	10.067	10.029	8.477
13	F00Z00S00G0	8.271	8.127	6.598

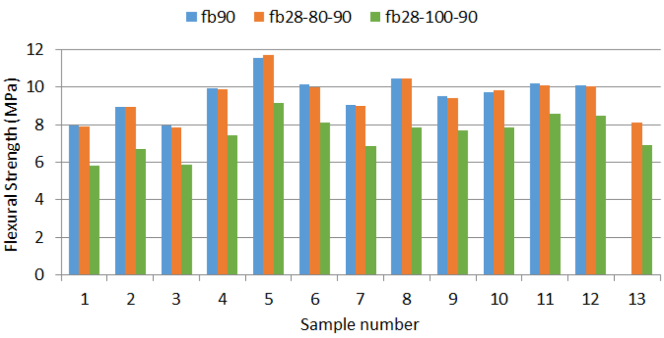

Figure 8. 28-day flexural strengths of pre-loaded samples after 90-day.

Experiments indicate that there is not a subtle difference between flexural strength in the presence or absence of pre-loading to the rupture of 80 %. This discrepancy is at most 1.5 %, indicating a flexural strength decline in a number of samples and an enhancement in others, particularly the designs containing steel fibres.

Also, investigating the values attributed to pre-loading of 100 %, it can be seen that the 28-day flexural strength of all samples declines in the absence of pre-loading, which is between 16-27 %. In that case, the maximal resistance decline is attributed to sample 1 (only containing steel fibres) and the minimal to samples 11 and 12 (containing both types of pozzolan). In general, we can conclude that thanks to pozzolan, particularly using silica fume and zeolite, the samples design under pre-loading condition has better performance until the cracking moment and it loses a lower level of its initial flexural strength. Comparing the samples containing composite fibres indicates that sample 3 (only containing fibres) has the maximum decline in flexural strength. In that case, sample 12 (containing maximal pozzolan content) has the minimum flexural strength decline level, demonstrating the positive effect of using pozzolan in diminishing the flexural strength by virtue of the pre-loading effect. Also, comparing the two designs containing composite fibres (one of them containing silica fume and the other zeolite) indicates a lower decline of flexural strength in the design containing zeolite. The obtained values indicate that by increasing the fibres in the design, the resistance decline level would be lower. However, replacing a part of steel fibres with glass fibres (using composite fibres) reduces the resistance decline percentage.

In this section, the 90-day flexural strength of samples under the conditions of 7 and 28 days pre-loading until the cracking of 100 % are investigated and compared with the 90-day flexural strength without pre-loading. The respective values to samples' flexural strength are indicated in Table 8 and Fig. 9 with and without the pre-loading.

Table 8. 90-day flexural strength of samples in the absence of pre-loading and with pre-loading on days 7 and 28.

Number	Sample code	f_{b90} (MPa)	$f_{b7\text{-}28\text{-}100\text{-}90}$ (MPa)
1	F00Z00S05G0	7.953	5.586
2	F00Z00S10G0	8.921	6.385
3	F00Z00S05G5	7.961	5.672
4	F15Z00S05G0	9.93	7.141
5	F15Z00S10G0	11.548	8.779
6	F15Z00S05G5	10.158	7.783
7	F00Z10S05G0	9.061	6.634
8	F00Z10S10G0	10.447	7.566
9	F00Z10S05G5	9.536	7.325
10	F05Z10S05G0	9.723	7.442
11	F05Z10S10G0	10.169	8.15
12	F05Z10S05G5	10.067	8.039
13	F00Z00S00G0	8.271	6.372

$f_{b7\text{-}28\text{-}100\text{-}90}$: the 90-days flexural strength of the samples with the pre-loading until the cracking of 100% on days 7 and 28.

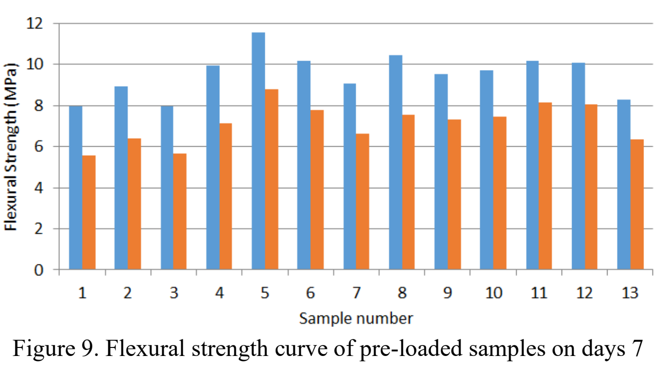

Figure 9. Flexural strength curve of pre-loaded samples on days 7 and 28 after 90 days.

Investigating the obtained values, the 90-day flexural strength of pre-loaded samples declines on days 7 and 28 by 20-30 % compared to the condition where pre-loading is absent. Such being a case has decreased compared to previous conditions with a single pre-loading step. Sample 1 (merely containing steel fibres) has the maximum decline level, and samples 11 and 12 (containing two types of pozzolan and fibres) have the minimal decline value in flexural strength among samples. Comparing the designs containing composite fibres indicates that those containing pozzolan designs have a lower decrease in flexural strength than those without pozzolan. Also, design 12, containing both types of silica fume and zeolite pozzolan, has a lower decrease in strength compared to designs merely using a single type of pozzolan. Investigations demonstrate that increasing the fibres diminishes the declining level of flexural strength in the presence of pre-loading. Also, compared to the designs merely containing steel fibres, those containing two types of fibres (steel and glass) have lower strength decline in the presence of pre-loading.

HIGHLIGHT RESULT

The flexural strength of 7, 28 and 90 days of all samples except the sample without silica and zeolite and the lowest percentage of steel and glass fibres (sample 1) is higher than the control sample. Also, in the flexural strength of preloaded specimens at the 7 days age, all specimens except those without silica and zeolite and with the lowest percentage of steel and glass fibres (samples 1 and 3), have a higher flexural strength of 28 and 90 days than the control sample. This trend is observed in 28-day preload for 90-day flexural strength and also in 7-day and 28-day preloads for calculating 90-day flexural strength. The 90-day flexural fracture energy of different designs pre-loaded at different ages is indicated in Fig. 10.

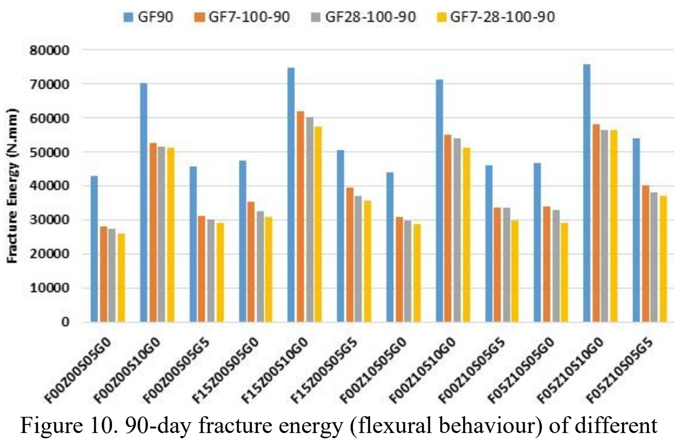

Figure 10. 90-day fracture energy (flexural behaviour) of different designs pre-loaded at different ages.

The substantial reduction of fracture energy after the damage is the first important point in Fig. 10. However, the damage age does not make any difference in the samples' fracture energy on day 90. In general, designs containing 1 % of steel fibres have maximal fracture energy, indicating the fibres' proper performance. After being damaged, the trend is not different; it seems that the cracking in fibre designs does not necessarily contribute to the disruption in energy variations. The flexural fracture energy of the pre-loaded samples at different ages on day 90 is indicated in Fig. 11.

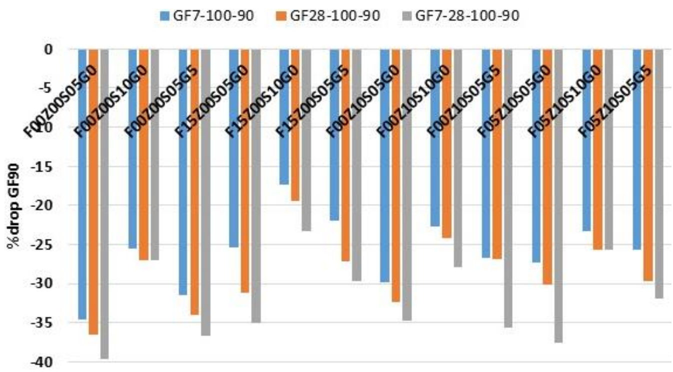

Figure 11. Reduction of fracture energy (flexural behaviour) on day 90 among pre-loaded samples at different ages, compared to samples not being pre-loaded.

Respective results to the fracture energy are substantially different from flexural strength. According to the results, it can be seen that the ash 15 % design has the least decline, and this difference is at least 7.6 % apart from the damaging age. However, the difference would be lower in the two-step pre-loading, and the silica fume would lose the regeneration chance. Although the designs containing zeolite have paved the way for the regeneration of flexural strength, and they had a competition with the silica fume 15 %, we can assert that in terms of fracture energy, the silica fume is accompanied by more regeneration. In the design with the composite pre-loading, where the silica fume decreases, the difference among results would be lowered by reducing silica fume, indicating that the zeolite has a more pivotal part in reconstructing the cracks shorter periods.

CONCLUSION

According to the conducted studies, the obtained results from the experiments are provided below.

As a general result in pre-loading, the flexural strength of all samples except those without silica and zeolite and the lowest percentage of steel and glass fibres is higher than the control sample.

In the designs without pozzolan and despite pre-loading, increasing the steel fibres increases the flexural strength, while increasing glass fibres has not substantially impacted the flexural strength enhancement.

Regarding the samples containing composite fibres, it can be seen that their 28-day flexural strength decreases before the pre-loading 100 % on day 7. However, regarding the flexural strength of pre-loading, 80 % of samples 3 and 6 (without zeolite) decline, and declined for samples 9 and 12 (containing zeolite).

Regarding 28-day pre-loaded samples after 90 days, the presence of pozzolan, particularly two types of silica fume and zeolite pozzolan, in the samples design under the pre-loading condition until cracking period, shows better performance and a lower level of its initial flexural strength.

Regarding the 28-day pre-loaded samples after 90 days, comparing the two designs containing composite fibres, one containing silica fume and the other containing zeolite, indicates a lower decline level of flexural strength in the design containing zeolite.

Regarding the 28-day pre-loaded samples after 90 days, the strength decline level is lowered by increasing the fibres in the design. However, replacing a part of steel- with glass fibres (using composite fibres) lowers the percentage of strength decline.

Regarding the pre-loaded samples at ages 7 and 28 days after 90 days, comparing the designs containing composite fibres indicates that pozzolan designs have a lower reduction in flexural strength than those without pozzolan.

Regarding the pre-loaded samples at ages 7 and 28 days after 90 days, the investigations indicate that increasing the fibres lowers the flexural strength decline level under the pre-loading condition.

Regarding pre-loaded samples at ages 7 and 28 days after 90 days, the designs containing two types of fibres (glass and steel) have lower strength decline under the pre-loading condition than those merely containing steel fibres.

In the design with composite pre-loading where the silica fume effect is mitigated, by reducing the percentage of silica fume, the results difference is declined, demonstrating that the zeolite has a more pivotal part in crack reconstruction in a shorter time.

Investigating the fracture energy level with pre-loading situation indicates that designs containing 1 % steel fibres have maximum fracture energy, thanks to the performance of the fibre. After being damaged, the trend is the same; it seems that the cracking in fibre designs does not necessarily contribute to the disruption in the energy variation trend.

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