Study of Early Age Behavior of Fiber-Reinforced Cement-Based Materials Containing Expansive Agent

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ABSTRACT: Aim of this experimental work was to characterize the early-age behavior of several Fiber-Reinforced Cement-based Composites (FRCCs) containing CaO-based expansive agent. The influence of different amounts of fibers (namely 2.0%, 1.75% and 1.5% by volume of FRCC) on the mechanical performance of FRCCs was investigated. The attention was focused on the strength development at early ages, with tests carried out at 0.25 (i.e. 6 hours, corresponding to time of demolding), 1, 2, 7 up to 28 days of curing. FRCCs were characterized at both fresh and hardened state, by measuring fresh consistency as well as compressive and flexural strength up to 28 days on prismatic specimens. The addition of different amounts of fibers did not influence the values of compressive strength, while there is a difference of about 4 MP in terms of 28-day residual flexural strength between the mixture with 1.5% and 2% of fibers. A minimum value of 20 MPa was achieved for the 28-day peak flexural strength in all cases.

1 INTRODUCTION

Cement-based materials (i.e. mortars and concretes) are the most widely used construction materials because they offer outstanding economic efficiency compared to other construction materials, as well as remarkable mechanical performances and durability. However, cement-based materials also involve some problems, such as low strength (especially in bending) compared to their weight, and brittleness. Recently, research for the development and practical use of FRCCs, and especially UHPCs, has been actively carried out to solve such problems.

The addition of expansive agent on plain concrete (without fibre reinforcement) proved to be able to increase compressive strength a little, to leave the same flexural strength, and above all to produce initial expansion with consequent reduced final shrinkage at long ages (Chatterji, 1995; Neville, 1995; Corinaldesi, 2012).

Moreover, an interesting application is that of the so-called Chemical Prestressed Reinforced Concrete (CPRC), which is obtained by adding expansive agent to the mix, without fibre reinforcement (Sahamitmongkol & Kishi, 2011a, 2011b). Sahamitmongkol & Kishi found a certain compressive prestress effect due to the external constraint offered by the reinforcement bars to the expanding cement matrix, which was able to increase the flexural behaviour. However, this reinforcement, which was localized (and not diffused), did not allow to fully utilize the prestress effect because it involved only a small portion of material, that was the thin layer located nearby the reinforcement bars. In theory, it would have been much more effective a fibrous reinforcement uniformly distributed throughout all the portion of material undergoing tensile stress when put in bending.

Nevertheless, the study of concrete containing both short fibre reinforcement and expansive agent in the cement mixture has been quite limited until now (Sun et al, 2001; Tuotanji, 1999; Huang et al., 2011; Aiguo et al., 2011; Cao et al., 2013; He et al. 2011),

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and this combination has been mainly investigated with the aim of reducing autogenous shrinkage more than of improving mechanical performance in bending.

Sun et al. (2001) showed that the incorporation of expansive agent with proper content made the interfacial strength between shrinkage resisting components (aggregates and fibres) and cement paste improved, especially in the early hydration period. They found improved pore structure of concrete, as well as improved shrinkage resistance and impermeability of concrete.

Toutanji (1999) showed that the effect of expansive agent combined with a SRA in the presence of polypropylene fibres has led to a slight decrease of: compressive strength, splitting tensile strength and elastic modulus.

Huang et al. (2011) studied a cementitious mixture in order to produce a shotcrete that contains both expansive agent and short steel fibres. They noticed an improvement of 28-day flexural strength without reaching values greater than 7 MPa indeed.

Aiguo et al. (2011) studied a cementitious mixture containing magnesium oxide as expansive agent and steel fibres. They noticed some improvement of splitting tensile strength (+38%). Cao et al. (2013) produced a lightened high-strength mixture by using both high-modulus steel fibres and expansive agent in which a certain synergic effect of expansive agent and steel fibre was detected in terms of flexural strength.

He et al. (2011) found that, by adding an expansive agent to cement-based materials reinforced by steel bars and/or steel fibres, it can be produced the so-called 'self-stressing cement', in which the expansion after cement hydration is so significantly restrained that the steel bars/steel fibres are tensioned, and able to create compressive pre-stresses in cross section, usually in the range 3-6 MPa.

Finally, Corinaldesi et al. (2015a; 2015b) found that the use of CaO-based expansive agent can enhance flexural strength of FRCCs, especially if used with either brass- and zinc-coated hooked fibres (Corinaldesi & Nardinocchi, 2016a) or ribbon-shaped metallic fibers (Corinaldesi & Nardinocchi, 2016b).

2 RESEARCH SIGNIFICANCE

The scope of this work was to evaluate the influence of different amounts of fibers on the mechanical performance of concretes containing CaO-based expansive agent. Mixtures were reinforced with three different amounts of hooked brass-coated fibres: 156, 137, 118 kg/m^3 corresponding to percentages of 2%, 1.75% and 1.5% by volume of concrete, respectively.

The attention was particularly focussed on the early ages: 0.25 (6 hours, corresponding to demoulding), 1, 2, 7 and 28 days of wet curing. In particular, the information collected after only 6 hours are important if application in precast concrete plant of these mixtures is considered (e.g. Robinson et al., 2013).

3 MATERIALS AND METHODS

Commercial portland cement, type CEM I 52.5 R, according to EN-197/1 was used. The Blaine fineness of cement was 0.48 m^2/g and its relative specific gravity was 3.15.

Well-graded very fine quartz sand was used as aggregate, with particle size up to 4.0 mm. Moreover, 120 kg/m^3 of silica fume (SF) with grain size smaller than 1 μm, obtained as industrial by-product of the silicon processing, was used. Silica fume powder had a specific surface area of about 18 m^2/g, evaluated by means of BET surface method, and a relative specific gravity of 2.20.

A limestone filler made of calcium carbonate was used at a dosage of 55 kg/m^3 in order to obtain a volume of very fine particles (all those with grain size under 0.150 mm) of about 250 litre per m^3 (including also silica fume and cement). These mineral additions were necessary (besides high dosage of superplasticizer) in order to obtain high fluidity without segregation.

Hooked brass-coated steel (Br) fibers (30-mm long, 0.50 mm diameter) were used, with ann aspect ratio of 60, relative specific gravity of 7.82, and elastic modulus of 210 GPa.

Dead-burnt calcium oxide (CaO) was used at a dosage of 40 kg/m^3: usually values between 30 and 50 kg/m^3 are recommended to use the CaO as an expansive agent (Chatterji, 1995; Neville, 1995; Collepardi et al., 2005; Collepardi et al., 2008).
The mixture proportions are shown in Table 1.

Table 1. Mixture proportions (kg/m^3)

Dosage (kg/m^3)	Br-2%	Br-1.75%	Br-1.5%
w/c	*0.34*	*0.34*	*0.34*
Cement	*590*	*595*	*595*
Water	*203*	*205*	*205*
Sand (0-4 mm)	*1275*	*1280*	*1285*
Superplasticizer	*15*	*15*	*15*
Silica Fume	*120*	*120*	*120*
Brass fibers	*156*	*137*	*118*
Limestone filler	*55*	*55*	*55*
Expansive Agent	*40*	*40*	*40*

All the mixtures were prepared with the same w/c ratio of 0.34 and sand/cement ratio of 2.16, as well as the same dosage (2.5% by weight of the cement) of a 27% aqueous solution of carboxylic acrylic ester polymer based superplasticizer.
Workability of fresh mixtures was evaluated by means of the flow table according to EN 1015-3 (Determination of consistence of fresh mortar by flow table, 1999), and all fresh mortars had a consistency corresponding to S5 class (i.e. slump more than 210 mm). All the specimens have been demoulded after six hours (just after the end of the setting time, in order to avoid expansion occurrence within steel forms). After two days of wet curing they were exposed to a dry environment at a constant temperature of 20°C up to 28 days.
Two prismatic specimens (100 x 100 x 400 mm) and three cubic specimens (100 x 100 x 100 mm) were manufactured for each FRCC mixture and for each curing time in order to evaluate their mechanical behavior. They were cast in steel forms (vibrated for 15 seconds after casting, i.e. till air bubbles stopped).
Flexural strength of FRCCs was evaluated after 0.25, 1, 2 and 7 days of curing, according to EN 12390-5 (Testing hardened concrete: flexural strength of test specimens, 2002) on two prismatic specimens for each mixture and curing time with a nominal size (width and depth) of 100 mm, 400 mm long.

4 RESULTS AND DISCUSSION

Compressive strength of FRCCs was evaluated on cubic specimens with 100 mm side after 0.25 (6 hours, corresponding to demoulding), 1, 2, 7 and 28 days of wet curing. Based on the results reported in Figure 1, it can be observed that a compressive strength of at least 50 MPa after 24 hours of curing was reached in all cases. After 7 days of wet curing the results obtained are in the range 90 to 100 MPa, while after 28 days a value of at least 115 MPa was reached in all cases. The amount of fibers does not seem to have influenced the compressive strength.
Based on the results reported in Figure 2, it can be observed that at very early age the addition of different dosages of fibers does not seem to have affected the flexural strength. However, a value of at least 13 MPa after 24 hours of wet curing was reached in all cases. A minimum value of 20 MPa was obtained after 28 days even with the minimum dosage of fibers, equal to 1.5% by volume. The highest dosage of fibers (equal to 2% by volume) seems to have positively influenced the post-cracking behavior, with higher residual stresses (see Figure 7).
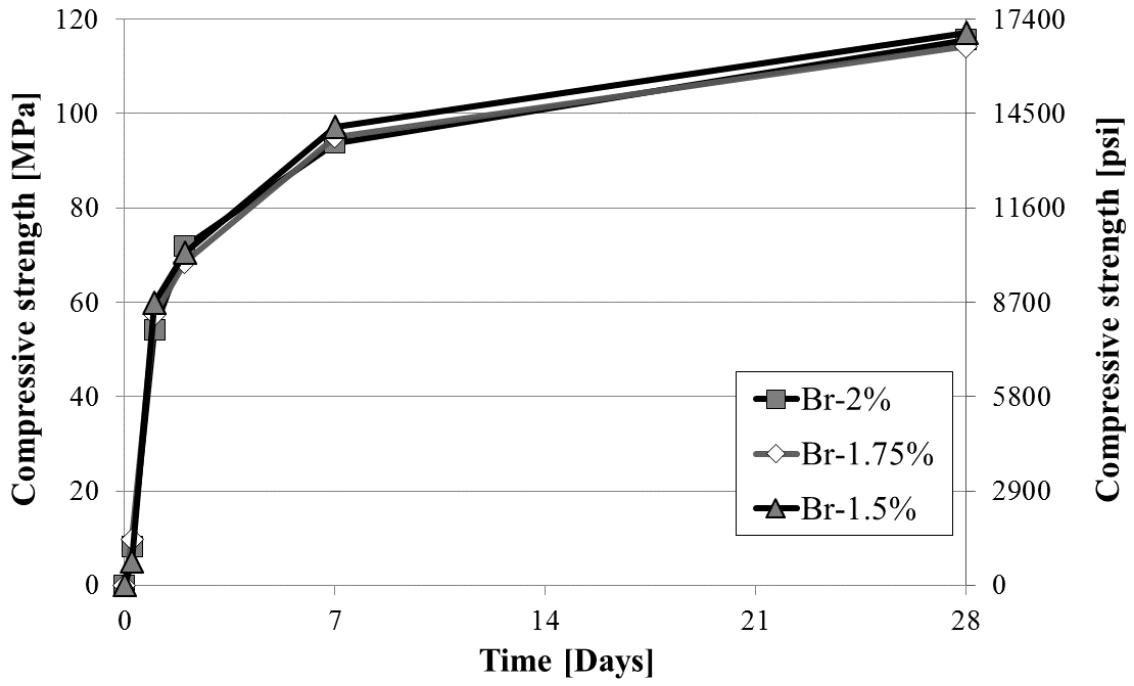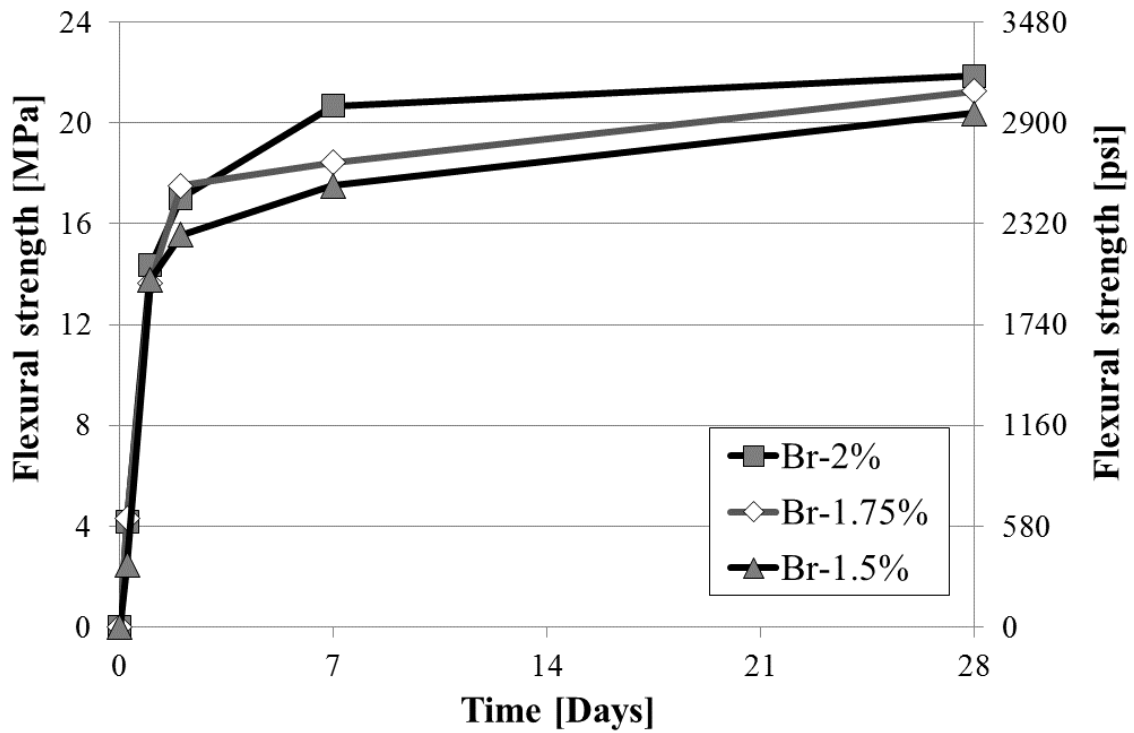
Figure 1. Compressive strength vs. curing time.

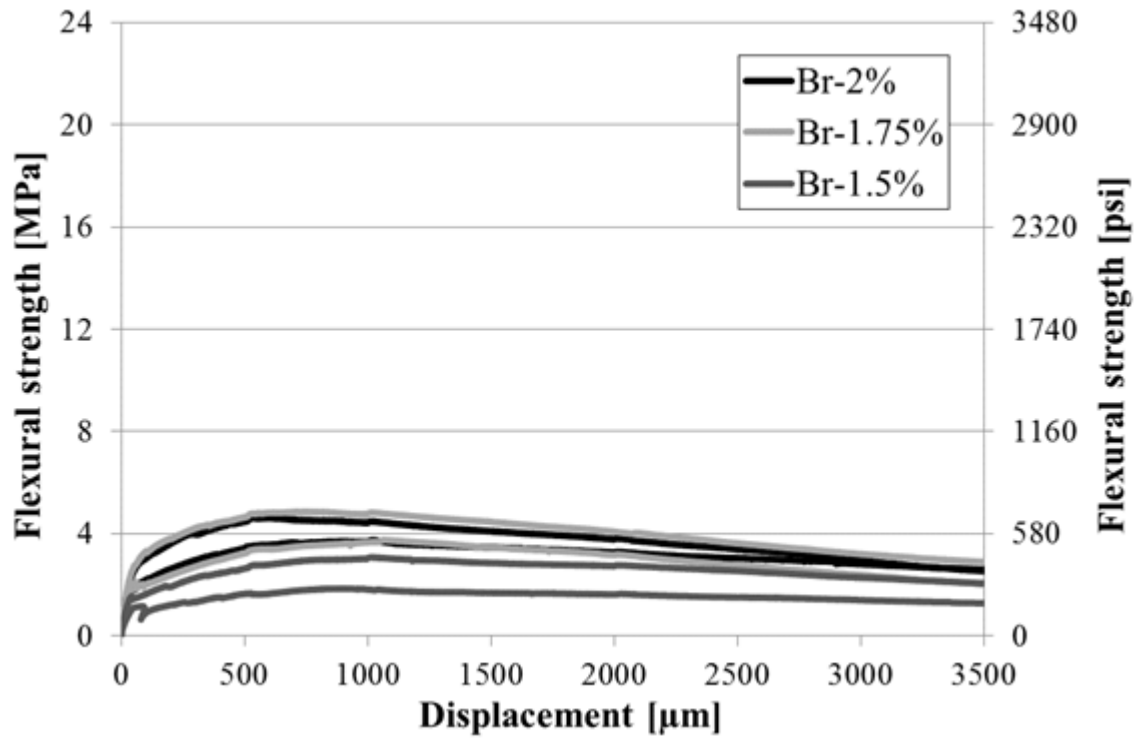
Figure 2. Flexural strength vs. curing time.

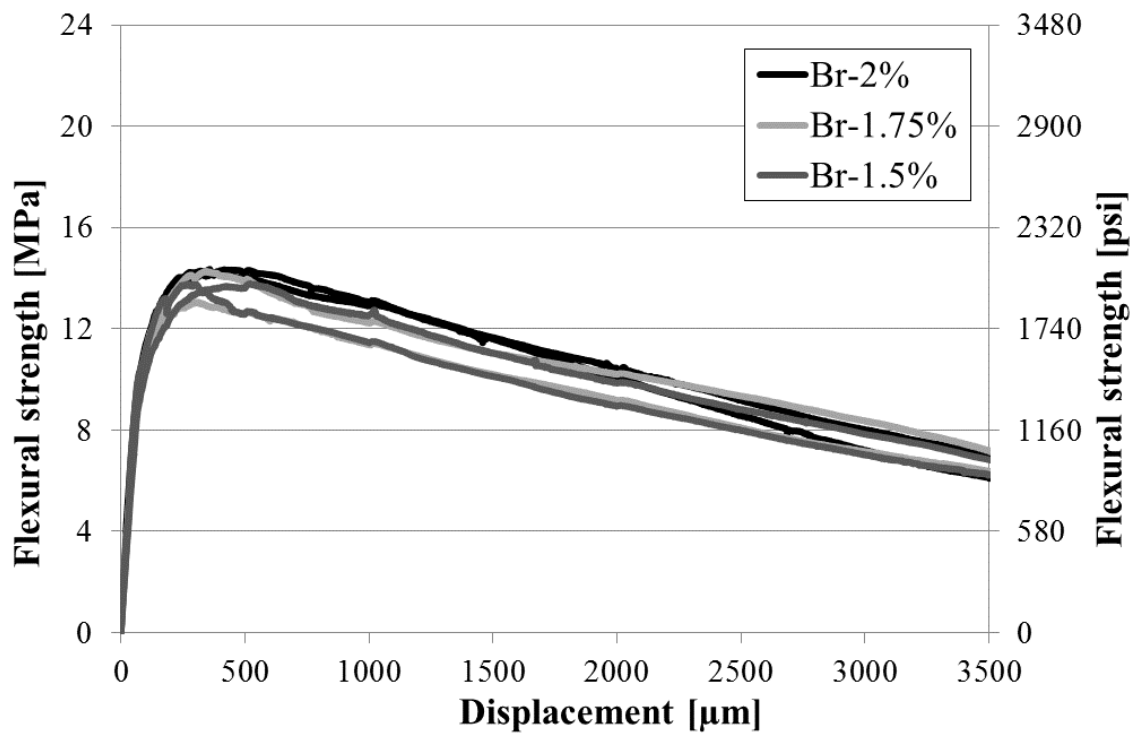*Figure 3. 6-hour flexural strength vs. displacement*

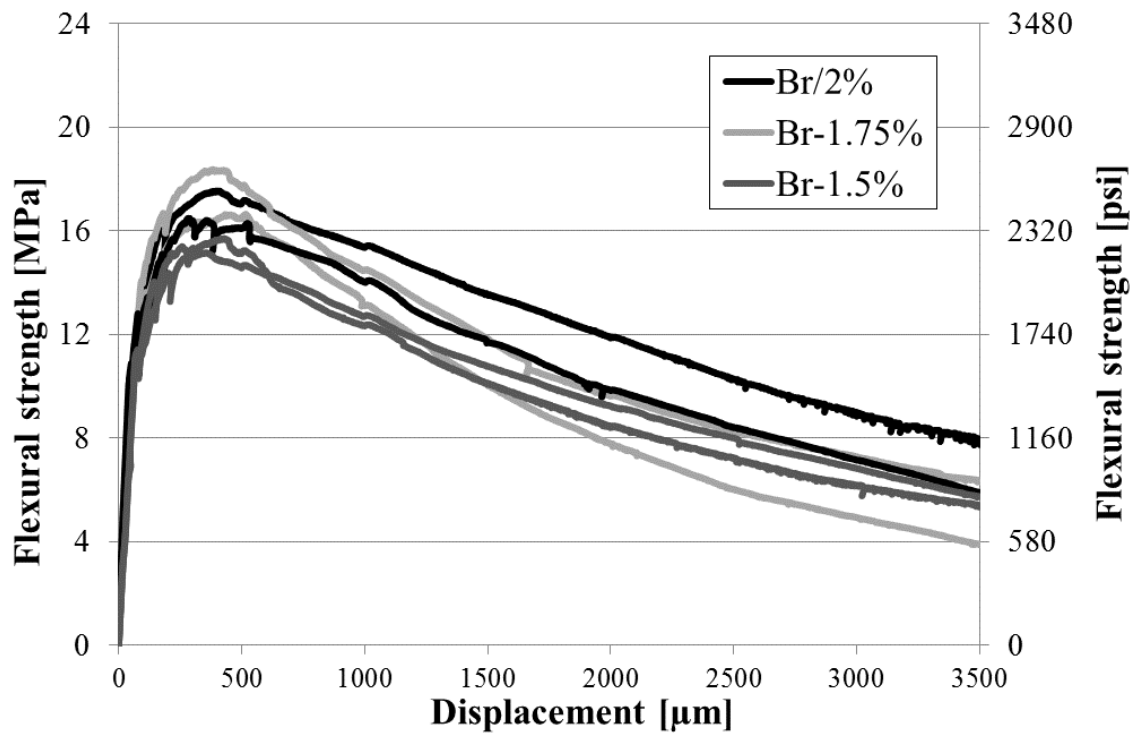*Figure 4. 1-day flexural strength vs. displacement*

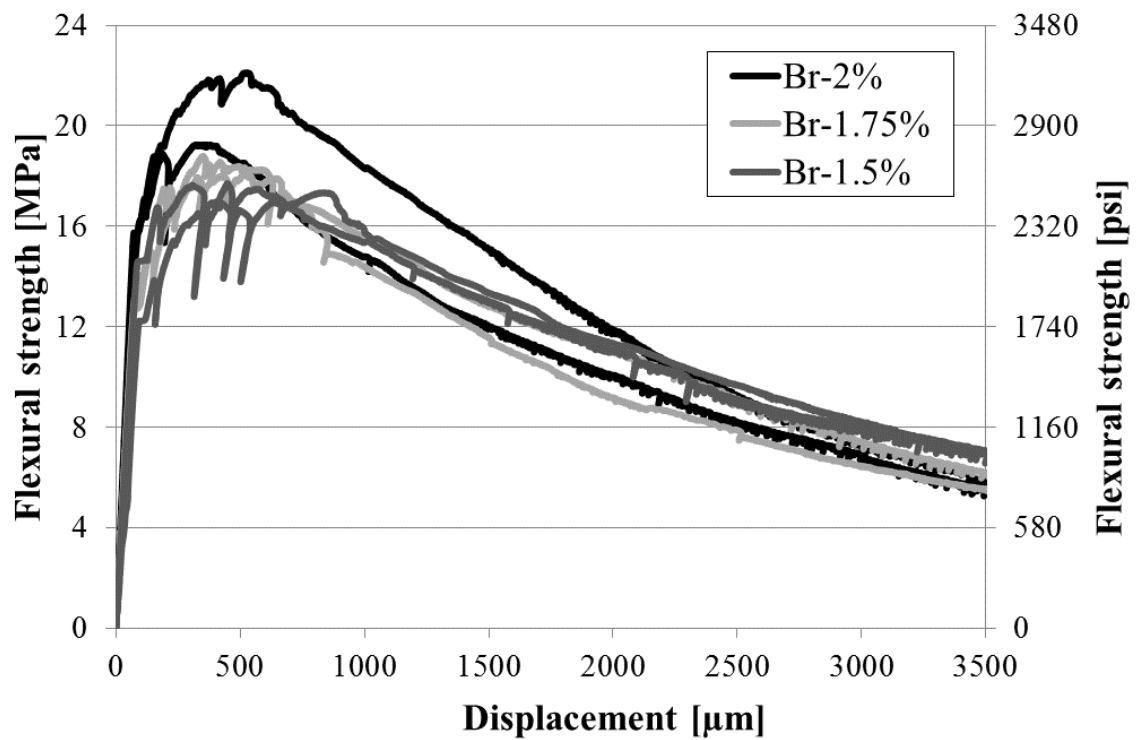*Figure 5. 2-day flexural strength vs. displacement*

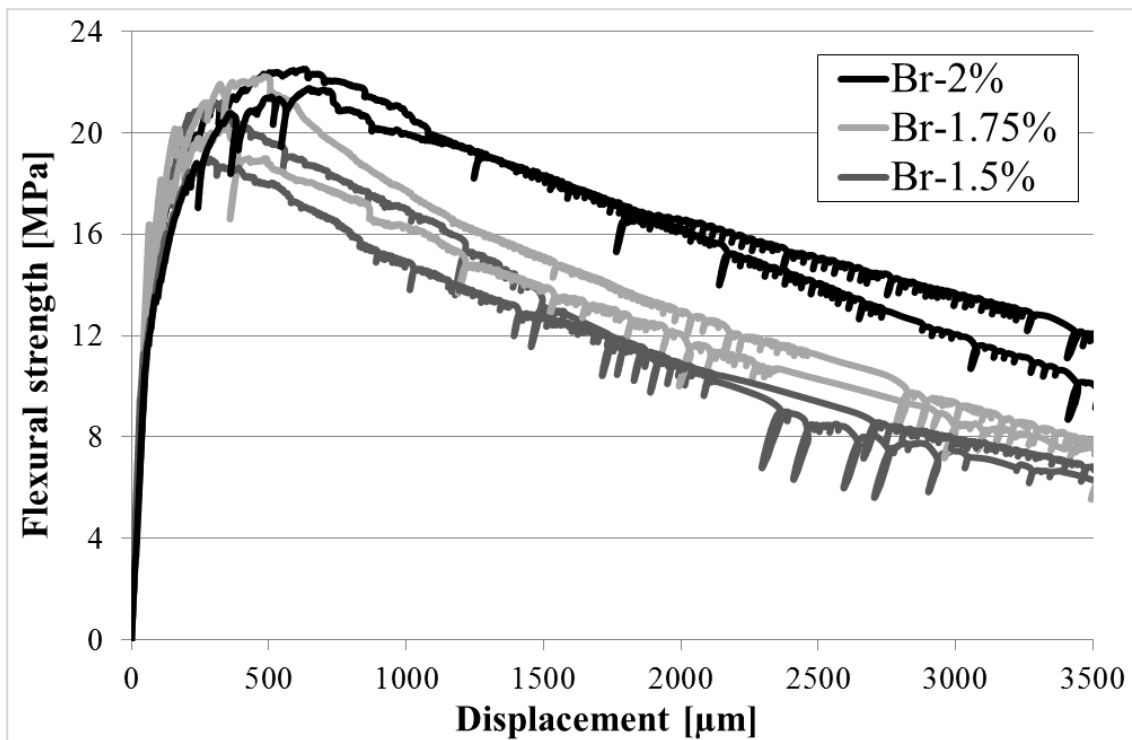*Figure 6. 7-day flexural strength vs. displacement*

Figure 7. 28-day flexural strength vs. displacement

5 CONCLUSIONS

The following general conclusions can be drawn from this study:
− The addition of different amounts of fibers did not influence the compressive strength; a value of at least 50 MPa was reached in all cases after 24 hours of curing, while the 28-day compressive strength was in the range of 115-120 MPa, independently of the amount of fibers.
− At very early ages (up to 24 hours) the different dosage of fibers did not influence the flexural strength value, while after 7 days of curing a difference of about 3 MPa between the mixtures with minimum (1.5%) and maximum dosage (2%) of fibers was observed. However, at least 13 MPa of 24-hour flexural strength was reached in all cases, as well as a minimum 28-day flexural strength of 20 MPa.
− Residual flexural strength at 3.5 mm of displacement seems to be independent of the amount of fibers up to 7 days of curing, then the higher dosage of 2% by volume seems to promote a better post-cracking behaviour.

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