IMPACT RESISTANCE OF SUSTAINABLE SFRCC ROAD PAVEMENT

Jacek Katzer

*Dept of Civil and Environmental Engineering, Koszalin University of Technology,
ul. Śniadeckich 2, 75–453 Koszalin, Poland
E-mail: jacek.katzer@tu.koszalin.pl*

Abstract. The examinations of properties of steel fiber reinforced cement composite (SFRCC) specimens do not reflect properties of these composites in an actual pavement, tunnel or bridge. Each, even the most basic road pavement or structure, works within constantly changing conditions, where different loads appear and disappear in time. The impact strength of SFRCC is strongly influenced by a number of factors that tend to increase the statistical variations. Therefore the design of SFRCC elements should be based on statistical considerations of their properties. A drop weight test is the simplest test for evaluating impact resistance as the relative performance of plain cement composite and SFRCC containing different types and volume fractions of fibers. The research program was divided into three main stages. The first stage covered VeBe test, measurement of density of hardened composite and compressive strength. The main aim of the first stage of this research program was to check quality and homogeneity of the cement composites. The second stage covered multiple drop-weight load. During the drop weight procedure, the ultrasound test was conducted after each five impacts. The third stage covered statistical analysis of achieved results. The carried out experiments have shown that the ultrasound method combined with statistical methods are well used to monitor changes of mechanical properties of SFRCC used for road pavements or structure during dynamic destruction process. Time needed for the ultrasound wave to pass through a composite was main information about process of destruction occurring during an impact test (internal cracks in the composite structure make the way that ultrasound wave propagates longer comparing to undamaged structure of the composite). The results of the ultrasound propagation time measurements were analyzed based on a statistical approach.

Keywords: concrete, fiber, pavement, aggregate, reinforced, impact.

1. Introduction

Cement composites modified by steel fibre become more and more popular construction material in civil and structural engineering (Zollo 1997). The actual origins of steel fiber reinforced cement composite (SFRCC) go back more than one hundred and thirty years. The first patent for SFRCC was filed in 1874 in California by A. Bernard (Maidl 1995). The addition of steel fibers significantly improves several mechanical properties of cement composite (Ponikiewski 2011; Song, Hwang 2004; Szmigiera 2007; Šalna, Marčiukaitis 2007; Veselý, Frantík 2011). The main advantage of harnessing such composites, are their dynamic properties. The dynamic mechanical performance of SFRCC under impact or dynamic loading has drawn increasing attention in recent years because of a rapid adoption of SFRCC in bridges, pavements and tunnels. However, there is still a lack of information about dynamic performance of SFRCC. Dynamic properties of SFRCC were the main factor which decided that these composites are now used to erect airport runways, highway paving,

bridge decks, marine structures, and varied types of thin-shell structures (Balaguru, Shah 1992; Johnston 2001; Maidl 1995) and composite steel-SFRC columns (Szmigiera 2007). There are also examples of other SFRC structures exposed to impact dynamic loads which originate from sources such as impact from projectiles (Luo *et al.* 2000), wind gusts, earthquakes, moving vehicles, and industrial machines (e. g. pneumatically powered hammers). The impact strength of SFRCC (toughness under impact) is strongly influenced by a number of factors (e.g. mixing, casting, sampling) that tend to increase the statistical variations (Nataraja *et al.* 1999). Therefore, the design of SFRCC elements should be based on statistical considerations of their properties.

2. Research program

The impact resistance of SFRCC is measured using numerous different test methods (Nataraja *et al.* 1999). A drop weight test is the simple test for evaluating impact resistance as the relative performance of plain cement composite and

SFRCC containing different types and volume fractions of fibers (Song *et al.* 2005). For the impact test a drop-weight apparatus was used. A steel ball of 2381 g was falling onto the centre of a plate ((250×250×50) mm) from a fixed height of 500 mm. The plate was freely supported on two parallel edges. Energy passed to the plate during one weight drop was equal to 11.7 J. After each weight drop a plate was visually examined considering crack appearance. Due to the complex deterioration process (micro and macro cracks forming) of SFRCC element during multiple impacts the question was raised how to define and determine its beginning. It was decided that "the first crack" attempt, thoroughly described in literature (Johnston 2001; Maidl 1995), will be employed in this research programme. According to this method "the first crack" is recognised when it propagates through a whole cross-section of a specimen (it is clearly visible on both surfaces of a plate). "The first crack" is critical for plate mechanical behaviour (Johnston 2001; Maidl 1995) and for possible fast corrosion of steel fibre exposed to the elements. During the procedure of the drop-weight test an influence of plastic deformation to cracking behaviour is not followed unlike during the traditional beam flexural test according *ACI 544-3R 08 Guide for Specifying, Proportioning, and Production of FRC, ASTM C1018-97 Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete, EN 14651 Test Method for Metallic Fibre Concrete – Measuring the Flexural Tensile Strength, and JSCI-SF4 Method of Tests for Flexural Strength and Flexural Toughness of Fibre Reinforced Concrete Commentary.*

The number of weight drops until the appearance of the first crack and until the ultimate destroy of the plate was counted. Taking into account the main factors influencing data scattering of the impact test of SFRCC (the variability, the non-homogeneous internal structure), the research program was planned to cover a large number of tests (over 1800).

Materials consisted of Portland cement with a 28-day compressive strength of 32.5 MPa (CEM II/B-V 32.5 R), fine aggregate of a max size of 4 mm, tap water for mixing and curing and superplasticizing admixture containing silica fume. The superplasticizer was codified as CRSP, characterized by density equal to 1.45 g/cm^3 and batched in quantities equal to 1% (by weight of cement). The water/cement ratio was 0.50. The final proportions per cubic meter of cement composite for both plain and fiber-reinforced consisted of 400 kg cement and 1760 kg waste fine aggregate.

The SFRCC matrix was prepared on the basis of local fine aggregate. In the local Pomeranian pit deposits, fractions from 0 to 4.0 mm constitute 97% by weight of all aggregate (Katzer, Kobaka 2006; Katzer 2012). Approximately half of documented deposits are constituted by deposits hydroclassified during the exploitation. This sand is a by-product of hydroclassification of natural all-in-aggregate. During the process of hydroclassification, all-in-aggregate is divided into gravel and sand. There is a deficit of gravel in the region, therefore gravel received during hydroclassification of all-in-aggregate is constantly being sold. Fine aggregate received during the same process, due
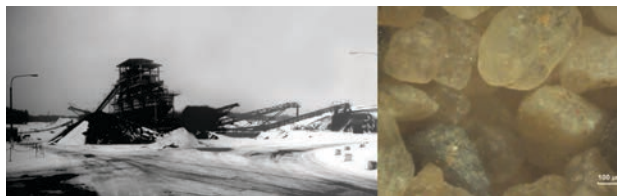

Fig. 1. Aggregate pit in Sępólno Wielkie and its fine aggregate

Fig. 2. Magnified (125 times) ending of the steel fibre

to its excessive amount, is recognized as a waste and stored on continuously growing wasteheaps.

Fine aggregate used in this research study was obtained from aggregate pit in Sępólno Wielkie (Fig. 1). This aggregate has a lower grain-size distribution, a smaller amount of stone dust and a higher content of minerals and crystal rocks than the pit sand obtained from the same mine. In the Fig. 1 fine aggregate used during the research programme is shown. White grains are quartz, black grains are granite. Properties of aggregate utilized for the composite mixes were described in detail in previous publications (Katzer, Kobaka 2006; Katzer 2012).

Currently, in the world there are about 30 major producers of steel fibers used for modifying concrete and they offer over 100 types of fiber (Katzer, Domski 2012; Odelberg 1985). Over 90% of currently produced fibers are shaped fibers of five most popular types: hooked, crimped, coned and mechanically deformed. Other types of fiber are encountered relatively seldom and they are almost always produced for specific orders of clients. A statistical analysis of the assortment produced in the world allows claim that 67.1% of fiber consist of the hooked type. Other most popular fibers are: straight fibers (9.1%), mechanically deformed fibers (9.1%), crimped fibers (7.9%) and other fibers of different endings (6.6%) (Katzer, Domski 2012).

The matrix was modified by the addition of steel hooked end fiber (as most popular in civil and structural engineering and thoroughly described in literature) with an aspect ratio $\frac{l}{d} = 77$, circular cross-section and tensile breaking strength of 1100 MPa. The addition of fiber varied from 0% to 2.8% by volume. All the matrix mixtures had the same contents – the only difference between mixtures was the volume of the applied steel fiber. Magnified ending of used fiber is presented in the Fig. 2.

A rotary drum mixer was used to prepare composite mixtures. Workability of fresh mix was tested after mixing using VeBe apparatus. Compaction of fresh fibrous mixtures was performed externally, using a vibrating table. Each specimen was vibrated in two layers, with each layer filling half of the thickness. Each layer was vibrated for 20 s (until a thin film of bleed water appeared on the surface) (Tountanji, Bayasi 1998). The first step of curing was to keep the specimens in their moulds covered with polyethylene sheets for 24 h. The specimens were then removed from their moulds and then cured in water conditions for 50 days. The next step of curing was drying specimens in an oven for 8 days and then cooling them down for 24 h. All specimens were tested after 60 days of curing. The examination results were statistically processed, and the objectivity of the experiments was assured by the choice of the sequence of the realizations of specific experiments from a table of random numbers (Borovikov, Borovikov 1998; Nataraja 1999).

The research program was divided into three main stages. The first stage covered VeBe test, quality control of the specimens, and measurement of density of hardened
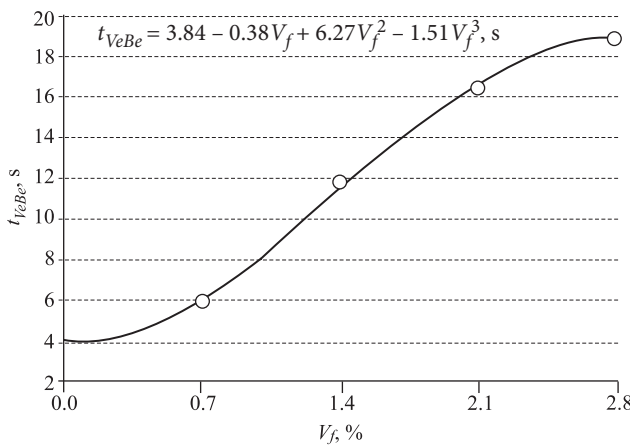

Fig. 3. Workability of SFRCC tested according to the *VeBe* procedure
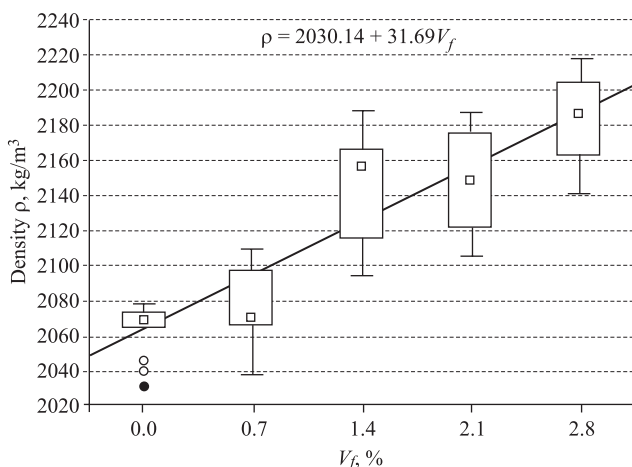

Fig. 4. Density of tested SFRCC

composite and compressive strength test. The main aim of the first stage of this research program was to check the quality and homogeneity of the cement composites. Achieving a homogeneous dispersion of fibers throughout the cement composite mass seems to be the most significant concern while preparing and casting a SFRCC mix. Any mistake during performing the mixing procedures can breed "balling" (Sather 1974) (these "balls" may consist only of the fibers themselves or a combination of materials present in the cement composite mix, such as fibers and cement slurry, fibers and sand, and fibers coated with cement) and poor dispersion of fibers. It is also known that the method used for compaction and the degree of compaction affect the fiber orientation (Johnston 2001; Maidl 1995). Upon placement and compaction of steel fibrous composite, fibers tend to settle towards the bottom part of the casted element. Depending on the flowability of the fibrous mixture, fiber settlement may be extensive, moderate or mild, and test results (e.g. of flexural strength) are affected accordingly (Toutanji, Bayasi 1998).

In the research program an electromagnetic induction device exploiting low frequency electromagnetic field was used to check fiber spacing in the hardened composite. During the quality control procedure the time-varying magnetic field was generated which propagated into the element and reacted with the electric and magnetic properties of the composite and its reinforcement. The coil system is able to detect targets up to 100 mm deep into the composite. The magnetic apparatus intended by manufacturer for detecting reinforcement bars, the diameter of bars and thickness of cement composite cover was employed. The electromagnetic field was applied to characterize the volume fraction of steel fibers in prepared SFRCC specimens. The deviation from theoretical behavior served as the basis for quantifying fiber dispersion. The results of the electromagnetic quality control of specimens confirmed that there are no fiber dispersion issues e.g. gravitational settling of fibers or local aggregation.

The second stage covered impact test. During the drop weight procedure, the ultrasound test was conducted after each five impacts. The employed ultrasound apparatus had two transducers (one pulse generator and one receiver) and was generating an ultrasound pulse with a frequency of 54 kHz. The third stage covered statistical analysis of achieved results.

3. Results

Workability of tested mixes varied from $t_{VeBe} = 4$ s to $t_{VeBe} = 19$ s. Mixes were becoming "stiffer" together with the increased addition of steel fibres. Results of workability tests are presented in Fig. 3. Compressive strength increased from $f_{cube} = 46.5$ MPa for unreinforced composite (plain matrix) to $f_{cube} = 53.5$ MPa for composite of fibre contents $V_f = 2.1\%$. Density of the composites with a different fiber volume fraction is shown in a form of a box-whiskers graph in Fig. 4.
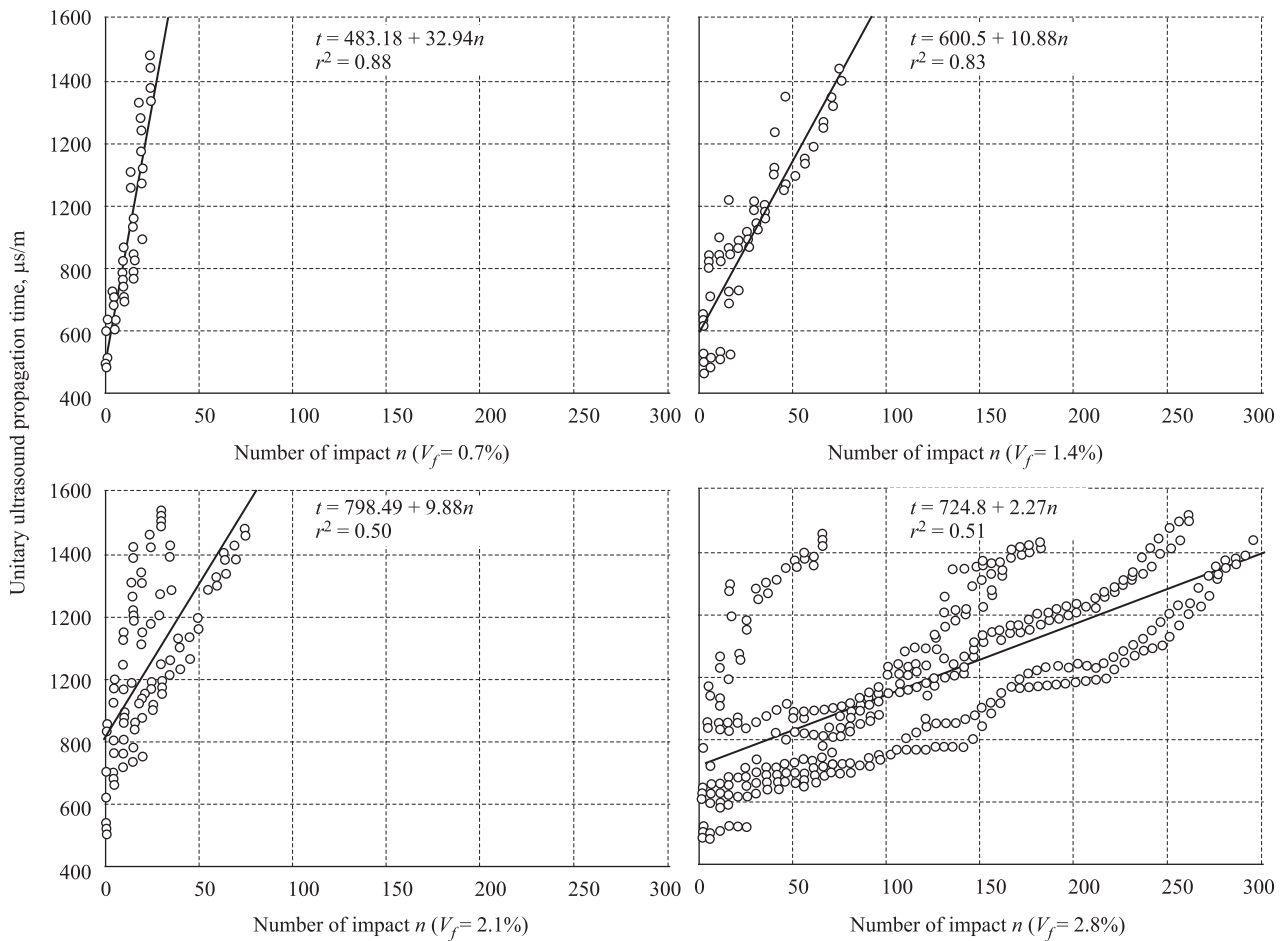
Fig. 5. Unitary ultrasound propagation time, µs/m

A strong linear correlation is observed between the two parameters characterizing composite material (r^2 over 0.7). Equations of skewness (1) and kurtosis (2) of density depending on fiber volume fraction show that best homogeneity of results can be achieved at relatively low volume fractions of fiber.

$$S = -1.56 + 1.94V_f - 0.54V_f^2, \qquad (1)$$

$$K = 1.97 - 4.29V_f + 1.17V_f^2, \qquad (2)$$

where S – skewness of density; K – kurtosis of density; V_f – fiber volume fraction, %.

Unitary ultrasound propagation time measured in a material, µs/m, (Fig. 5) strongly corresponds to the degree of destruction caused by impacts. Impacts destroy structure of the material causing the appearance of cracks. The more cracks appear in a material, the longer route of the ultrasound wave (also a unitary ultrasound propagation time) (Katzer, Kobaka 2007). Fig. 5 shows that failure of the tested material with low fiber volume fraction occur much earlier (about 20 impacts) than in the case of material with high volume fraction applied (up to 300 impacts). Slope coefficients of linear functions are approx equal to

33, 11, 10 and 2 for fiber volume fractions 0.7; 1.4; 2.1 and 2.8 respectively, indicating slowing the cracking progress. The number of impacts to first observed crack and to ultimate destruction were counted and presented in the Fig. 6. Specimens were recognized as destroyed when deflection was equal to 20 mm. The results confirm the phenomenon
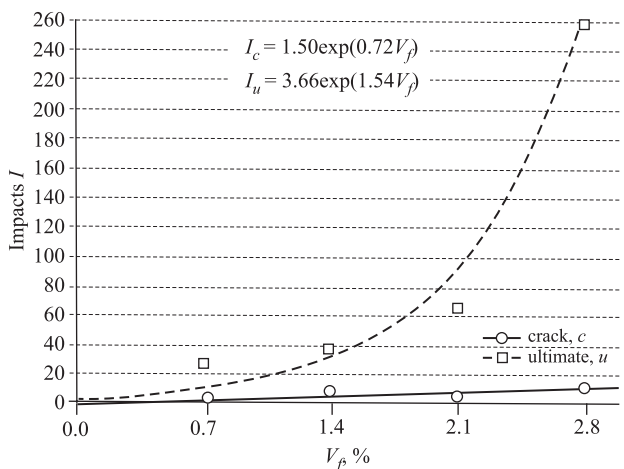

Fig. 6. Number of impacts to first observed crack and to ultimate destruction m
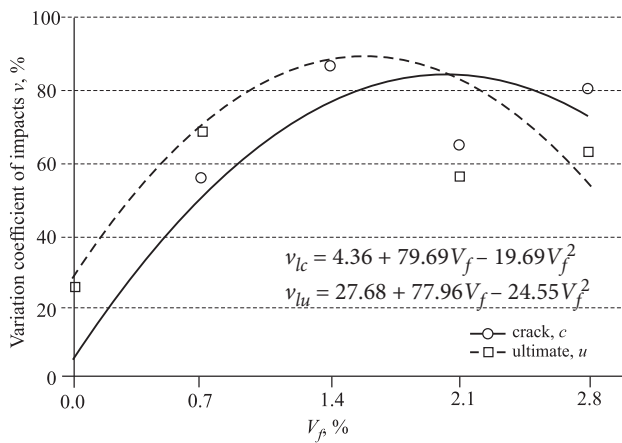
Fig. 7. Variation coefficient of impact results

The equations shown in the figure:

$$v_{lc} = 4.36 + 79.69V_f - 19.69V_f^2$$
$$v_{lu} = 27.68 + 77.96V_f - 24.55V_f^2$$

of increased impact resistance of composites containing high volume fractions of fiber. The best fit was obtained for exponential function.

The chart shows that the composite containing 2.8% of fiber is about 10 times more resistible for impacts causing ultimate failure than the one containing 0.7% of fiber. Variation coefficient of impact results with highest values was observed for fiber volume fractions ranging from 1.4 to 2.1%. Over the value of 2.1% test results were more stable, however, still relatively high (Fig. 7).

4. Conclusions

The carried out experiments have shown that the ultrasound method combined with statistical methods are well used to monitor changes of mechanical properties of SFRCC during dynamic destruction process. Time needed for the ultrasound wave to pass through a composite was main information about process of destruction occurring during an impact test. The results of the ultrasound propagation time measurements were analyzed based on a statistical approach.

Composites modified by high volume fraction of fiber (2.8%) are characterized by impact resistance up to 10 times larger than composites modified by low volume fraction of fiber (0.7%). The phenomenon is explained as follows: fibers are able to carry most of the stress only after matrix cracks so the more cracks appear, the more fibers are employed into carrying stress. The process of destruction begins when first crack appears, which happens long time before the ultimate failure of a specimen, even in composites with high fiber volume fractions. Recording the destruction process of fiber composite and plain matrix directly before failure brings useful and detailed information about the influence of fiber volume fraction on composite behavior. Future research should cover assessing impact resistance of SFRCC applying sophisticated nondestructive equipment allowing to measure a number of cracks, their width, depth, direction and distance from an impact.

References

Balaguru, N.; Shah, S. P. 1992. *Fiber Reinforced Cement Composites*. McGraw Hill, New York. 530 p. ISBN 0070564000.

Borovikov, I. P.; Borovikov, V. P. 1998. *STATISTICA: Data Preparation and Analysis*. Moscow.

Johnston, C. D. 2001. *Fiber Reinforced Cements and Concretes*. Taylor & Francis. 500 p. ISBN 1851664157

Katzer, J.; Domski, J. 2012. Quality and Mechanical Properties of Engineered Steel Fibres Used as Reinforcement for Concrete, *Construction and Building Materials* 34: 243–248.
http://dx.doi.org/10.1016/j.conbuildmat.2012.02.058

Katzer, J. 2011. Impact and Dynamic Resistance of SFRCC Modified by Varied Super-Plasticizers, *Archives of Civil and Mechanical Engineering* 11(1): 103–113.
http://dx.doi.org/10.1016/S1644-9665(12)60177-0

Katzer, J.; Kobaka, J. 2009. Influence of Fine Aggregate Grading on Properties of Cement Composite, *Silicates Industriels* 74(1–2): 9–14.

Katzer, J.; Kobaka, J. 2007. Impact Resistance of SFRM Modified by Varied Superplasticizers, *in Proc. of Transcom 7th European Conference of Young Research and Science Workers*. June 25–27, 2007, Žilina, Slovakia. 61–64.

Katzer, J.; Kobaka, J. 2006. The Assessment of Fine Aggregate Pit Deposits for Concrete Production, *Kuwait Journal of Science and Engineering* 33(2): 165–174.

Luo, X.; Sun, W.; Chan, S. Y. N. 2000. Characteristics of High-Performance Steel Fiber-Reinforced Concrete Subject to High Velocity Impact, *Cement and Concrete Research* 30(6): 907–914.
http://dx.doi.org/10.1016/S0008-8846(00)00255-6

Maidl, B. R. 1995. *Steel Fibre Reinforced Concrete*, Ernest&Sohn, Berlin 1995, Germany.

Nataraja, M. C.; Dhang, N.; Gupta, A. P. 1999. Statistical Variations in Impact Resistance of Steel Fibre-Reinforced Concrete Subjected to Drop Weight Test, *Cement and Concrete Research* 29(7): 989–995.
http://dx.doi.org/10.1016/S0008-8846(99)00052-6

Odelberg, G. 1985. Producing and Promoting of Swedish Steel Fibers to the Market, in *Proc. of Steel Fiber Concrete US-Sweden Joint Seminar*. June 3–5, 1985, Stockholm, Sweden.

Ponikiewski, T. 2011. The Rheology of Fresh Steel Fibre Reinforced Self-Compacting Mixtures, *ACEE Architecture Civil Engineering Environment* 4(2): 65–72.

Sather, W. R. 1974. Fibrous Concrete Field Batching Sequences, *ACI Journal*: 504–505.

Song, P. S.; Hwang, S. 2004. Mechanical Properties of High-Strength Steel Fiber-Reinforced Concrete, *Construction and Building Materials* 18(9): 669–673.
http://dx.doi.org/10.1016/j.conbuildmat.2004.04.027

Song, P. S.; Wu, J. C.; Hwang, S.; Sheu, B. C. 2005. Statistical Analysis of Impact Strength and Strength Reliability of Steel-Polypropylene Hybrid Fiber-Reinforced Concrete, *Construction and Building Materials* 19(1): 1–9.
http://dx.doi.org/10.1016/j.conbuildmat.2004.05.002

Szmigiera, E. 2007. Influence of Concrete and Fibre Concrete on The Load-Carrying Capacity and Deformability of Composite Steel-Concrete Columns, *Journal of Civil Engineering and Management* 13(1): 55–61.

Šalna, R.; Marčiukaitis, G. 2007. The Influence of Shear Span Ratio on Load Capacity of Fibre Reinforced Concrete Elements with Various Steel Fibre Volumes, *Journal of Civil Engineering and Management* 13(3): 209–215.

Toutanji, H.; Bayasi, Z. 1998. Effects of Manufacturing Techniques on the Flexural Behaviour of Steel Fiber-Reinforced Concrete, *Cement and Concrete Research* 28(1): 115–124. http://dx.doi.org/10.1016/S0008-8846(97)00213-5

Veselý, V.; Frantík, P. 2011. Reconstruction of Fracture Process Zone during Tensile Failure of Quasi-Brittle Materials, *Applied and Computational Mechanics* 4(2): 237–250.

Zollo, F. R. 1997. Fiber-Reinforced Concrete: an Overview after 30 Years of Development, *Cements and Concrete Composites* 19(2): 107–122. http://dx.doi.org/10.1016/S0958-9465(96)00046-7