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Disperse reinforced concrete: composition-structure-properties correlations

Authors:

Assoc.Prof. **Marin Amareanu**, PhD. Chem
Technical University of Civil Engineering of Bucharest
Faculty of Railways, Roads and Bridges
Bucharest, Romania
mirel.amareanu@utcb.ro

Assoc.Prof. **Larisa Melita**, PhD. Eng.
Technical University of Civil Engineering of Bucharest
Faculty of Railways, Roads and Bridges
Bucharest, Romania
larisa.melita@utcb.ro
Corresponding author

Research Paper

Marin Amareanu, Larisa Melita

Disperse reinforced concrete: composition-structure-properties correlations

This study focuses on the influence of metal fibres on the physical and mechanical properties of dispersed reinforced concrete with additions. The final aim is to design and obtain high-performance concrete. Mechanical strength is not always the primary requisite imposed on high-quality concrete. However, the durability provided by very low permeability and aggressive environment resistance can lead to high-performance concrete. Fly ash, granulated blast-furnace slag, and microsilica were used for concrete preparation, and metal fibres were used for disperse reinforcement. The effects of these additions and the presence of steel fibres are used to increase concrete ductility, its ability to absorb energy (to increase mechanical strength), and the improvement of general durability.

Key words:
concrete composition, dispersed reinforced concrete, metal fibers, mechanical strengths

Prethodno priopćenje

Marin Amareanu, Larisa Melita

Disperzivno armirani beton: korelacije između sastava, strukture i svojstava

U ovom radu istraživan je utjecaj čeličnih vlakana na fizikalna i mehanička svojstva disperzivno armiranog betona s dodacima. Konačni cilj je stvaranje i dobivanje betona visokih uporabnih svojstava. Mehanička čvrstoća nije uvijek primarni uvjet kod visokokvalitetnog betona. Međutim, trajnost betona koja je osigurana kroz vrlo nisku propusnost i otpornost na agresivno okruženje može voditi do betona visokih uporabnih svojstava. Za pripremu betona korišten je leteći pepeo, granulirana zgura iz visokih peći i silicijska prašina, a za disperzivnu armaturu čelična vlakna. Učinci ovih dodataka i prisutnost čeličnih vlakana koriste se za povećanje duktilnosti betona, njegovu sposobnost apsorpcije energije (za povećanje mehaničke čvrstoće) i poboljšanje opće trajnosti betona.

Ključne riječi:
sastav betona, disperzivno armirani beton, čelična vlakna, mehanička čvrstoća

1. Introduction

Dispersed-reinforced concrete is defined as concrete made of hydraulic cement with fine or large aggregates and discontinuous fibres [1] or concrete made of hydraulic cement with or without aggregates of different sizes, incorporating mainly discontinuous fibre reinforcements [2]. In Romania, dispersed reinforced concrete with metal fibres (BFM) is defined as a material obtained by mixing cement, aggregates, metal fibres, additives, mineral admixtures, and water in predetermined proportions, whose attributes are acquired by the hydration and strengthening of the cement and by the interaction between the metal fibres and the matrix [3].

Many studies have investigated the effects of mineral additions or metal fibres in concrete structures [4-10]. However, few studies have quantitatively investigated the cumulative effect of dispersed reinforcements and the influence of additives on the structure and properties of concrete [11-13].

Given the superior properties of dispersed reinforced concrete compared to conventional concrete, various additions, and metal fibres can be justified to improve the composition and structure of concrete without affecting the strengthening properties.

The primary aim of this study was to obtain high-performance concrete through compositional and structural changes and by dispersing the reinforcement. This study focused on obtaining concrete with homogeneous cement (CEM I 42.5) and various additions of fly ash, granulated blast-furnace slag, and microsilica. Subsequently, the influence of these additions on the hydration-hydrolysis processes of the cement was studied. Therefore, there is an obvious parallel between the ability of the components in the cement-admixture system to interact with water and their ability to develop mechanical strength after hardening. The influence of dispersion reinforcement on the physical and mechanical properties of concrete was also studied.

The role of fibre reinforcement in conventional or classical reinforced concrete is highlighted by controlling the cracking process, thus improving the mechanical strength and properties of energy absorption, impact resistance, wear resistance, fire resistance, shrinkage, and durability. In addition, the tangential stress values of the adhesion between the fibre and matrix were calculated from the appearance of the first visible cracks in the ultimate limit state, and the elasticity modulus values were determined using various mathematical calculus models. These results were compared with the experimental results.

2. Experimental

In this study, compositional changes in the studied concrete were made to achieve the proposed objectives by adding slag, ash, and microsilica admixtures.

2.1. Materials

The cement used to obtain the concrete was CEM I 42.5, and blast furnace slag, fly ash, and microsilica were added. The chemical and physical characteristics of CEM I 42.5 are presented in Table 1, and the chemical compositions of the additions [14] are presented in Table 2.

Table 2. Chemical compositions of used additions

<table>
<tr><td rowspan="10">CEM I 42.5 R</td><td colspan="11">Chemical composition [%]</td></tr>
<tr><td>LOI</td><td>CaO</td><td>SiO_2</td><td>SO_3</td><td>Al_2O_3</td><td>Fe_2O_3</td><td>MgO</td><td>Na_2O</td><td>K_2O</td><td>R_{ins}</td><td>Free CaO</td></tr>
<tr><td>2.11</td><td>63.72</td><td>20.13</td><td>3.09</td><td>4.49</td><td>3.28</td><td>2.35</td><td>0.30</td><td>0.91</td><td>0.20</td><td>0.90</td></tr>
<tr><td colspan="11">Mineralogical composition [%]</td></tr>
<tr><td colspan="2">C_3S</td><td colspan="3">C_2S</td><td colspan="3">C_3A</td><td colspan="3">C_4AF</td></tr>
<tr><td colspan="2">67.18</td><td colspan="3">11.768</td><td colspan="3">6.355</td><td colspan="3">9.97</td></tr>
<tr><td colspan="11">Physical characteristics</td></tr>
<tr><td colspan="3">Specific surface [cm^2/g]</td><td colspan="4">Stability [mm]</td><td colspan="4">Setting time [min.]</td></tr>
<tr><td colspan="3" rowspan="2">3198</td><td colspan="4" rowspan="2">0.0</td><td colspan="2">initial</td><td colspan="2">final</td></tr>
<tr><td colspan="2">165</td><td colspan="2">230</td></tr>
</table>

Tablica 2. Chemical compostions of used additions

Chemical composition / Composition [mass %]	Slag	Fly ash	Silica fume
LOI	3.56	3.08	2.85
SiO_2	34.23	56.24	87.88
Al_2O_3	11.01	22.44	2.96
Fe_2O_3	1.00	8.03	1.69
CaO	42.78	5.65	2.36
MgO	3.99	0.00	0.00
SO_3	0.33	1.33	0.94
Na_2O	0.81	0.56	0.21
K_2O	0.81	2.22	0.79
Mn_2O_3	0.83	0.00	0.00
Ins. rez. HCl-Na_2CO_3	1.05	0.00	0.00
Reactive SiO_2	u.d.	52.04	u.d.

Table 3. Main physical characteristics of used additions

Used additions / Physical characteristics	Slag	Fly ash	Silica fume
Moisture [%]	13.54	0.05	0.00
Density [g/cm³]	2.78	1.75	2.24
Volumetric weight [kg/m³]	750.2	650	

Table 4. Chemical modules for granulated blast furnace slag

Features / Chemical modules	Granulated blast furnace slag	Required conditions by SR EN 197-1
% ($CaO + SiO_2 + MgO$)	79.95	min. 66
% ($CaO + MgO$) / SiO_2	1.41	min. 1.0

Table 5. Properties of used steel fiber

Type of fiber	Density [g/cm³]	Tensile strength [MPa]	Elasticity modulus [GPa]	Length [mm]	Look ratio [lf/df]*
Corrugated fiber	7.8	2500	200	50	60

Other characteristics of the additives are shown in Tables 3 and 4 and Figures 1 to 3 respectively. The properties of the steel fibres used for concrete reinforcement are listed in Table 5.

In the obtained concrete, additives were introduced into the cement admixture. Fly ash, granulated blast-furnace slag, and silica are materials that, when combined with Portland cement, develop the hardened properties of concrete through their hydraulic influence, pozzolanic activity, or both.

2.1.1. Granulated blast-furnace slag

The slag was chemically analysed [15], and its chemical composition is listed in Table 2. The chemical moduli were calculated based on the chemical compositions. The obtained values are listed in Table 4 and compared with the requirements [16].

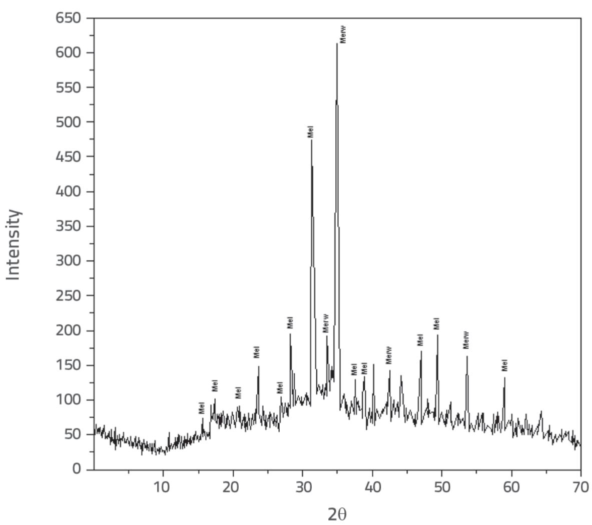

Figure 1. XRD analysis of the slag sample

From the data presented in Table 4, the slag used was within the conditions of admissibility imposed by SR EN 197-1.

In terms of mineralogy, the X-ray diffraction analysis of the slag sample, shown in Figure 1, indicated the presence of *mellilit (Mel)* and *merwinit (Merw)* compounds as the majority of crystalline phases.

In addition, X-ray diffraction analysis showed that the granulated slag sample contained 70 % amorphous phase, which is greater than the value for this type of material. Thus, in terms of the content of the amorphous phase (vitreous), the analysed granulated slag meets the requirements of SR EN 197-1.

2.1.2. Fly ash

The ash was obtained from Govora, Romania, a thermal power station equipped with a dry-capture system. The physical and chemical properties of the samples were analysed. The particle size distribution is shown as a granulometric curve in Figure 2.

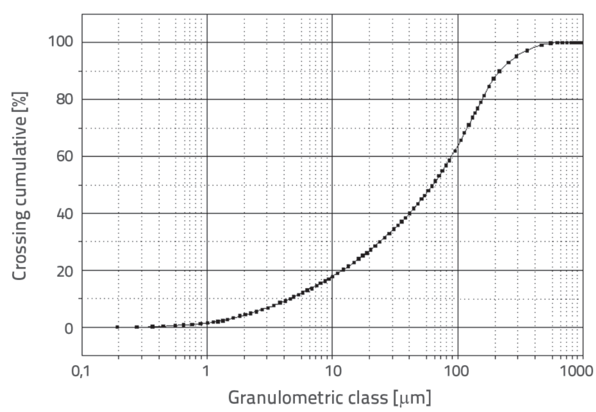

Figure 2. Granulation size distributions for Govora ash sample

From the data presented in Table 2, regarding fly ash, it can be stated that:

- The Govora fly ash fully complied with the conditions laid down in SR EN 197-1;

- The ash sample was of the silica–aluminous type, in which the sum of the (SiO_2 + Al_2O_3 + Fe_2O_3) acid oxides was greater than 70 %.

2.1.3. Microsilica

The granulometric characteristics of used silica are presented in Figure 3.

Microsilica has a very advanced fineness (Blaine specific surface ≈ 23750 cm^2/g) [17] resulting from the particle size distribution; the share of particles under 50 μm is ≈ 99 %.

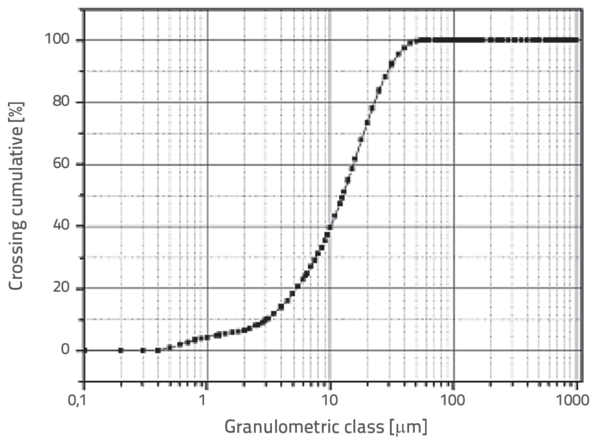

Figure 3. Granulation size distributions for silica fume sample

The data presented in Table 2, regarding microsilica, indicates that the:

Loss on ignition is below the permitted maximum of 4 %;

The sum of the SiO_2+Al_2O_3+Fe_2O_3 acid oxides was ≈ 92 %), indicating the material's excellent reactivity.

2.1.4. Steel fibers

The properties of the steel fibres used are listed in Table 5, and their shapes are shown in Figure 4.

Figure 4. Corrugated fibers

2.2. Terms and experimental procedure: Methods of calculation

To obtain concrete with slag, fly ash, and microsilica, the following composition was considered:

- Water / cement ratio, W/C ≈ 0.4
- Dosage of cement, 450 kg/m^3
- Addition (slag, fly ash, and silica), 20 % relative to cement
- Percentage of reinforcement, 2 %
- Super plasticiser (SP) additive Glenium 27 BASF, 1 % vs. cement
- Freeze-thaw resistance, 100
- Entrapped air, 2 %
- River aggregate sorts, (0-4) of 52 %, and (4-8) of 48 %.

The required quantities to obtain 1 m^3 of concrete are presented in Table 6. All types of obtained concrete were dispersing reinforced. Batches of concrete were made using the necessary quantities according to Table 6 to make the concrete volume adequate for manufacturing three prismatic specimens (10 × 10 × 55 cm) for each type of concrete obtained: conventional and disperse-reinforced.

For all the studied systems, mechanical strength tests were carried out on three prismatic specimens. Each specimen was prepared using the materials presented above with a W/C ratio of 0.4 constant. The flexural strength f_f was determined for all the prisms, and the compressive strength f_c was determined for the prism heads.

Prismatic samples for mechanical strength determination according to SR EN 12390-4:2002 - Test on hardened concrete. Part 4: Compressive strength and SR EN 12390-5:2019 - Test of hardened concrete. Part 5: The bending strengths of the test specimens were maintained in air for 7, 14, and 28 days. The variation in the mechanical strengths of the dispersed reinforced concrete, compared to conventional concrete, was calculated using Eq. (1).

$$f = \frac{f_{reinforced} - f_{conventional}}{f_{reinforced}} \cdot 100\ [\%] \tag{1}$$

where:

$f_{reinforced}$ – the mechanical strength (f_f, f_c) of reinforced concrete samples;

$f_{conventional}$ – the mechanical strength (f_f, f_c) of conventional concrete samples.

According to Thoman and Raeder [18] and other researchers [19-27], the elasticity modulus as the slope of the tangent to the stress-strain curve was determined under uniaxial compression and calculated to be 25 percent of the maximum value of the stress. The elasticity modulus was calculated according with relation (2).

In this study, the stress-strain curve of the studied concrete was obtained under stress from axial compression. The tests were conducted on cylindrical samples (diameter ϕ = 150 mm and height h = 300 mm) using the Advantest 9 CONTROLS universal testing machine with the following characteristics : range of operation: 3000 kN, purpose: compressive strength, elasticity modulus of concrete, accuracy - 0,1 kN. For normal-weight concrete, a correlation between the elasticity modulus, E_c, and compressive strength, $f_c^{'}$ has been reported [26] and is presented in Eq. (2):

$$E_c = 3320 \times \sqrt{f_c^{'}} + 6900\ [MPa] \tag{2}$$

for: 21 MPa < $f_c^{'}$ < 83 MPa.

Table 6. Materials for 1m³ of concrete with slag, ash and silica fume additions

Compositions	Cement [kg/m³]	Water/ binder ratio	Water/ cement ratio	Addition of superplasticizer [L]	Aggregates		Slag [kg]	Fly ash [kg]	Silica fume [kg]	Metallic fibers [kg]	Calc. density [kg/m³]
					(0-4)	(4-8)					
I. Reference concrete											
1. Conventional concrete	450	0.4	0.4	4.5	944	872					2446
2. Disperse reinforced concrete	450	0.4	0.4	4.5	944	872				157	2603
II. Concrete with slag											
1. Conventional concrete	450	0.34	0.4	4.5	899	829	90				2448
2. Disperse reinforced concrete	450	0.34	0.4	4.5	899	829	90			157	2605
III. Concrete with fly ash											
1. Conventional concrete	450	0.34	0.4	4.5	872	805		90			2397
2. Disperse reinforced concrete	450	0.34	0.4	4.5	872	805		90		157	2554
IV. Concrete with silica fume											
1. Conventional concrete	450	0.34	0.4	4.5	938	767			90		2425
2. Disperse reinforced concrete	450	0.34	0.4	4.5	938	767			90	157	2582

The tangential bond stress between the fibre and matrix was calculated using the equations proposed in [28-30]. For reinforced elements with dispersed fibres subjected to flexure, the flexural tensile strength of the composite material f_{tf}^{f} can be expressed as

$$f_{tf}^{f} = A \cdot (1-\mu) \cdot f_{tf} + C \cdot \mu \cdot \sigma_f \quad (3)$$

where:
A - coefficient which considers the change in the load and unit stress diagram in the elongated area
μ - volumetric percentage of reinforcement
f_{tf} - flexural tensile strength of the matrix
C - efficiency coefficient of the length
σ_f - Longitudinal bond stress.

Considering that: $C \cdot \mu \cdot \sigma_f = 0.82 \cdot \tau_m \cdot \mu \cdot l/d$, relation (3) becomes:

$$f_{tf}^{f} = A \cdot (1-\mu) \cdot f_{tf} + B \cdot \mu \cdot \frac{l}{d} \quad (4)$$

where:
B - coefficient which depends by the tangential bond stress, τ_m.

The authors mentioned above determined the following relations by processing the experimentally obtained data.

a) The flexural tensile strength f_{tif}^{f} of the material at the occurrence of the first crack is expressed as follows:

$$f_{tif}^{f} = 0{,}843 \cdot (1-\mu) \cdot f_{tf} + 0{,}82 \cdot \tau_f \cdot \mu \cdot \frac{l}{d} \quad (5)$$

b) The flexural tensile strength, f_{til}^{f} of the material at ultimate limit state:

$$f_{til}^{f} = 0{,}97 \cdot (1-\mu) \cdot f_{tf} + 3{,}41 \cdot \tau_l \cdot \mu \cdot \frac{l}{d} \quad (6)$$

where:
τ_f - tangential bond stress between the fibres and matrix at the occurrence of the first crack
τ_l - tangential bond stress between the fibres and matrix in the ultimate limit state.

Therefore, to assess the flexural tensile strength of fibre-reinforced elements, Eq. (4) can be used, where the B parameter depends on the concrete quality. The validity of this relationship is also limited by the (μ·l/d) parameter.

In this study, the tangential bond stress between the fibres and matrix was calculated using Equations (5) and (6) and was experimentally determined from the flexural tensile strength of the dispersed reinforced concrete at the occurrence of the first crack and the ultimate limit state [31].

3. Results and discussions

The mechanical strength variations (compression f_c, and flexural f_f) during the hardening process (up to 28 days) [32] of the studied concretes are presented in Table 7.

The influence of the addition type on the evolution of the mechanical strength (f_c, f_f) during the hardening process (up to 28 d) of the studied concretes is presented in Figures 5 to 8.

Table 7. Variation of mechanical strengths during the curing process (up to 28 days) for concretes: conventional and reinforced with 2 % (vol. %) metal fibers

Compositions	Curing time [days]	f_c [MPa]			f_f [MPa]			Flexural strength f_f [MPa] of dispersed reinforced concrete on first cracks		
		7	14	28	7	14	28	7	14	28
I. Reference concrete	1. Conventional concrete	59.05	59.70	71.90	9.60	10.40	11.70			
	2. Disperse reinforced concrete	68.75	71.10	85.95	15.35	17.50	20.40	10.3	12.2	15.1
II. Concrete with slag	1. Conventional concrete	59.85	60.80	72.05	9.75	10.45	11.70			
	2. Disperse reinforced concrete	62.35	64.85	86.90	15.00	19.20	21.10	10.0	12.9	15.3
III. Concrete with fly ash	1. Conventional concrete	62.05	65.55	72.50	10.65	11.35	14.75			
	2. Disperse reinforced concrete	63.15	66.70	87.80	14.85	23.45	26.95	10.67	16.9	19.6
IV. Concrete with silica fume	1. Conventional concrete	68.45	75.00	88.45	9.95	10.80	14.30			
	2. Disperse reinforced concrete	69.40	85.60	93.45	15.85	19.95	25.80	10.9	14.9	18.9

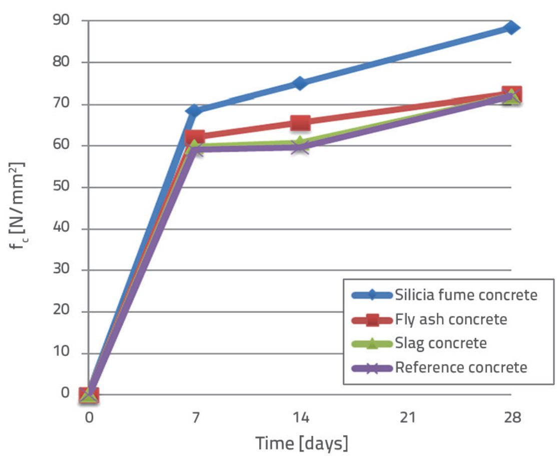

Figure 5. Additions type influence on compressive strength evolution during the curing time for conventional concrete

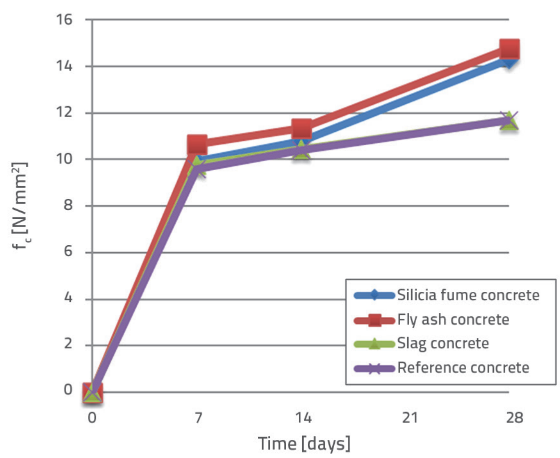

Figure 6. Additions type influence on flexural strength evolution during the curing time for conventional concrete

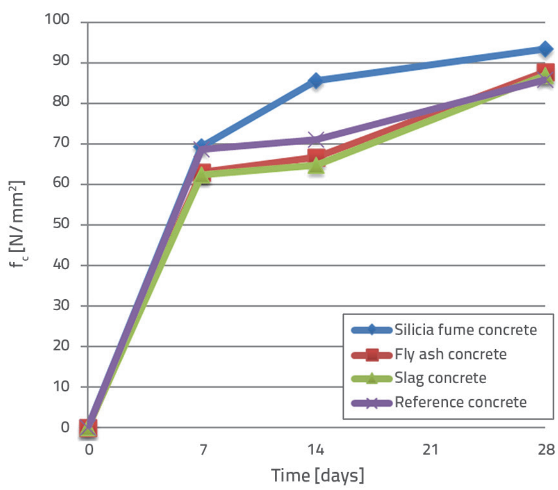

Figure 7. Additions type influence on compressive strength evolution during the curing time for reinforced concrete

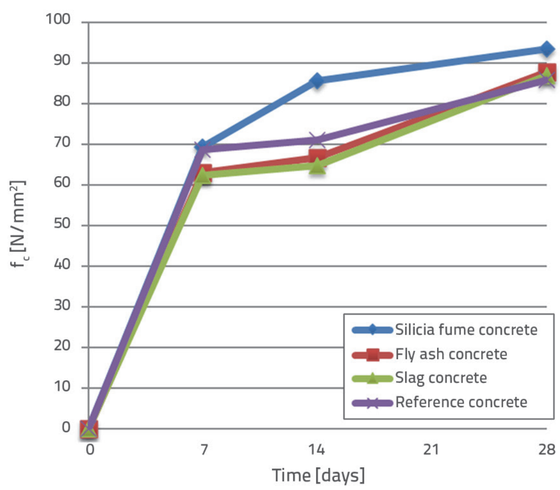

Figure 8. Additions type influence on flexural strength evolution during the curing time for reinforced concrete

According to Figures 5 and 7, for conventional and dispersed reinforced concretes, there is a relatively similar behaviour: for the concrete made with slag and ash additions subjected to compressive tests, the mechanical strengths showed no significant increase compared to the reference sample; the concrete made with microsilica addition is distinguished from other concretes by a considerable increase in the strengths throughout the hardening process (up to 28 days).

Figures 6 and 8 for the conventional and dispersed-reinforced concretes with microsilica and fly ash additions significantly increase the flexural strength compared with the reference concrete and concrete with slag addition. The mechanical strength increase, as shown in Figures 5 to 8, can be assigned to the possible occurrence of calcium hydrous silicates in a higher quantity in the concretes with microsilica and fly ash additions, as opposed to the concretes with slag addition and the reference sample. The positive effect of microsilica on mechanical strength is due to the densification of the transition area between the aggregate and matrix by compositional and textural changes in this area. The microsilica particles were nucleation germs for $Ca(OH)_2$ crystallisation [33].

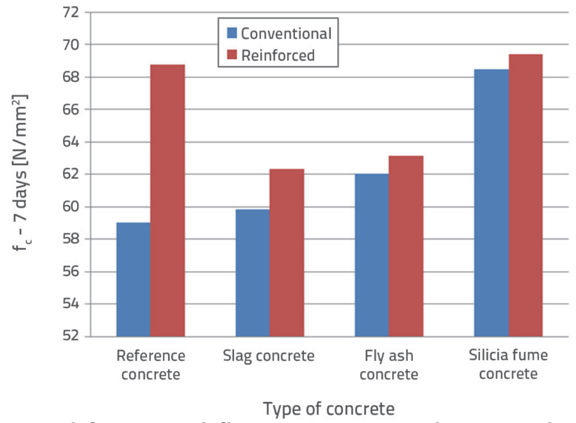

Figure 9. Reinforcement influence on compressive strength of concrete, calculated at 7 days

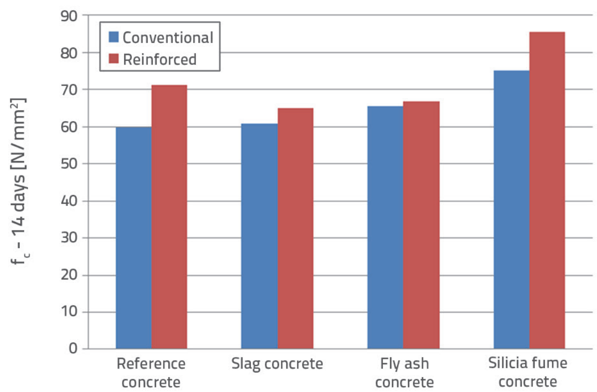

Figure 10. Reinforcement influence on compressive strength of concrete, calculated at 14 days

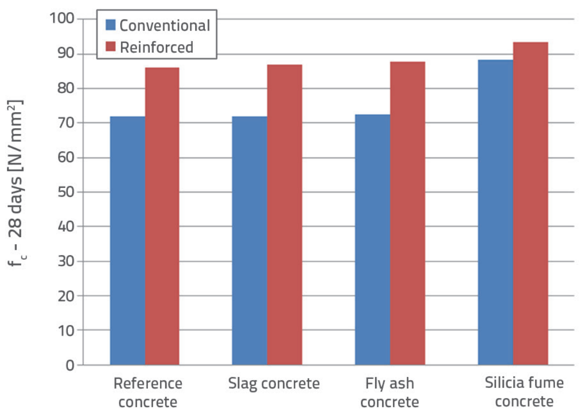

Figure 11. Reinforcement influence on compressive strength of concrete, calculated at 28 days

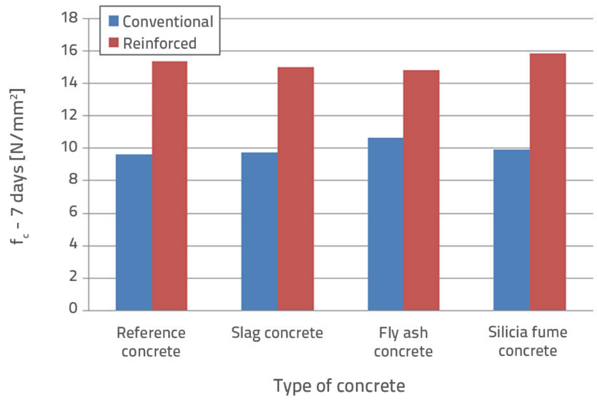

Figure 12. Reinforcement influence on flexural strength of concrete, calculated at 7 days

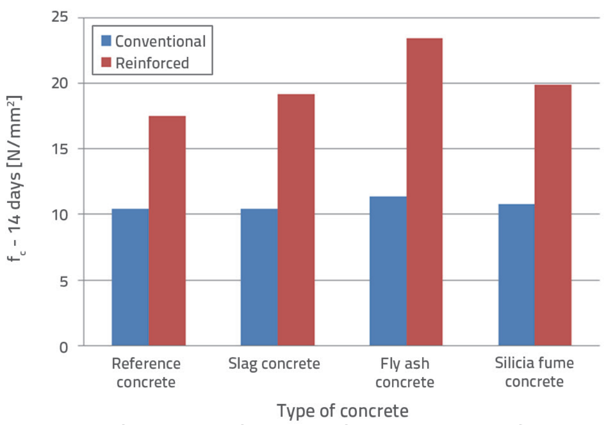

Figure 13. Reinforcement influence on flexural strength of concrete, calculated at 14 days

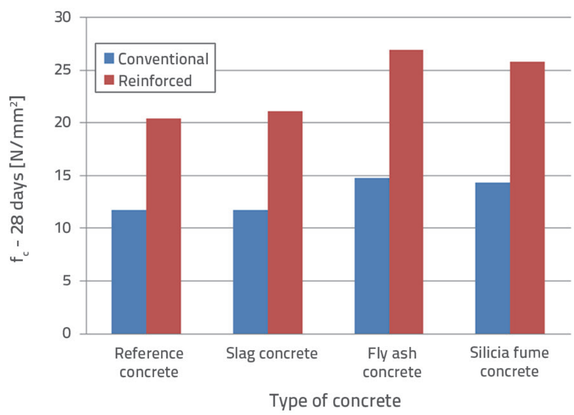

Figure 14. Reinforcement influence on flexural strength of concrete, calculated at 28 days

The effects of reinforcement on the mechanical strength (f_c, f_f) evolution of the studied concretes are presented in Figures 9 to 14, respectively.

In Figures 9 to 11, similar behaviour of the dispersed reinforced concrete subjected to compression can be observed for conventional concrete, except for the reference sample at the initial curing time (7 days). In this case, a significant increase in mechanical strength was observed using dispersed reinforcement compared with the same conventional concrete samples. This can be attributed to the faster evolution of the crystallinity degree of the hydro-compounds in the reference sample without additives compared to the evolution of the crystallinity degree of the hydro-compounds in systems with significantly higher additives. Thus, the adherence between the metallic fibres and the matrix in this initial range (up to 7 days) in the reference sample was improved compared to the concrete with additions.

The increase in the mechanical strength of dispersed reinforced concrete compared to conventional concrete is presented in Figures 9-14 and has also been highlighted by other researchers [26, 27, 30, 32]. According to Table 7, the mechanical strength values obtained for these concretes fell within the high-performance concrete (HPC) category.

3.1. The breaking mode of the studied concrete

The failure mechanism of the dispersed reinforced concrete samples was different from that of the conventional concrete samples. A sudden drop in the bearing capacity was observed in conventional concrete, with the appearance and propagation of the first crack. This value was exceeded in the case of the dispersed reinforced concrete. For this concrete, as the cracks open, the fibres succeed in shifting the efforts to the opposite side of the matrix, thereby increasing its bearing capacity.

The crack characteristics of the dispersed reinforced concrete are significantly different from those of conventional concrete. The cracks occur at the maximum load level, according to the tensile strengths; they have a homogenous distribution in the matrix mass and develop with smaller openings toward conventional concrete, as evidenced by other researchers [27, 34-36].

The unreinforced beams yielded suddenly with the appearance of the first cracks and concrete bearing a brittle fracture (especially in the case of stress to obtain the bending strength values). In dispersed reinforced concrete, more beam cracks were observed, the tensile strength was superior, and the strength increased after the appearance and development of cracks in the concrete structure. Owing to the different stress distributions in the contact areas between the aggregate and matrix in the unreinforced concrete (BIR), a less developed network of cracks is obtained. The low-stress redistribution capacity led to the spread and development of cracks, followed by a sudden rift in the concrete. he ductile behaviour of this type of concrete was improved by dispersing it with metallic fibres.

By dispersing the BIR concrete, the efforts in the contact area between the aggregate and matrix were evenly distributed owing to the better cooperation between the aggregate, matrix, and metallic fibres. A network of cracks began to develop at a specific stress intensity level. When the tension rises, some of the applied energy is consumed to increase this crack network and provide an internal redistribution of stretching in the concrete structure, leading to its rift. This can be attributed to the excellent adhesion of the fibre matrix, as shown in Figure 15.

Figure 15. Fracture and fibre–matrix adhesion

When the load increases, the fibres act as arresters of the openings of the crack, similar to the effect of large aggregates in conventional concrete. In this situation, slight crack propagation occurs simultaneously with the destruction of the fibre–matrix adhesion [37]. The matrix and fibres cooperate until breaking, which contributes to material strength.

Owing to the bending tensile stress, the ductility of dispersed reinforced concrete with metallic fibres was higher than that of concrete without fibres. In addition, a certain reserve of strength was observed after the peak load due to adhesion between the fibre and matrix. The "sewing" effect of the cracks (Figure 15), especially during the diffuse cracking, was mentioned [38]. This delays the emergence and development of cracks in the structure, thereby increasing the strength and ductility of the material.

3.2. Mechanical properties of the studied concrete

The flexural tensile strength of fibre-reinforced concrete depends on the concrete matrix and the fibre dosage used for reinforcement. From the data and figures presented above, an increase in the matrix crack strength compared to the matrix of conventional concrete can be observed. In Table 8, the values of the tangential bond stress between the fibres and matrix are calculated from the appearance of the first visible crack to the ultimate limit state in the dispersed reinforced concrete using Eqs. (5) and (6), and the data from Table 7 are presented.

In Table 9, the evolution of the concrete hardening processes, expressed by variation of f_c / $f_{c(28\ days)}$ and f_f / $f_{f(28\ days)}$ ratios during the study (28 days), is presented. According to data from Table 9, the development stages of the hardening processes are: first stage – the development is fast (up to 7 days) and second stage

Table 8. Tangential bond stress τ between fibers and matrix

Compositions	τ [N/mm²]	Curing time [days]		
		7	14	28
I. Reference concrete	τ_f	6.3	7.74	9.43
	τ_l	2.41	3.67	5.52
	Δτ	3.92	4.07	3.91
II. Slag concrete (reinforced)	τ_f	5.82	9.42	10.14
	τ_l	1.98	4.34	5.73
	Δτ	3.84	5.08	4.41
III. Fly ash concrete Fly ash concrete (reinforced)	τ_f	4.80	12.87	13.14
	τ_l	1.90	7.65	7.53
	Δτ	2.90	5.22	5.61
IV. Silica fume concrete (reinforced)	τ_f	6.50	9.84	12.40
	τ_l	2.72	6.07	7.20
	Δτ	3.78	3.77	5.20

Table 9. Variation of $f_t/f_{t\,(28\,days)}$* ratio for studied concrete samples

Compositions / Curing time [days]		f_c/f_c (28 days)			f_f/f_f (28 days)		
		7	14	28	7	14	28
I. Reference concrete	1. Conventional concrete	0.821	0.830	1	0.821	0.889	1
	2. Disperse reinforced concrete	0.800	0.827	1	0.752	0.858	1
II. Slag concrete	1. Conventional concrete	0.831	0.844	1	0.833	0.893	1
	2. Disperse reinforced concrete	0.717	0.746	1	0.711	0.910	1
III. Fly ash concrete	1. Conventional concrete	0.856	0.904	1	0.722	0.769	1
	2. Disperse reinforced concrete	0.719	0.760	1	0.551	0.870	1
IV. B Silica fume concrete	1. Conventional concrete	0.774	0.848	1	0.696	0.755	1
	2. Disperse reinforced concrete	0.743	0.916	1	0.614	0.773	1

*f_t – mechanical strengths (f_c, f_f) of studied concrete at 7, 14 and 28 days; *f_t (28 days) – mechanical strengths (f_c, f_f) of studied concretes at 28 days

Table 10. Variation of mechanical strengths (Δf_c, Δf_f) for conventional concrete against reinforced concrete

Compositions / Curing time [days]	Δf_c [%]			Δf_f [%]		
	7	14	28	7	14	28
I. Reference concrete	14.11	16.03	16.35	37.45	40.57	42.65
II. Slag concrete	4.01	6.25	17.09	35.00	45.57	44.55
III. Fly ash concrete	1.74	1.72	14.43	28.28	51.60	45.27
IV. Silica fume concrete	1.37	12.38	5.35	37.22	45.86	44.57

Table 11. Values of elasticity modulus: calculated, $E_{c\,calc}$ and experimental, $E_{c\,exp}$ at 28 days

Compositions	$f_{c\,(28\,days)}$ [MPa]	$E_{c\,calc.}$ at 28 days [GPa]	$E_{c\,exp.}$ at 28 days [GPa]
I.1. Reference concrete (conventional)	71.9	35.051	49.015
I.2. Reference concrete (reinforced)	85.95	37.679	57.850
II.1. Slag concrete (conventional)	72.05	35.080	49.350
II.2. Slag concrete (reinforced)	86.9	37.849	57.940
III.1. Fly ash concrete (conventional)	72.5	35.168	49.650
III.2. Fly ash concrete (reinforced)	87.8	38.008	58.230
IV.1. Silica fume concrete (conventional)	88.45	38.123	58.124
IV.2. Silica fume concrete (reinforced)	93.45	38.994	66.314

– a slower growth of the mechanical strengths after 7 days of hardening is observed.

In Table 10, the mechanical strength variation for the reinforced concrete against that of conventional concrete at the studied time periods, calculated according to Eq. (1), is presented.

A steady increase in the difference between the mechanical strengths of the dispersed reinforced concrete and unreinforced concrete was observed throughout the hardening period (28 days). Silica fume concrete, for which the difference in compressive strengths between the reinforced concrete and unreinforced concrete after 14 days is higher than that after 28 days, is an exception.

The values of the calculated elastic modulus, obtained using Eq. (2), and the values of the experimental modulus at 28 days are presented in Table 11.

There are major differences between the real and calculated values of the elasticity modulus in relation to 2. The real values rank the studied concretes in the category of high-performance concretes (HPC) [39-42].

4. Conclusions

The presented data shows that by using additions of slag, ash, and microsilica in the concrete composition, the physical and mechanical characteristics of the obtained concretes significantly increased against the reference concrete in terms of flexural and compressive stress and elastic modulus.

The increase in the mechanical strength of the concrete with additions was due to the densification of the transition zone between the aggregate and matrix through compositional and textural modifications of this zone. Table 8 summarises these effects. The concretes with disperse-reinforcement additions showed an increase in the tangential bond stress between the fibres and matrix compared to those with dispersed reinforcement without additions.

The influence of the addition on the active hydraulic properties of the structure and the strength properties of the reinforced concrete is explained by the overlapping of two effects: the filler and pozzolanic effects. Thus, densification of the cement stone and modification of its composition by calcium hydroxide were observed. The formation of weakly basic hydrosilicates, with a higher degree of polymerisation, is more stable and essential in the transition areas of aggregate–cement stone and fibre–cement stone.

The extremely low porosity of the hydrated cement paste was different from that of conventional concrete (reference sample). Thus, unbound water induces an open pore network, which reduces the density of the cement matrix and leads to a lower compressive strength.

The results presented regarding the increase in the mechanical strengths in the case of dispersed reinforced concrete are due to both the densification of the structure and the different breaking modes compared to conventional concretes. For dispersed reinforced concrete, as the cracks open, the fibres, through their sewing effect, increase the ductility and load-bearing capacity (the strength increases even after the appearance and development of cracks in the concrete structure). The unreinforced beams suddenly gave way with the appearance of the first cracks, and the concrete bore a fragile rift.

Fibre reinforcement is an efficient technique for improving the flexural strength of cement-based composite materials.

A combination of improved efforts and ductile behaviour is required to achieve high performance in concrete flexure. Therefore, it is recommended to reinforce high-performance composites with fibres. Through dispersion reinforcement, the effective control of microcracks was achieved, which increased the mechanical shock strength, durability, and service life of the obtained concrete.

The elasticity modulus of the concrete, tangential bond stress between the fibre and matrix, breaking mode, and flexural strength of the dispersed reinforced concrete at the first cracks were comparable to the results obtained and explained by other researchers [16-23] in their works. These results indicate that the proposed approach is applicable for predicting the mechanical properties of the dispersed reinforced concrete.

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