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1. Relationship between mechanical properties and conductivity of SCC mixtures with steel fibres

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Abstract

Self-compacting concretes are more and more often combined with steel fibre reinforcement. In the paper the relationship between mechanical properties and conductivity of self-compacting concretes mixtures with steel fibres was studied. It was proven that there is a correlation between the amount of steel fibre and conductivity. However this relationship is not linear.

Keywords: conductivity, SCC, steel fibre, concrete

1.1. Introduction

The use of self-compacting concrete in combination with steel fibres increases its importance. With respect to some important properties such as the reduction of surface cracking, the improvement of some mechanical properties (e.g., bending strength), it is desirable to examine self-compacting concrete mixtures with steel fibers (Pająk and Ponikiewski, 2013). There is some disadvantages, of course. For fiber-concrete is limited design guidance (see e.g. FIB, 2011), there are different views of preparing mixtures themselves, and also there is some incompatibility in test methods. Since the durability of concrete exposed to aggressive agents is a significant issue. Thus, it is important to evaluate the ability of new concrete designs to resist harsh environment (Ghosh and Tran, 2015; Seddik Meddah, 2015; Ghosh *et al.*, 2017; Nguyen *et al.*, 2017). One of typical evaluation of quality of concrete against chloride ingress are based on evaluation of chloride profile(see e.g. Nordtest NTBuild 443, 1995; AASHTO T259, 2012). Those penetration test procedures require exposure of samples to chloride solution for several weeks, analysis of chloride profile using drilling or grinding, chemical analysis of chloride content in the profile with subsequent computation of steady-state diffusion coefficient. The electrochemical procedures (AASHTO-TP95, 2011; ASTM C1202, 2012) are significantly faster. It is accepted that concrete ability against the penetration of aggressive agents is related to the passage of electrical current (electrical resistivity) (Feliu *et al.*, 1996; Morris, Moreno and Sagüés, 1996; Smith *et al.*, 2007; AASHTO-TP95, 2011). The evaluation via resistivity is nowadays rather standard in United States. The steel is much more conductive and that affects the reading. Since fibres of metallic nature have a significant influence on the measurement of the electrical resistance of concrete, which serves to determine the conductivity and consequently the coefficient of diffusion (Feliu *et al.*, 1996),

Evaluation of electrochemical properties on steel fibres reinforced concrete is not recommended (see e.g. Abad Zapico, 2015). The more advanced method such as Electrical Impedance spectroscopy shall be used if the steel is embedded in concrete (Martínez and Andrade, 2011; Jaśniok, 2013).

Since the knowledge of these electrochemical properties, may be related to the knowledge of diffusion of chloride ions (Lu, 1997; Konečný *et al.*, 2017) and relate the material property to the model of the concrete durability. Thus it would be interesting to be able to filter the effect of embedded steel fibres.

Thus, the evaluation of the effect of the amount of fibres on the concrete resistivity is conducted in this chapter. On the other hand, the partial task of measuring can be to prove whether the electrochemical methods used to determine the diffusive properties of concrete are at all appropriate in the use of wires or, conversely, totally inappropriate.

1.2. Laboratory experiments

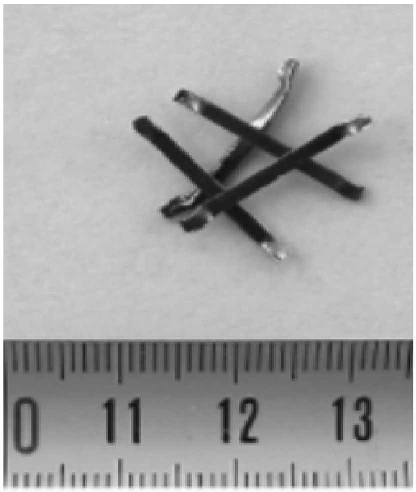

Fig. 1.1. Steel fibres KE20/1.7

Laboratory experiments were composed of several mechanical tests and electrical resistance measurements (AASHTO-TP95, 2011) on four concrete mixtures. The laboratory experiments were prepared at the laboratories of Silesian University of Gliwice and VŠB - Technical University of Ostrava.

The reference concrete was formed from Ordinary Portland Cement (OPC). The Self-Compacting Concrete (SCC) with several values of added steel fibres - 0 %, 1 % and 2 % of weight were casted in order to investigate the effect of fibres. The steel fibres were of type KE20/1.7 (Fig. 1.1). The composition of the mixtures is shown at Table 1.1 and it is based on earlier SCC research at the SUT in Gliwice (Pająk and Ponikiewski, 2013; Sucharda *et al.*, 2017).

Table 1.1. Characteristics mixtures

Mixture No.	OPC	SCC 0%	SCC 1%	SCC 2%
Cement type I 42.5 R	313 kg/m3	490 kg/m3		
Water	164 kg/m3	201 kg/m3		
Sand	387 kg/m3	807 kg/m3		
River gravel	1546 kg/m3	807 kg/m3		
Superplasticizer	-	12.25 kg/m3		
Stabilizer	-	1.96 kg/m3		
Steel Fibres	-	-	80 kg/m3	160 kg/m3
Water/cement ratio (W/C)	0.52	0.41		

It should be noted that the cement applied in the mixture has been in laboratory storage for more than two years and partial hydration has been in progress. The concrete slump test was executed and all mixtures the similar value of workability. However, the data for slump were not properly recorded.

A complete range of tests including basic mechanical properties, fracture test and electrical resistance measurements in the (AASHTO-TP95, 2011), the Chloride Rapid Penetration Test (ASTM C1202, 2012) and accelerated penetration tests with chloride (Nordtest NTBuild 443, 1995) were performed.

Fig. 1.2. Example of preparation of laboratory samples for one set of mixtures

In Fig. 1.2 we can see a photograph of the set of laboratory samples consisted of seven large cylinders (diameter 150 mm, height 300 mm) six smaller cylinders (diameter 100 mm, height 250, 200 and 100 mm), four cubes (dimension 150 mm) and three beams (150 x 150 mm, length 450 mm). Each of the four mixtures contained such a set of samples. Three small cylinders and one large, with a different shape coefficient, were used for the tests described herein.

The evaluated experiment, calculations and results are part of the campaign discussed partly with respect to SCC without fibres in (Lehner, Konecny and Ponikiewski, 2018).

1.3. Mechanical properties

The basic measurements on each of the four sets were mechanical properties. Measurements of compressive strength were performed on standard cubes and cylinders samples (see Fig. 1.3). Further, a tensile splitting strength measurement was performed and a modulus of elasticity was determined (see Fig. 1.4).

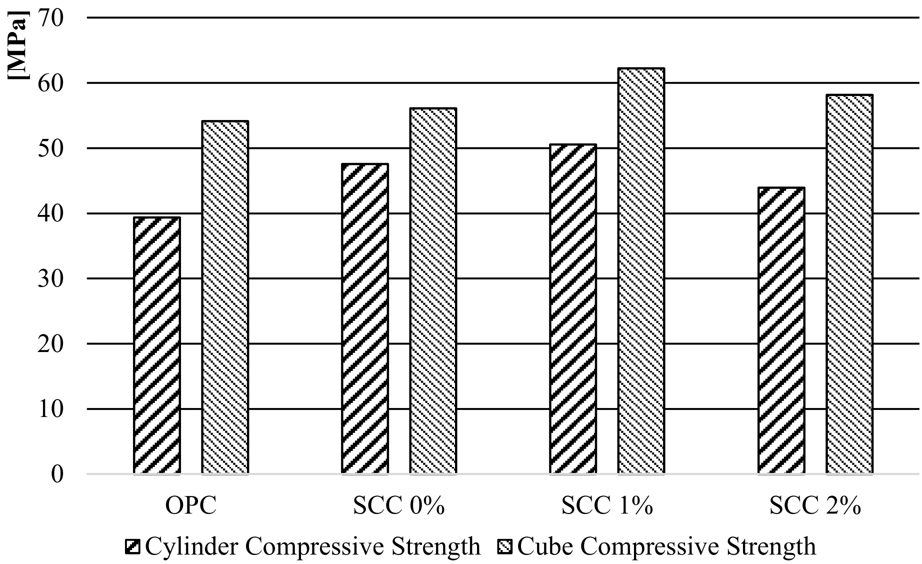

Fig. 1.3. Results of compressive strength for four mixtures sets

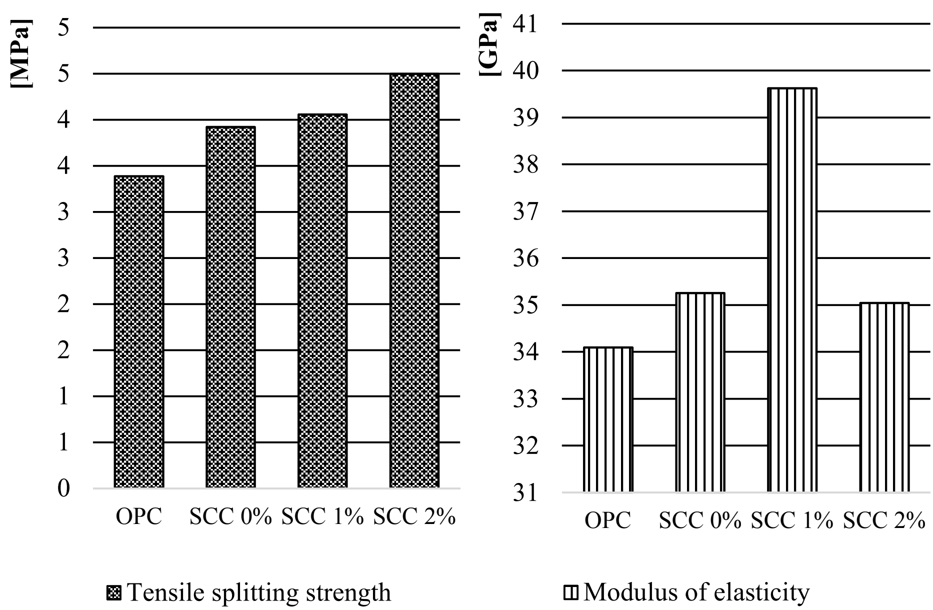

Fig. 1.4. Results of material characteristics for all mixtures

The results shown in the Fig. 1.3 and Fig. 1.4 can be interpreted from several aspects. Firstly, it is possible to compare the results between mixture from Ordinary Portland Cement and mixture from Self-Compacting Concrete. In all cases, SCC values are higher than OPC, but their difference is not as large as expected.

Another option is to look at the material properties compared to the number of steel fibres in the SCC mixture. It depicts that the higher is relative weight value of steel fibres, the higher is the tensile spitting strength.

On the other hand, other mechanical properties cannot be correlated like that. The greatest deviation can be seen in the modulus of elasticity, where the SCC 1%, i.e. 1% by weight of steel fibres per total weight, is almost twice the value of the other (SCC mixtures with 0% and 2% of steel fibres).

The modulus of elasticity is also interesting in view of the fact that for SCC 2% it is slightly smaller than for SCC 0%. The compressive strength view reveals that the SCC 2% is weaker than SCC 0% and SCC 1% in test at cylinder. But the in test at cube the value of SCC 2% is weaker than SCC 1% only. It is consistent with the typical limitation of the application of steel fibres up to 1.55 by mass of concrete. Further comparison and evaluation of results are contained at the end of the chapter.

1.4. Electrochemical properties

There are three procedures of detection of concrete diffusion coefficient. It can be evaluated using methods of rapid chloride penetration test (Nordtest NTBuild 443, 1995; AASHTO-T259, 2012), accelerated penetration tests with chloride (ASTM C1202, 2012) as well as surface measurement of electrical resistivity using Wenner probe (AASHTO-TP95, 2011), as mentioned above. For the purpose of the paper, the results from the electrical resistance measurement of Wenner's probe are selected.

The Wenner probe consists of four electrodes with a pitch of approx. 5 cm. The external electrodes use electrical current and the internal electrodes measure the electrical potential difference. The benefit of the method is rapid manipulation of instruments and samples. The method is non-destructive so the repeated measurement is possible in order to obtain to determine the time depending of diffusion.

Unfortunately, this measurement method may have a relatively large variation, partly due to the heterogeneity of the test material and also by the use of rather uncontrollable contact conditions. The contact between the electrodes and the concrete is maintained via a wet sponge where the electrical connection is influenced by the contact pressure level and saturation of the sponge. After casting, the samples are cured in a water bath or lime water.

When using a lime bath, the container is filled with saturated lime solution to the edge and closed so that it is airtight. The samples are tested dry on a dry surface. The test of resistance for each of the cylinders is conducted four times around a diameter.

It should be noted, that surface resistivity can be converted to volume resistance using geometric correlation relationships (Morris, Moreno and Sagüés, 1996).

Knowledge of the electrical resistance of the concrete can be further used. The inverse parameter to the resistance is conductivity σ (S / m). Many factors have influenced these properties: relative humidity, type of cement used, w / c ratio, the presence of chloride ions or among others (Bertolini *et al.*, 2004). It is well-known, that electrical properties are influenced by conductive materials. Thus, it may be interesting to note the electrical conductivity values for self-compacting concrete with steel fibres admixtures.

As mentioned, it is a non-destructive test. Thus it is possible to measure electrical properties during maturing of concrete. In our case, it was tested at 7, 14, 28, 56, 91 and 161 days after concreting. The initial results of these tests is the evaluation of change in conductivity over time for all four mixtures under study (see Fig. 1.5.). Several interesting results can be seen in the Fig. 1.5. At the first measurement, 7 days after concreting, the OCP and SCC mixtures are different. Similarly, the weight ratio of steel fibres significantly influences the conductivity value, which was expected.

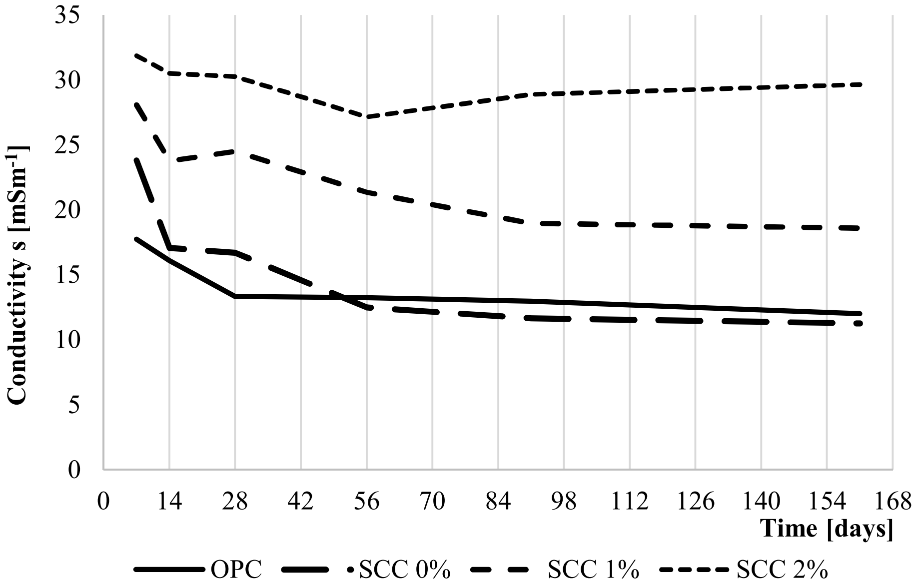

Fig. 1.5. The resulting of calculation conductivity over time for all the studied mixtures

Looking at the change in conductivity over the time for individual mixtures, we may derive following findings. First of all, the OPC mixture significantly reduces the conductivity between the seventh and the twenty-eighth day, but subsequently decreases its value less.

For SCC mixtures, pikes in graphs are observed. Although the relationships of pikes between 14 and 28 days are visible in all three mixtures, their absolute difference cannot be considered as constant or similar. Even with SCC 2%, the conductivity increases slightly from 56 days (see Fig. 1.6.).

Thus the absolute difference between the time-dependent conductivities of SCC with fibres is derived at Fig. 1.6., where the conductivity of SCC without fibres were subtracted from respective values of SCC with 1%, and SCC 2% of fibres, respectively.

It can be seen that if the influence of the conductivity based on the amount of added steel fibres would be proportional than we observe to horizontal lines in Fig. 1.6. This is not the case here. Thus there are also other influences that affect the readings such as start of corrosion of steel fibres.

Since mechanical properties have been measured at 28 days age only, the conductivity is compared with this data at this point in time. The Fig. 1.7. shows the conductivity results for all 4 mixtures under study at 28 days. These results are evaluated in the next chapter.

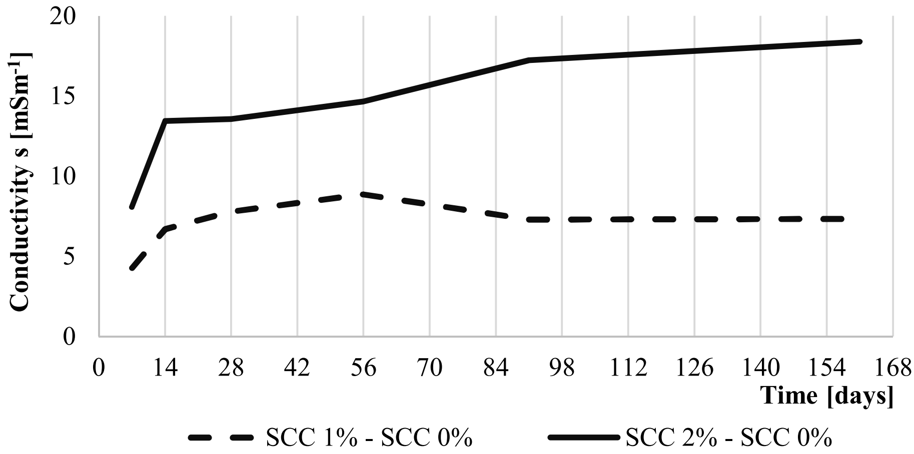

Fig. 1.6. Conductivity results for SCC 1% and SCC 2% after subtraction of SCC 0%

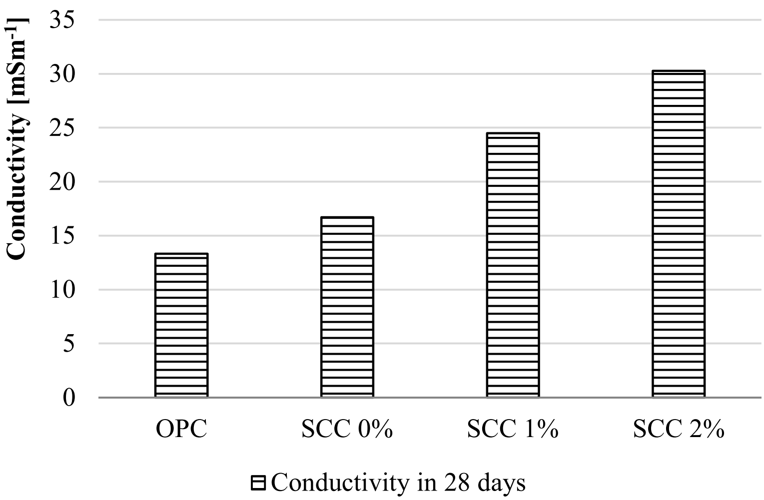

Fig. 1.7. The resulting of calculation conductivity all the studied mixtures at the age 28 days

1.5. Comparison of results

For the purpose of comparison, OPC mixture results were considered as the base values (100%), and the SCC mixtures difference are shown in the Fig. 1.8. There is relative values for cube and cylinder compression strength, tensile splitting strength, modulus of elasticity and electrical conductivity.

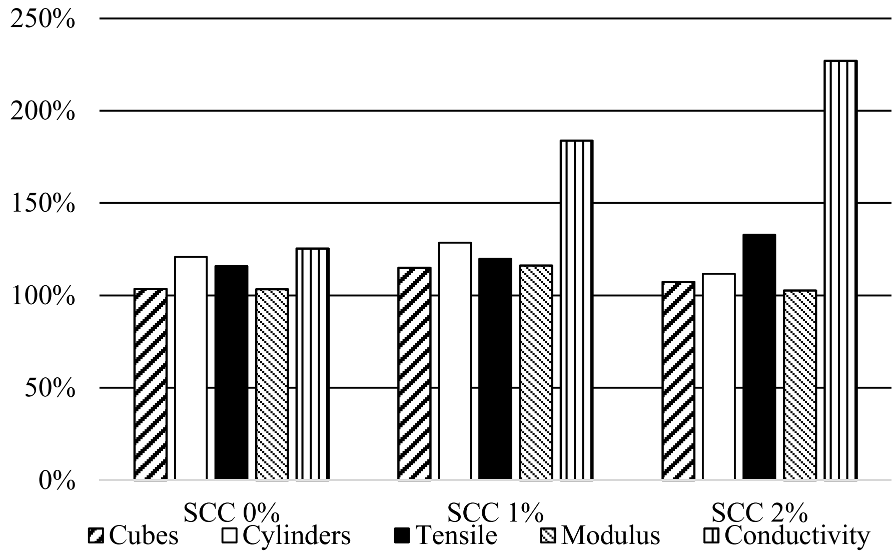

Fig. 1.8. Comparison of measured electrical conductivity values and material properties of SCC mixtures as a percentage of the OPC mixture values at the age 28 days

Looking at the percentage results, the conductivity is noticeably affected by the amount of steel fibres as expected. For mechanical properties such differences are not, and even there is not always, a gradual increase. For a SCC 2% mixture, values of cube and cylinder compression strength, modulus of elasticity are smaller. Only tensile splitting strength gradually increasing.

1.6. Conclusions

The comparison of relatively fast method for the evaluation of concrete ability to resist aggressive agents was conducted on the sample self-compacting concrete. There was correlation between the amount of steel fibres and conductivity as expected. However this relationship was not linear.

It should be noted that testing of mechanical properties over time could have contributed to the possibility of a subsequent correlation with the measurement of electrical conductivity. Since the conductivity measurement using Wenner's probe is a non-destructive and simple test, if it finds certain correlation relationships, its use will be widely used. On the other hand, mechanical properties and electrochemical properties can influence different factors in a way that cannot always be determined in the same way. For example, in the case of a 2% SCC mixture, it is possible to estimate that there is excessive porosity. This causes some worse mechanical properties and, on the contrary, tends to increase the electrical conductivity of the saturated material. Also the cement applied in the mixture was in laboratory storage for more than two years and partial hydration has been in progress. Authors assumes that this affected the results.

From the point of view of the amount of fibres in the concrete, it would be advisable to prepare other mixtures, e.g., 1.2%, 1.4%, etc. That can leads to find the threshold at which the increasing properties change to decreasing.

The presented results are part of a campaign that includes another electrochemical tests, three-point bending fatigue test, calculation of the diffusion coefficient etc. However, the evaluation is still ongoing and the results will be published in a comprehensive work.

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