

## MODIFICATION OF PROPERTIES OF STRUCTURAL LIGHTWEIGHT CONCRETE WITH STEEL FIBRES

Lucyna Domagała

*Institute of Building Materials and Structures, Cracow University of Technology,  
ul. Warszawska 24, 31-155 Cracow, Poland*

*E-mail: ldomagala@pk.edu.pl*

*Received 28 Jun. 2009; accepted 29 Apr. 2010*

**Abstract.** Structural lightweight aggregate concrete (SLWAC) is an alternative building material to normal-weight one, due to its ability to reach a relatively high compressive strength at still significantly lower density. Nevertheless, the application of lightweight aggregate instead of normal-weight one to concrete must result in deterioration of some characteristics of the composite. One of the methods of improving SLWAC properties is incorporation of fibers into concrete. This paper focuses on the influence of steel fibres on modification of properties of structural lightweight concrete with sintered fly ash aggregate. Two different concrete mixtures, producing various levels of matured composite density and compressive strength, were modified with three dosages of fibers: 30, 45 and 60 kg/m<sup>3</sup>. The applied amounts did not result in significant deterioration of the rheological parameters of concrete mixtures. Despite relatively low volume content of fibres, a considerable increase of flexural and tensile splitting strength was observed. Fibres also improved concrete shrinkage as well as post-peak deformability in uni-axial compression. The effect of steel addition on compressive strength proved to be dependent on specimen type. Nevertheless, it was not as crucial as in the case of the above characteristics. However, the modulus of elasticity of SLWAC was not affected by fibre addition.

**Keywords:** lightweight aggregate concrete, steel fibres, compressive strength, flexural strength, tensile splitting strength, modulus of elasticity, stress-strain relationship, shrinkage, rheology, scale effect.

### 1. Introduction

Structural lightweight aggregate concrete (SLWAC) is a versatile building material which has been used in building engineering since Roman times. Intensive development of artificial lightweight aggregate production resulted in the fact that concrete can no longer be treated as a material applied only in order to improve thermal insulation or to lower the dead load of a structure. With appropriate selection of aggregate type, it is possible to achieve structural lightweight concrete with strength ranging from only 15 MPa up to over 100 MPa. Therefore SLWAC may be used successfully both to ordinary structures (e.g. precast elements, monolithic buildings, tanks, bridges) and more impressive ones (such as oil platforms, high rise buildings, long-span public structures, sport halls, long span bridges, pontoon bridges and other floating structures). To obtain higher concrete strength at considerable porosity of the applied lightweight aggregate it is usually necessary to increase the content of cement and modern admixtures and additives. Nevertheless, it must be noted that increasing compressive strength and durability of SLWAC does not involve proportional improvement of the other mechanical and physical properties. Therefore, in comparison to normal weight concrete of a given compressive strength, lightweight aggregate concrete is characterized by higher shrinkage, higher brittleness, lower shear, flexural and

tensile strength, lower modulus of elasticity and lower fracture parameters (Chandra and Berntsson 2003; Clarke 1993; Domagała 2006).

The most popular additives applied to SLWAC to improve its properties are fly ash and silica fume. But there is also some research into improving lightweight concrete characteristics by adding less conventional materials such as: catalyst waste material (Mačiulaitis *et al.* 2009), polymers (Kurugöl *et al.* 2008); and different types of fibres: polymer (Kayali *et al.* 2003, 1999; Bilodeau *et al.* 2004; Chen and Liu 2005; Arisoy and Wu 2008; Tanyildizi 2009; Perez-Pena and Mobasher 1994; Noumowé *et al.* 2009; Toutanji *et al.* 2010; Xu *et al.* 2010), steel (Kayali *et al.* 2003, 1999; Chen and Liu 2005, 2004; Gao *et al.* 1997; Balendran *et al.* 2002; Campione and Miraglia 2001; Campione and La Mendola 2004; Campione *et al.* 2005; Rao and Seshu 2003), glass (Perez-Pena and Mobasher 1994; Mirza and Soroushian 2002; Park *et al.* 1999), carbon (Chen and Liu 2005) or hybrid (Chen and Liu 2005). It should be emphasized that generally the number of publications and research projects on how fibres influence lightweight concrete, as well as the number of applications of SLWAC reinforced with fibres in structures are essentially lower than in the case of normal weight concrete. Meanwhile, because of lower tensile strength and higher brittleness of SLWAC, the enhancement of some parameters with fibres may be

even better than in the case of normal weight concrete of the same strength level. It seems that from among all types of fibres steel ones are the most effective additives to modify mechanical properties of lightweight concrete at a rational concrete cost. Most research carried out on this subject (Kayali *et al.* 2003; Chen and Liu 2005, 2004; Gao *et al.* 1997; Balendran *et al.* 2002; Campione and Miraglia 2001) indicates that, using steel fibres, it is possible to enhance fracture parameters, shear and flexural as well as tensile strength. Moreover, such characteristics of SLWAC as shrinkage, compressive strength, modulus of elasticity and stress-strain relationship are in some cases affected by steel fibres, yet in others there is no such effect. Considerable differences in effectiveness of fibres strongly depend first of all on aggregate type (polystyrene, pumice, expanded clay, sintered fly ash), secondly on fibre type (straight or hook ended; 5 to 50 mm long) and its content (0.5–2.0% by volume). The results discrepancy may be additionally extended by different types of applied test specimens.

This paper is focused on effects of steel fibres on properties of lightweight concrete with sintered fly ash aggregate. It takes into consideration the differences in cement matrix composition, fibres content (at their economically most-effective and technologically convenient level) and types of test specimens. The objectives of this study were: first, to establish the fiber influence on rheological parameters of the mixture, SLWAC swelling and shrinkage, its compressive, flexural and tensile splitting strength, modulus of elasticity and stress-strain relationship in compression; secondly, to compare the obtained results with the existing references and, finally, to explain the mechanisms of modeling SLWAC properties with steel fibres.

## 2. Experimental details

### 2.1. Materials and mix proportions

Tests were carried out on two series of lightweight concrete of different strength and density levels. The series, marked as I and II, were characterized by nominal water-cement ratio of 0.55 and 0.37 respectively.

Sintered fly ash Pollytag 4/8 mm was used as a course lightweight aggregate (LWA). In spite of its high water absorption (25%), but owing to its better mechanical properties (crash strength of ca 8 MPa), this aggregate appears to be the most suitable to structural concrete in comparison to other locally available lightweight aggregates. In order to limit water absorption of the aggregate in the concrete mixture, it was moistened to 17% prior to use.

The other materials applied to lightweight concrete were: CEM I 42.5 R, natural sand as a fine aggregate, superplasticizer added in suitable dosages in order to obtain a workable mixture. Steel fibres were of the Dramix type, hook ended, 50 mm long with the diameter of 0.75 mm. They were added to the concrete mixture in the following dosages  $V_f$ : 0; 0.4; 0.6 and 0.8% by concrete volume. Mix proportions of all 8 concretes are presented in Table 1.

**Table 1.** Concrete mix proportions, kg/m<sup>3</sup>

Mix	Cement	Water	Superpl.	Sand	LWA	Fibres
IS0	345	190	0.0	414	765	0
IS1	345	190	0.0	414	765	30
IS2	345	190	0.7	414	765	45
IS3	345	190	1.4	414	765	60
IIS0	446	164	3.6	458	700	0
IIS1	446	164	3.6	458	700	30
IIS2	446	164	4.0	458	700	45
IIS3	446	164	4.5	458	700	60

### 2.2. Tests methods

Rheological tests were carried out immediately after mixing the concrete. The basic mixture parameter to control was its consistency specified according to VeBe test. Additionally, two other rheological parameters determining the mixture workability were measured: yield value ( $\tau_0$ ) and plastic viscosity ( $\mu$ ). These measurements were performed with the use of a rheometer (Domagała and Urban 2006).

Due to marks concreted into samples tests of volume changes were possible as quickly as 5 hours after sample moulding. Specimens to be tested for volume changes during first 28 days were stored in room temperature of  $20 \pm 2^\circ\text{C}$  and humidity of  $95 \pm 5\%$ . After wet curing, samples were drying in  $50 \pm 5\%$  RH and  $20 \pm 2^\circ\text{C}$  for almost one year.

The other specimens, destined to be tested at the hardened state later on, were cured in room temperature of  $20 \pm 2^\circ\text{C}$  and humidity of  $95 \pm 5\%$  RH until the time of the concrete tests arrived. All strength properties as well as density were specified after standard 28 days, but they were also repeated after one year. The tests were carried out according to appropriate European Standards. Since there are no appropriate standards for the other mechanical properties, such as modulus of elasticity and stress – strain ( $\sigma - \epsilon$ ) relationship in uniaxial compression, they were tested after a year according to the procedure developed for the needs of this research. Modulus of elasticity was determined in a stress range from 0.1 to 0.3 of concrete compressive strength. The apparatus for measurements of both the modulus and stress-strain relationship consisted of three sensors of displacement, a force sensor, an amplifier for the force sensor, a measurement set with four channels (input) and a converter transforming signals from the set to digital form. The measurement apparatus was connected to a PC, which allowed for continuous control of stresses and corresponding strains. The frequency of measurements was 5 Hz and the rate of loading was constant 0.5 MPa/s and 0.05 MPa/s for Young's modulus and  $\sigma - \epsilon$  relationship respectively.

The types of tests carried out, the applied test specimens and their number are presented in Table 2. Apart from standard moulded specimens, some drilled ones were also used to avoid a wall effect. The effect could be marked in the case of smaller samples, such as cubes of the 100 mm-side.

**Table 2.** Test methods, specimen parameters and number

Test	Specimen		
	Type	Dimensions, mm	Number
Swelling	moulded beam	100 × 100 × 500	8 × 3
Shrinkage	moulded beam	100 × 100 × 500	8 × 3
Density	moulded cube	150 × 150 × 150	8 × 5
Compressive strength	moulded cube	150 × 150 × 150	8 × 5
	moulded cylinder	ϕ 150/300	8 × 5
Tensile splitting strength	drilled cube	100 × 100 × 100	8 × 3
	moulded cube	150 × 150 × 150	8 × 5
Flexural strength (three-point bending)	drilled cube	100 × 100 × 100	8 × 3
	moulded beam	100 × 100 × 500	8 × 6
Modulus of elasticity	moulded cylinder	ϕ 150/300	8 × 5
σ – ε relationship in compression	moulded cylinder	ϕ 150/300	8 × 5

### 3. Results and discussion

#### 3.1. Rheological properties

The time of compaction of moulded lightweight concrete on a vibrating table of  $15 \pm 5$  s was adopted as a criterion for workability. Addition of fibres in the amount of over  $V_f = 0.4\%$ , without modifying the mixture fluidity with a superplasticizer, caused deterioration of the mixture workability. Concretes reinforced with fibres in the amounts of  $V_f = 0.6\%$  and  $V_f = 0.8\%$ , were characterized by less liquid consistency and higher both yield value ( $\tau_0$ ) as well as plastic viscosity ( $\mu$ ).

Therefore, in order to fulfill the workability requirement, mixtures with higher content of steel fibres (over  $V_f = 0.4\%$ ) needed higher dosages of superplasticizers (up to 1% of the cement mass) to prevent the concrete mixture from blocking on fibres. On the other hand, such a mechanism prevented lighter aggregate from segregating during compaction. It should be noted that while preserving the same workability, mixtures reinforced with fibres in the amount of over  $V_f = 0.4\%$  were characterized by more liquid consistency – assessed at 5–7 s according to the Vebe method – in comparison to 8–10 s for plain concrete and concrete with the lower fibre content. The differences in times of concrete compaction assessed with the Vebe apparatus and in moulds compacted on the vibrating table were caused by different shapes of the forms used (cone and prism respectively), which resulted in different mixture load per compacted area unit.

Addition of higher dosages of superplasticizers to concrete reinforced with fibres in the amount of  $V_f = 0.6\%$  and  $V_f = 0.8\%$  to ensure the appropriate workability changed not only its consistency but also the other rheological parameters. These mixtures were characterized by lower yield value ( $\tau_0$ ) but a little higher plastic viscosity ( $\mu$ ) in comparison to plain concrete or concrete with fibre content of  $V_f = 0.4\%$ .

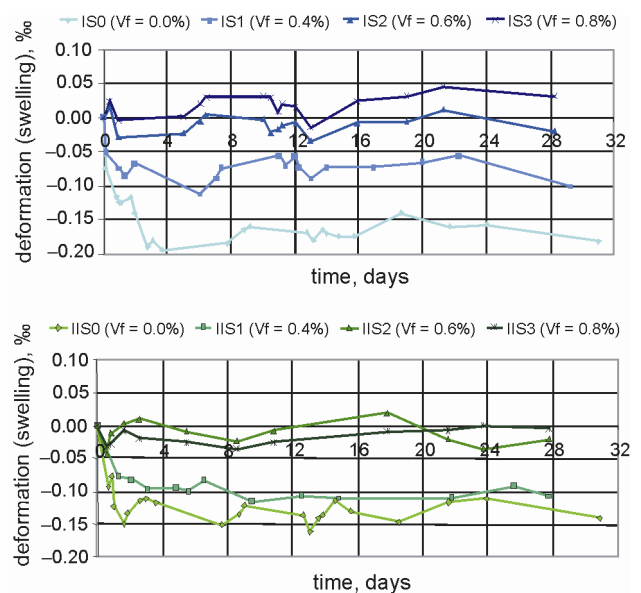
Exemplary appearance of lightweight concrete mixture reinforced with steel fibres is presented in Fig. 1.

#### 3.2. Swelling

Curing of lightweight concrete in high humidity conditions resulted in not so much limitation of shrinkage, but of swelling. After 28 days, plain concretes IS0 and IIS0

revealed linear elongation of 0.20 and 0.15 mm/m respectively (Fig. 2).

The higher the water-cement ratio was, the higher level of swelling occurred. Nevertheless, it should be emphasized that specified volume changes appeared to be higher than in the case of a comparable normal

**Fig. 1.** Concrete mixture before compaction (IIS3)**Fig. 2.** Mean swelling of plain lightweight concrete and steel fibre reinforced lightweight concrete in  $95 \pm 5\%$  RH

weight concrete. In the case of lightweight concrete swelling is caused not only by absorption of water from the external environment, but also from internal reservoirs in the form of initially moistened porous aggregate. Because of lower capability of depercolation exhibited by the matrix of higher water-cement ratio, stabilization of swelling strains occurred later for concrete IS0 (after 4 days) than for concrete IIS0 (after 2 days).

As it can clearly be seen in Fig. 2, incorporation of fibres into lightweight concrete restricted swelling considerably. In the cases of both concrete series, fibre content of  $V_f = 0.4\%$  was enough to eliminate volume changes completely.

### 3.3. Shrinkage

Final shrinkage strains for plain lightweight concrete were 0.60 mm/m and 0.53 mm/m for IS0 and IIS0 respectively (Fig. 3). These values of linear strains are higher by ca 20% and 8% than for normal weight concrete of the same compressive strength. Higher shrinkage results from less stiff lightweight aggregate grains and their lower content in a given concrete volume unit. Despite higher volume changes, the risk of concrete cracking from shrinkage is lower in the case of tested SLWAC, because of better composite homogeneity resulting from both excellent adhesion between sintered fly ash aggregate and cement matrix, and their comparable modulus of elasticity.

While assessing the risk of cracking it should also be noticed that due to water cumulating inside aggregate grains, shrinkage of both lightweight concretes during the first period of drying (up to 50 days) when the composite is the most prone to cracking, was lower than typically for normal weight concrete of comparable strength.

Nevertheless, shrinkage of the tested lightweight concrete was twice and four times lower (at 100 days of drying) in comparison to lightweight concrete of comparable strength made with expanded clay aggregate (Chen and Liu 2005) or polystyrene one (Chen and Liu 2004). It was considerably lower even in the case of other lightweight concrete with sintered fly ash, mainly because of much lower content of cementitious materials (Kayali *et al.* 1999).

Steel fibres caused reduction of final shrinkage by up to 25%, which means strains of 0.50 mm/m and 0.40 mm/m for series I and II respectively (Fig. 3). This decrease was much more pronounced than the one observed by other researchers (Kayali *et al.* 1999; Chen and Liu 2005). The shrinkage decrease was rather independent from fibres content, which is consistent with results achieved in other research project, even when a higher range of fiber volume were used (Kayali *et al.* 1999; Chen and Liu 2005, 2004). While assessing the influence of steel fibres on lightweight concrete shrinkage, the role of moisture curing can not be omitted. Fibres preventing concrete from swelling made it impossible for the concrete structure to cumulate higher amount of water during wet curing. As a result during first ca 40 days of drying, shrinkage of plain concrete IS0 was even lower than for concretes with fibres, which can be attributed to the huge amounts of water stored inside.

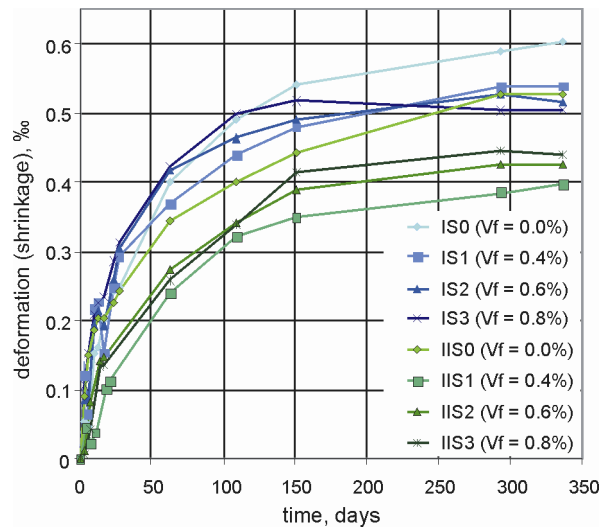


Fig. 3. Mean drying shrinkage of plain lightweight concrete and steel fibre reinforced lightweight concrete in  $50 \pm 5\%$  RH

### 3.4. Density

Oven dry density of plain lightweight concrete was  $1580 \text{ kg/m}^3$  and  $1710 \text{ kg/m}^3$  for concrete IS0 and IIS0 respectively.

The densities of fibre reinforced lightweight concrete are higher proportionally to steel content, which confirms proper composite homogeneity (Fig. 4).

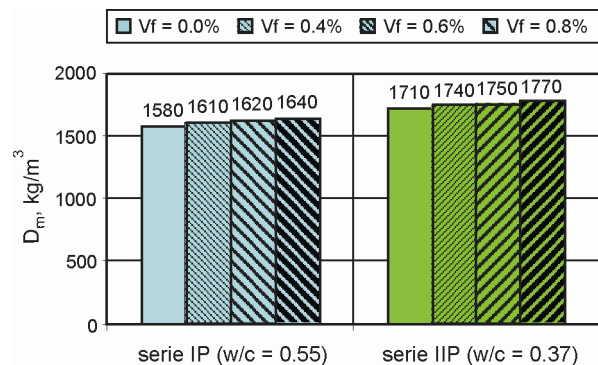


Fig. 4. Mean oven dry densities of plain lightweight concrete and steel fibre reinforced lightweight concrete

### 3.5. Compressive strength

All compressive strength results for plain and fibre reinforced lightweight concrete obtained on various type specimens after 28 and 365 days are presented in Fig. 5.

Compressive strength of plain lightweight concrete after 28 days of curing was 39.0 MPa and 47.5 MPa for concrete IS0 and IIS0 respectively. These are relatively high values, taking into consideration the low densities obtained. The strength assessed after one year is a little higher: ca 45.0 MPa and 53.0 MPa. The increase of strength in time is lower than in the case of normal weight concrete because it is limited by low strength of the porous aggregate itself.

Contrary to normal weight concrete, no scale effect was observed for plain lightweight concrete. Compressive strength tested on the smallest specimens (cubes of



100 mm-side) produced results equal to values observed on the biggest ones (cylinders 150/300 mm). The reason of this phenomenon is, as mentioned before, incomparably better structure homogeneity of the tested lightweight concrete.

Addition of steel fibres to lightweight concrete had no influence on its compressive strength, when it was tested on cubic specimens, regardless of their size and age at the time of testing. Such results are consistent with most research conclusions for normal weight concrete (Balaguru and Shah 1992). Despite incomparably higher strength of steel fibres, they are not usually able to change compressive strength of the composite because of their insignificant volume contribution (if  $V_f \leq 2\%$ ). It should be noted that sometimes research even shows the decrease of compressive strength and/or modulus of elasticity, resulting from steel fibre incorporation (Kurugöl *et al.* 2008; Kayali *et al.* 2003; Altun *et al.* 2007). These cases may probably be explained by inappropriate rheological properties of the mixture, preventing it from being homogeneous and well compacted. Nevertheless, there are a few research examples, especially regarding lightweight concrete, indicating positive impact of steel fibres on compressive strength (Chen and Liu 2005; Gao *et al.*

1997; Campione and Miraglia 2001). All three cases concern concrete with expanded clay aggregate, whose adhesion is weaker than that of sintered fly ash aggregate or crushed pumice stone. Moreover, considering the influence of steel fibres on compressive strength, the type of test specimen should not be ignored. In cubic specimens casting/compaction direction and loading direction are perpendicular, while in cylindrical specimens they are parallel (Fig. 6). The latter case, more common in situ, promotes advantageous alignment of fibres enabling them to bridge the cracks forming during concrete loading. Additionally, the different patterns of concrete fracture, resulting from differences in test cube and cylinder slenderness, should also be taken into consideration. This mechanism of steel fiber effect is confirmed by a slight increase of compressive strength (ca by 10%) observed on cylindrical specimens made of tested lightweight concrete, while the same concrete did not reveal any fiber influence when it was tested on cubes (Fig. 5).

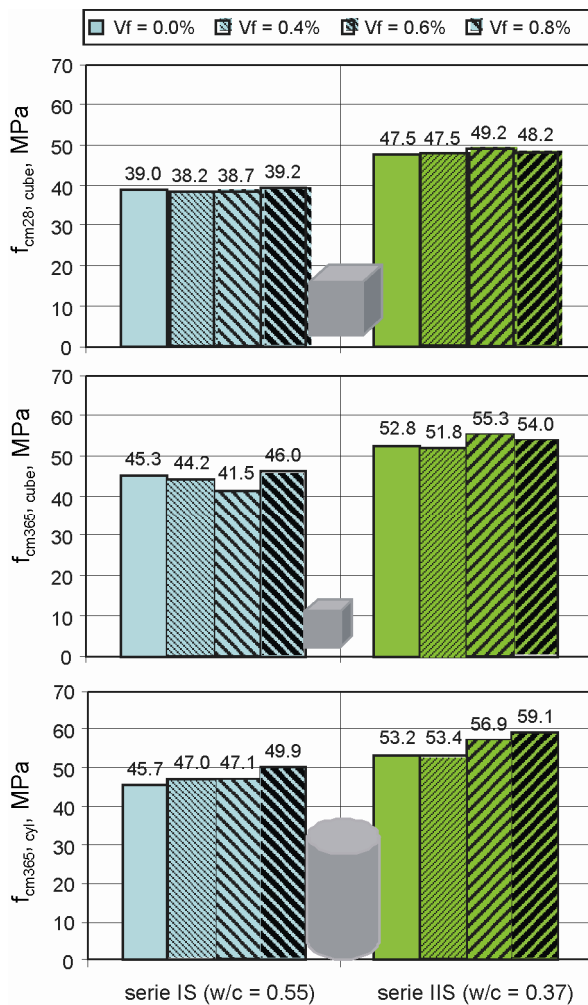


Fig. 5. Mean compressive strength of plain lightweight concrete and steel fibre reinforced lightweight concrete

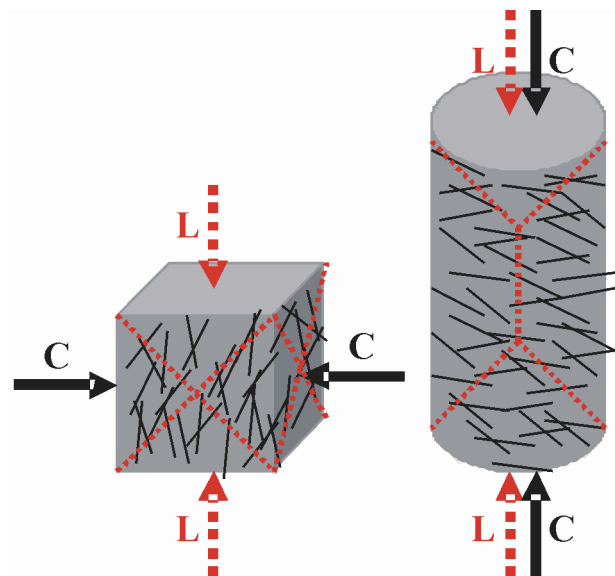


Fig. 6. The influence of steel fibres on the ability to bridge cracks occurring during loading of concrete cubes and cylinders. C – casting and compaction direction; L – loading direction

Increasing fiber content, one can increase the probability of location of fibers on the crack path. That is also the reason for lower results dispersion in the case of concrete with higher fibre content.

### 3.6. Modulus of elasticity

Due to lower stiffness of porous aggregate, the tested lightweight concrete characterized by significantly lower modulus of elasticity (on average by 45%) in relation to normal weight concrete of the same strength class. Therefore, steel fibres were expected to have stronger influence on modification of lightweight concrete modulus of elasticity.

Despite the fact that steel has incomparably higher modulus of elasticity (ca 210 GPa), its addition could not

change the modulus of the researched lightweight concrete because of its minor volume contribution (Fig. 7). This observation is consistent with most normal weight concrete, except the rare cases of higher steel content ( $V_f > 5\%$ ). Nevertheless, there are some cases of lightweight concrete with weaker aggregate revealing the increase of Young's modulus resulting from steel fibres addition (Gao *et al.* 1997; Campione and Miraglia 2001). The increase of the modulus resulting from steel content of  $V_f = 2\%$  was observed for lightweight concrete with expanded clay aggregate, while for comparable concrete with crushed pumice there was no fibre effect. Therefore, using weaker aggregate itself is not a reason for the modulus increment. Probably the most important factor is adhesion between the aggregate and the cement matrix. In the case of weak pumice, exactly as for much stronger sintered fly ash, the bond is very strong because of high water absorption and rough texture. Meanwhile expanded clay may have much more regular and smooth grains of lower water absorption. As a result, concrete with the latter aggregate may be less homogenous than the others, which means that cracking may occur earlier during loading, even in the range of stresses applied for modulus testing. In the case of concrete of such low Young's modulus, bridging mechanism of fibres may play a dominant part in modulus increment.

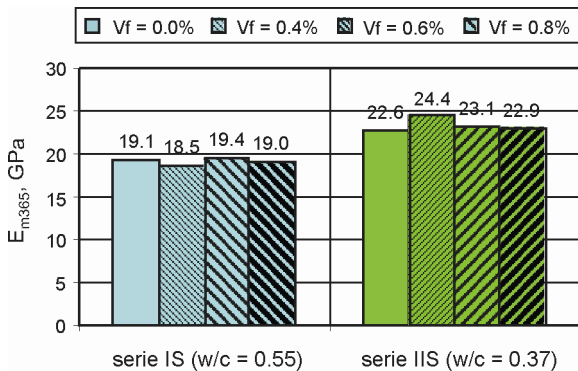


Fig. 7. Mean modulus of elasticity of plain lightweight concrete and steel fibre reinforced lightweight concrete

### 3.7. Deformability during compression

Because of lower modulus of elasticity plain lightweight concrete revealed higher deformability during compression when compared to normal weight one. In result the stress-strain ( $\sigma - \epsilon$ ) relationship is characterized by less steep slope in the ascending part. Therefore, the strain corresponding to maximum stress is considerably higher. For both plain concretes (IS0 and IIS0) it equaled 2.7 mm/m instead of typical 2.0 mm/m for normal weight concrete of comparable compressive strength. Due to better homogeneity of lightweight concrete resulting from both excellent bond and comparable elasticity modulus, the linearity of the ascending part is held up to 90–95% of maximum stress, while for normal weight concrete of the same strength class it is usually up to 30–45%. Plain lightweight concrete revealed no descending part, which was a consequence of its explosive fracture. As a result, after reaching its strength, lightweight concrete had no

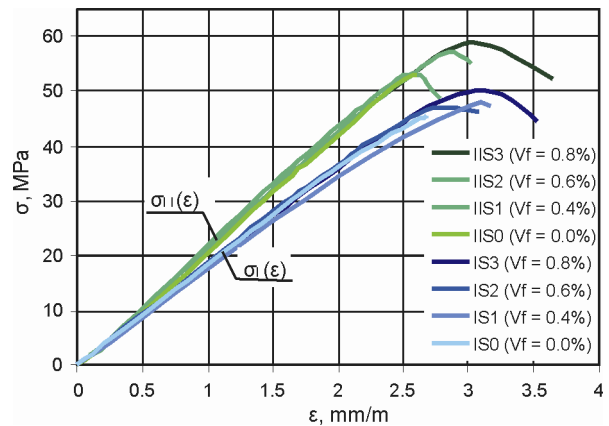


Fig. 8. Mean stress-strain relationship for plain lightweight concrete and steel fibre reinforced lightweight concrete

longer the ability to deform and transfer any stresses (Fig. 8).

Since addition of steel fibres didn't change the modulus of elasticity of the researched lightweight concrete, it could not modify the course of the ascending part of stress-strain relationship, either. The only difference occurred in the upper section before the peak, where reinforced concrete revealed, proportionally to fiber content, a higher maximum stress and slight curving of  $\sigma - \epsilon$  relationship course. The shape of the curve proved that the appearing cracks were bridged with fibres, which took part in stress transfer making it possible to reach a higher strength. In result steel fibres concrete, as it can be seen in Fig. 8, revealed lower linearity of  $\sigma - \epsilon$  relationship (up to 85% of its strength) and higher strains corresponding to the maximum stress (ca 3.0 mm/m for fiber content  $V_f = 0.8\%$ ).

Modification of deformability of lightweight concrete with steel fibres in post peak stage is most striking. Even the smallest content of fibres ( $V_f = 0.4\%$ ) completely eliminated the explosive nature of concrete damage. The ability to transfer stresses after reaching their peak increases with increasing fiber content. Therefore, steel fiber lightweight concrete revealed descending part of the  $\sigma - \epsilon$  relationship. For concrete with the highest steel content ( $V_f = 0.8\%$ ) maximum mean strain was as high as 3.7 mm/m. Nevertheless, for individual specimens the maximum strain could be as high as 4.5 mm/m. It should be emphasized that the effectiveness of steel fibres in modification of deformability of lightweight concrete depends on the probability that a fibre will be located on the crack path. When a propagating crack meets on its route a fibre able to bridge it, concrete may still become deformed. The proof of such a mechanism is not only the course of stress - strain relationships (Fig. 8), but also crack patterns visible on specimen surface (Fig. 9). In plain concrete paths of cracks run straight from the top to the bottom parallel to the loading direction, while in steel fibre concrete the course of cracks is determined by distribution of fibres. If a propagating crack meets on its route a fibre capable of transferring stress, it is arrested or it tries to bypass the fiber changing its course. In Fig. 10 there are some examples when fibres were no longer able to bridge the crack and they let it go.

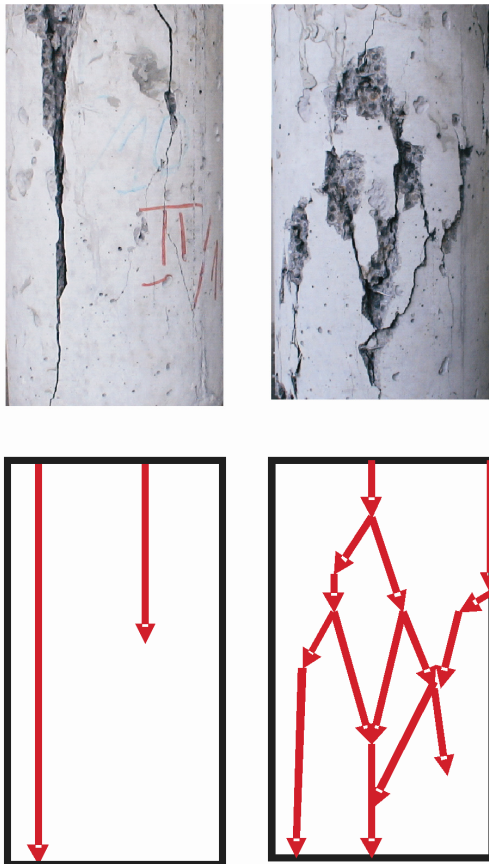


Fig. 9. Typical cracking patterns for plain lightweight concrete and steel fibre reinforced lightweight concrete

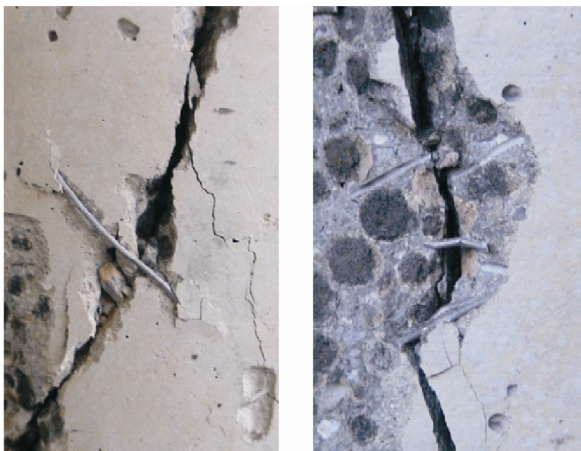


Fig. 10. Fibres which failed in crack arresting

### 3.8. Tensile splitting strength

Tensile splitting strength of the tested plain lightweight concrete (3.05 MPa for IS0 and 3.35 MPa for IIS0) was lower than for normal weight concrete of the same compressive strength. The relation of tensile to compressive strength  $f_{ts}/f_c$  here was about 8%, while it is usually 10% for normal weight concrete of such strength class.

As it was expected, steel fibres enhanced splitting tensile strength of lightweight concrete proportionally to their content (Fig. 11). The increase was strongly dependent on the specimen size. It was much more pronounced

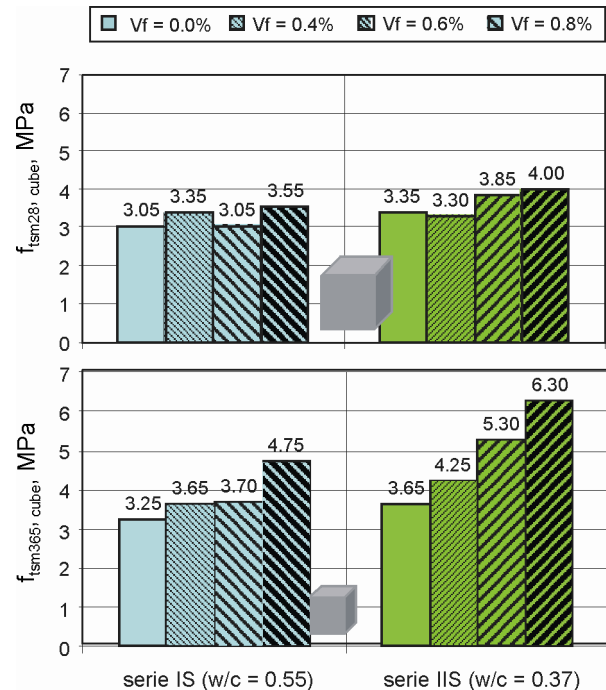


Fig. 11. Mean tensile splitting strength of plain lightweight concrete and steel fibre reinforced lightweight concrete

in the case of smaller size samples, which is consistent with (Balendran *et al.* 2002). In the case of cubes of 150 mm-side, the increase of tensile strength of  $V_f = 0.8\%$  was 16% and 19% for series IS and IIS respectively. However, the results enhancement was considerably higher: 46% and 73% respectively, when the strength was specified on cubes of 100 mm-side. In this case the ratio of splitting tensile strength to compressive strength  $f_{ts}/f_c$  became as high as ca 13%.

Because of higher brittleness of lightweight concrete, the increment of its tensile splitting strength resulting from steel fibre incorporation, appears to be more pronounced than for normal weight concrete of comparable strength class (Balaguru and Shah 1992; Altun *et al.* 2007).

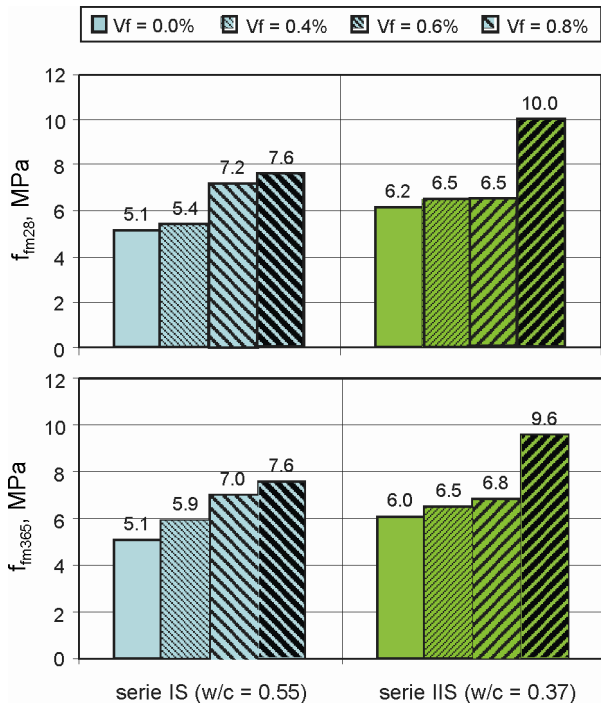
### 3.9. Flexural strength

Just as in the case of tensile splitting strength, flexural strength of plain lightweight concrete (5.1 MPa for IS0 and 6.2 MPa for IIS0) was lower than for normal weight concrete of the same compressive strength. There was no increase of strength observed between 28 and 365 days.

Incorporation of steel fibres into lightweight aggregate concrete caused considerable increase of flexural strength by 49% for IS3 and as much as 61% for IIS3 (Fig. 12). Thus the ratio of flexural strength to compressive one  $f_f/f_c$  changed from 13% for plain concrete up to 20% for concrete with fibres of  $V_f = 0.8\%$ . Therefore, the effectiveness of a given type of fibres is here higher than in the case of normal weight concrete of comparable compressive strength (Balaguru and Shah 1992).

Similarly to tensile splitting strength, the results dispersion for flexural strength was higher for reinforced





**Fig. 12.** Mean flexural strength of plain lightweight concrete and steel fibre reinforced lightweight concrete

concrete than for plain one. The probability of fibres location in the middle of a test beam in the right position (preferably perpendicular to the loading direction) is the factor responsible for higher results dispersion. Nevertheless, increasing the fibre content made this dispersion lower due to a higher probability of the fibers appearing on the route of a crack.

#### 4. Conclusions

Steel fibres may influence considerably these properties of lightweight aggregate concrete which are determined by cracks development and/or tensile strength. In carried out research the effectiveness of steel fibres in enhancement of lightweight concrete characteristics was dependent on fibres content, concrete strength level as well as test specimen type and size. The advantageous effect of steel fibres on properties modification of lightweight concrete with sintered fly ash aggregate turned out to be more essential in comparison to normal weight concrete of comparable strength class.

In the case of tested structural lightweight concrete applied steel fibres, in amount of up to  $V_f = 0.8\%$  by concrete volume ( $60 \text{ kg/m}^3$ ), reduced swelling as well as final shrinkage (up to 25%) and significantly improved both flexural and splitting tensile strength (up to 61% and 73%, respectively). The influence of steel fibres on slight compressive strength increase (up to 10%) was observed only in the case of cylindrical specimens. Due to relatively low contribution of steel and excellent concrete homogeneity, the addition of fibres did not modify concrete modulus of elasticity and its pre-peak course of stress-strain relationship, besides its upper section. However the fibres addition influenced post-peak relationship which resulted from further concrete ability to transfer strains

and stresses after reaching their maximum value. As a result even the smallest applied content of fibres ( $V_f = 0.4\%$ ) eliminated completely the explosive nature of concrete damage.

#### References

- Altun, F.; Haktanir, T.; Ari, K. 2007. Effects of steel fiber addition on mechanical properties of concrete and RC beams, *Construction and Building Materials* 21(3): 654–661. doi:10.1016/j.conbuildmat.2005.12.006
- Arisoy, B.; Wu, H.-Ch. 2008. Material characteristics of high performance lightweight concrete reinforced with PVA, *Construction and Building Materials* 22(4): 635–645. doi:10.1016/j.conbuildmat.2006.10.010
- Balaguru, P.; Shah, S. 1992. *Fiber-Reinforced Cement Composite*. McGraw-Hill. 531 p.
- Balendran, R. V.; Zhou, F. P.; Nadeem, A.; Leung, A. Y. T. 2002. Influence of steel fibres on strength and ductility of normal and lightweight high strength concrete, *Building and Environment* 37(12): 1361–1367. doi:10.1016/S0360-1323(01)00109-3
- Bilodeau, A.; Kodur, V. K. R.; Hoff, G. C. 2004. Optimization of the type and amount of polypropylene fibres for preventing the spalling of lightweight concrete subjected to hydrocarbon fire, *Cement and Concrete Composites* 26(2): 163–174. doi:10.1016/S0958-9465(03)00085-4
- Campione, G.; Cucchiara, C.; La Mendola, L.; Papia, M. 2005. Steel-concrete bond in lightweight fiber reinforced concrete under monotonic and cyclic actions, *Engineering Structures* 27(6): 881–890. doi:10.1016/j.engstruct.2005.01.010
- Campione, G.; La Mendola, L. 2004. Behavior in compression of lightweight fiber reinforced concrete confined with transverse steel reinforcement, *Cement and Concrete Composites* 26(6): 645–656. doi:10.1016/S0958-9465(03)00047-7
- Campione, G.; Miraglia, N. 2001. Mechanical properties of steel fibre reinforced lightweight concrete with pumice stone or expanded clay aggregates, *Materials and Structures* 34(4): 201–210. doi:10.1007/BF02480589
- Chandra, S.; Berntsson, L. 2003. *Lightweight aggregate concrete*. New York: Noyes Publications.
- Chen, B.; Liu, J. 2005. Contribution of hybrid fibers on the properties of the high-strength lightweight concrete having good workability, *Cement and Concrete Research* 35(5): 913–917. doi:10.1016/j.cemconres.2004.07.035
- Chen, B.; Liu, J. 2004. Properties of lightweight expanded polystyrene concrete reinforced with steel fiber, *Cement and Concrete Research* 34(7): 1259–1263. doi:10.1016/j.cemconres.2003.12.014
- Clarke, J. L. 1993. *Structural lightweight aggregate concrete*. Glasgow: Chapman & Hall. 240 p.
- Domagała, L. 2006. Strength prediction for structural lightweight aggregate concrete, in *The 16<sup>th</sup> International Conference on Building Materials, Ibausil (Internationale Baustofftagung): Proceedings*. September 20–22, 2006, Weimar, Germany, 941–948.
- Domagała, L.; Urban, M. 2006. Reologia lekkich betonów kruszywowych z dodatkiem włókien polipropylenowych [Rheology of lightweight aggregate concrete with polypropylene fibers], in *The 20<sup>th</sup> Scientific-Technical Conference "Jadwisin'06": Proceedings*. May 17–19, 2006, Poland, 117–124.



- Gao, J.; Sun, W.; Morino, K. 1997. Mechanical properties of steel fiber-reinforced, high-strength, lightweight concrete, *Cement and Concrete Composites* 19(4): 307–313. doi:10.1016/S0958-9465(97)00023-1
- Kayali, O.; Haque, M. N.; Zhu, B. 1999. Drying shrinkage of fibre-reinforced lightweight aggregate concrete containing fly ash, *Cement and Concrete Research* 29(11): 1835–1840. doi:10.1016/S0008-8846(99)00179-9
- Kayali, O.; Haque, M. N.; Zhu, B. 2003. Some characteristics of high strength fiber reinforced lightweight aggregate concrete, *Cement and Concrete Composites* 25(2): 207–213. doi:10.1016/S0958-9465(02)00016-1
- Kurugöl, S.; Tanaçan, L.; Ersoy, H. Y. 2008. Young's modulus of fiber-reinforced and polymer-modified lightweight concrete composites, *Construction and Building Materials* 22(6): 1019–1028. doi:10.1016/j.conbuildmat.2007.03.017
- Mačiulaitis, R.; Vaičienė, M.; Žurauskienė, R. 2009. The Effect of Concrete Composition and Aggregates Properties on Performance of Concrete, *Journal of Civil Engineering and Management* 15(3): 317–324. doi:10.3846/1392-3730.2009.15.317-324
- Mirza, F. A.; Soroushian, P. 2002. Effects of alkali-resistant glass fiber reinforcement on crack and temperature resistance of lightweight concrete, *Cement and Concrete Composites* 24(2): 223–227. doi:10.1016/S0958-9465(01)00038-5
- Noumowe, A. N.; Siddique, R.; Debicki, G. 2009. Permeability of high-performance concrete subjected to elevated temperature (600 °C), *Construction and Building Materials* 23(5): 1855–1861. doi:10.1016/j.conbuildmat.2008.09.023
- Park, S. B.; Yoon, E. S.; Lee, B. I. 1999. Effects of processing and materials variations on mechanical properties of lightweight cement composites, *Cement and Concrete Research* 29(2): 193–200. doi:10.1016/S0008-8846(98)00221-X
- Perez-Pena, M.; Mobasher, B. 1994. Mechanical properties of fiber reinforced lightweight concrete composites, *Cement and Concrete Research* 24(6): 1121–1132. doi:10.1016/0008-8846(94)90036-1
- Rao, G. T. D.; Seshu, R. D. R. 2003. Torsion of steel fiber reinforced concrete members, *Cement and Concrete Research* 33(11): 1783–1788. doi:10.1016/S0008-8846(03)00174-1
- Tanyildizi, H. 2009. Statistical analysis for mechanical properties of polypropylene fiber reinforced lightweight concrete containing silica fume exposed to high temperature, *Materials & Design* 30(8): 3252–3258. doi:10.1016/j.matdes.2008.11.032
- Toutanji, H.; Xu, B.; Gilbert, J.; Lavin, T. 2010. Properties of poly (vinyl alcohol) fiber reinforced high-performance organic aggregate cementitious material: Converting brittle to plastic, *Construction and Building Materials* 24(1): 1–10. doi:10.1016/j.conbuildmat.2009.08.023
- Xu, B.; Toutanji, H. A.; Gilbert, J. 2010. Impact resistance of poly(vinyl alcohol) fiber reinforced high-performance organic aggregate cementitious material, *Cement and Concrete Research* 40(2): 347–351. doi:10.1016/j.cemconres.2009.09.006

## LENGVOJO BETONO SAVYBIŲ MODIFIKAVIMAS PLIENINĖMIS FIBROMIS

L. Domagala

Santrauka

Konstrucinis su lengvaisiais užpildais betonas (SLWAC) yra normalaus svorio statybinių medžiagų alternatyva, turinti mažesnę tankį ir gebėjimą pasiekti gana didelį gniuždomąjį stiprį. Nepaisant to, lengvieji užpildai, naudojami vietoj normalaus svorio užpildų, realiai gali pabloginti kai kurias kompozito savybes. Vienas iš lengvojo betono SLWAC savybių tobulinimo būdų yra plieninių fibrų įterpimas į betono sudėtį.

Šiame darbe aptariamas plieninių fibrų poveikis konstrukcinio lengvojo betono su lakiaisiais pelenais savybėms. Tikslui pasiekti buvo parinktos pagal tankį ir gniuždomąjį stiprį dvi skirtingos betono sudėtys su skirtingais (30, 45 ir 60 kg/m<sup>3</sup>) plieninių fibrų tankiais. Paruošti bandiniai buvo naudoti gniuždomajam stipriui ir kitoms savybėms nustatyti. Tyrimų rezultatai parodė, kad plieninių fibrų priedas nepablogino reologinių betono mišinio rodiklių. Nepaisant palyginti mažo fibrų kiekio, labai padidėjo bandinių lenkiamasis ir tempiamasis stipris. Fibros taip pat pagerino deformacines betono savybes. Gauta kompozito gniuždomasis stipris iš dalies priklausė nuo naudojamų plieninių fibrų charakteristikų. Tačiau plieninių fibrų priedas nepakeitė SLWAC tamprumo modulių.

**Reikšminiai žodžiai:** lengvasis betonas, plieninės fibros, gniuždomasis, lenkiamasis, tempiamasis stipris, tamprumo modulis, įtempiai, susitraukimas, reologija, irimo pobūdis.

**Lucyna DOMAGAŁA.** PhD eng., Institute of Building Materials and Structures, Cracow University of Technology. Research interests: concrete technology, especially technology of structural lightweight concrete.