Possibility of using SFR-SCC for the production of the LILW disposal container

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Abstract. The disposal container with low and intermediate level radioactive waste (LILW) was developed using self-consolidating concrete (SCC), which provides long term mechanical properties and extremely low permeability for liquids. In the paper, some results of additional investigations are presented, which complement the assessment of the behaviour of SCC during use. The main focus is the presentation and discussion of the results of SFR-SCC (steel fibre reinforced - self-consolidating concrete) tests in fresh and harden state. From these results it can be seen that there is a possibility of further improving the properties of the SCC and thus the container.

1. Introduction

SCC was developed in the framework of the development project for the construction of a low and intermediate-level radioactive waste (LILW) disposal container. It is used for the production of reinforced concrete walls, bottom and container cover. In addition to the SCC, the following two composites were developed: 1. filling mortar to fill the space between the inserted barrels with LILW and the inner surface of the container and 2. sealing mortar to seal the unfilled space between the filling mortar and the inner surface of the cover and to seal the contact between the cover and the top surface of the walls.

Within the project, the requirements for the properties of the basic materials used for the preparation of composites and for the properties of all three composites (SCC, filling and sealing mortar) have been determined. These requirements are specified in the Program of testing of containers, measurements and tests [1]. They are also given in the paper by Sinur and Duhovnik [2]. In order to obtain the Slovenian Technical Approval (STA), it was necessary to develop composites with properties that met all the requirements. The results of the tests given in the report Results of container testing, measurements and tests [3] showed that all requirements were met. Containers with such composites were produced [4] and tested at the test facility at the Pomgrad production plant in Lipovci [5].
This paper provides only brief information about the container and the results of SCC investigations. The following section discusses results of investigations some of the key characteristics of SFR-SCC, based on which it would be able to make assessment of the possibility of using SFR-SCC for the production of the disposal container for LILW.

2. Short information on the disposal container and the properties of the SCC

A large team of experts from IBE (LILW disposal site and container designer), Pomgrad (manufacturer of container prototype), ZAG and IRMA (co-operating Institutes in the project) participated in the development project of the disposal container designated N2d.

2.1. Disposal container

Concrete container as one of the most important elements of the engineering part of the multi-tier system for preventing the passage of radioactive substances from the disposal site to the environment acts as: (a) biological shield in the time before the disposal, (b) mechanical protection of LILW during storage and disposal, (c) the basic safety element during the transport and internal transport (displacement) of LILW in the container, (d) the basic criterion of the profile in the process of preparing waste for disposal and (e) the central object of handling LILW in the area of the storage silo.

The most important and most specific container requirement is, in addition to the resistance and stability of all anticipated loads in the filling phase and the transport before the final disposal, also the durability in the expected life span of 300 years.

In view of the known environmental conditions to which containers will be exposed after disposal in the silo, the containers will be exposed to carbonization in the first phase (in the period 2020 – 2061), after the filling and closing the silo, and the abandonment of water pumping from 2062 onwards, the silo with containers exposed to underground water.

Storage containers ready for disposal will be transported to the disposal site in accordance with the provisions of the requirements for the transport of dangerous goods by road (ADR)[6]. Slovenia has implemented the ADR provisions [6] in national legislation through the Law on the Transport of Dangerous Goods (ZPNB)[7]. This precisely prescribes that containers for the transport of dangerous goods must be tested with a “drop test”.

In total, 950 containers of type N2d will be deposited, with a maximum permissible mass of 40 t. Containers deposited in the silo with the help of a portal crane and special grips. Empty spaces between containers and containers and the silo wall will be filled with filling concrete.

2.1.1. Geometric characteristic of the N2d container. The basic geometry of the container was determined based on the installation of 4 TTC barrels. The N2d container is an upgrade of the N2b container, where it differs substantially only in the design of the cover and anchorage of the cover in the reinforced concrete container. The specific solutions of the container are given below and are result of the development of the container through the acquisition of the Slovenian Technical Approval: (1) External dimensions (Width = 1,95 m, Length = 1,95 m, Height = 3,30 m), (2) Thickness of the bottom slab = 23 cm, (3) Wall thickness at the top = 20 cm, (4) Wall thickness at the bottom = 23 cm, (5) Cover thickness = 20 cm, (6) Mass of empty container with the cover = 14,92 t, (7) Maximum permissible mass of the full container = 40 t. 3D display of the container with reinforcement is shown in Figure 1.

2.2. Some properties of the SCC

In order to achieve a complete filling of densely reinforced elements of the container (walls, bottom and cover) [2], the mix proportion of SCC developed as part of the development project. SCC was placed into the elements by the continuous casting through the tube [4]. In preparing the mix proportion of SCC, the rules for SCC, which are set out in SIST EN 206:2013, have been followed. A large number of SCC mixtures were prepared in the laboratory, changing the proportions and ratios of
the individual components in such a way that a mixture was obtained that was suitable for the selected method of placing.

![Figure 1. 3D display of the container with reinforcement.](image)

The average results of measurements of fresh and hardened SCC are given in Tables 1 and 2. The results are within the limits of the required values [2, 3].

**Table 1.** The average results of the tests of the properties of fresh SCC.

| Property (measured by standard) | Average value |
|---------------------------------|---------------|
| Slump – flow (SIST EN 12350-8:2010) | 680/710 mm |
| Density (SIST EN 12350-6:2009) | 2393 kg/m³ |
| Air content (SIST EN 12350-7:2009, Chapter.5) | 2,0 % |
| w/c ratio (SIST 1026:2016, Appendix NC) | 0,37 |

**Table 2.** The average results of the tests of the properties of hardened SCC.

| Property (measured by standard) | Average value |
|---------------------------------|---------------|
| Compressive strength at 28 days (SIST EN 12390-3:2009) | 86,0 MPa |
| Water penetration at 28 days (SIST EN 12390-8:2009) | 3,0 mm |
| Shrinkage at 182 days (DIN 4227-Part 1) | 0,374 mm/m |
| Resistance to freeze/thaw up to 200 cycles (SIST 1026:2016, Appendix ND) | 101,0 % |
| Modulus of elasticity at 28 days (DIN 1048) | 42500 MPa |
| Total porosity (EN 1936: 2006) | 10,85 % |
| Chloride content (SIST EN 206: 2013, Chapter 5.2.8) | 0,070 % |
2.2.1. *Increasing the compressive strength of SCC.* The increase in the compressive strength of the SCC, the filling and sealing mortar depending on the time can be seen from Figure 2.

![Figure 2. Compressive strength of SCC, filling and sealing mortar depending on their age.](image)

The increase in compressive strength at an earlier age of SCC and a filling mortar up to 28 days is much more intense than in the case of an age above 28 days. A similar increase in the SCC modulus of elasticity was observed over time.

2.2.2. *Measurement of autogenous shrinkage of SCC.* Autogenous shrinkage is greater in high-strength concrete, or concrete, with a lower w/c ratio [8]. Autogenous shrinkage of concrete, also called hydration shrinkage, is the result of self-drying in the pores of cement stone that is water consumption in the process of hydration of cement. Thus, autogenous shrinkage occurs as soon as the process of hydration of the cement in the concrete begins. Depending on the type of concrete mixture, the shrinkage process begins about 2 to 24 hours after the mixing. Since concrete curing is already being established during this time and the concrete is placed in the formwork, evaporation of the water is significantly prevented. During this time, concrete deformations due to autogenous shrinkage and temperature deformations of concrete occur. After the curing of concrete is finished, the concrete is deformed - it is shrinking due to the evaporation of water from the surfaces of the concrete element.

Measurements of autogenous shrinkage were carried out at the laboratory of the Faculty of Civil Engineering and Geodesy in Ljubljana. Measurements were carried out in accordance with the Japanese standard JIS A 1129.

In Figure 3, the thin line shows the progress of the entire measured early shrinkage of SCC. This is the average value of the measurement results on three prisms with dimensions of $10 \times 10 \times 40$ cm. The development of the temperature of the SCC as a function of time is given by a red line (upper diagram). The course of the estimated autogenous deformation of SCC is presented with a thick line, which is determined by deducting the temperature deformation of concrete from the total measured
shrinkage. The results show a relatively small autogenous shrinkage of SCC. Also, a smaller shrinkage of SCC due to drying was determined. Average shrinkage of SCC at the age of 182 days is 0.374 mm/m.

Figure 3. Results of SCC autogenous shrinkage measurement up to 7 days after mixing.

Within one of the previous research projects [9], laboratory tests were carried out into the time history of the shrinkage of fibre reinforced high-performance concrete with volumetric contents of 0.25%, 0.50% and 0.75% containing longer (l = 32 mm, d = 0.5 mm) or shorter (l = 16 mm, d = 0.5 mm) steel fibres or polypropylene fibres.

Based on the results, and discussion of results, of the performed experimental investigation into the shrinkage of high performance concrete containing polypropylene or shorter / longer steel fibres, the following conclusions can be reached: (1) The total shrinkage of the fibre reinforced concrete was, in the case of all of the investigated volumetric contents and types of fibres used, less than that of the comparable concrete without fibres. At the end of the period of measurement, the total shrinkage of the investigated concrete was, depending on the volumetric content and type of fibres used, approximately 17% to 29% less than that of the comparable concrete without fibres. The differences in the total shrinkage of the composites, with different volumetric contents and containing different types of fibres, were relatively small. (2) For the reduction of the early autogenous shrinkage of concrete, the use of steel fibres is more effective than the use of dry polypropylene fibres. In the case of using of steel fibres with volumetric contents of 0.25% or 0.50%, the longer fibres are more effective, whereas in the case of a volumetric content of 0.75% shorter fibres are more effective. (3) For reducing the total autogenous shrinkage, at a volumetric fibre content of 0.25% longer steel fibres are the most, whereas polypropylene fibres are the least effective. In the case of volumetric contents of fibres of 0.50% and 0.75%, however, there is relatively little difference in the effectiveness of steel and polypropylene fibres in the reduction of total autogenous shrinkage. (4) • The drying shrinkage of concrete is, in the case of all the investigated volumetric contents and types of fibres used, significantly less than the corresponding drying shrinkage of the comparable plain concrete without fibres.
3. SFR-SCC

In the continuation of the laboratory investigations SFR-SCC (Steel Fibre Reinforced Self-Consolidating Concrete) was prepared and investigated. Different quantities (0.25, 0.5, 0.75 and 1 vol.%) of steel fibres with anchors were added, with an equal length of 16 mm and a different thickness (diameter of cross-section) of 0.50, 0.40 and 0.35 mm, and aspect ratios (the ratio between length and diameter of the fibre) \( l/d = 32, 40 \) and 46. This paper provides only information and some of the results of the investigations of SFR-SCC. The aim was to identify possible potential for further improvement in the behaviour of the container during use, in particular, ensuring its long life.

3.1 Investigation of fresh SFR-SCC

The same tests of fresh SFR-SCC were performed as for fresh SCC. It was searched how the amount of fibres and their aspect ratios affect the workability and place-ability of SFR-SCC. In this paper, only the results of the slump flow test are given. The mean spread of fresh SFR-SCC according to the standard SIST EN 12350-8 was measured. The obtained results are given in Figure 4 depending on the amount of added fibres and their aspect ratio (\( l/d = 32, 40 \) and 46).

![Figure 4](image.png)

**Figure 4.** Mean spread of fresh SFR-SCC depends on the amount of fibres and their aspect ratio.

The results show that the fibres in amount of up to 0.75 vol.% do not affect workability and place-ability of fresh SFR-SCC. Some results suggest that the presence of fibres even improves workability, as if the fibres increase the internal "sliding" of the fresh SFR-SCC mass and do not hinder its workability - the flow-ability, as happens with a larger amount of longer fibres. The workability of fresh SFR-SCC is slightly reduced when 1 vol.% of fibres are added. The reduction in workability is greater when fibres with a larger aspect ratio are used.

3.2 Investigation of hardened SFR-SCC

The main purpose of adding fibres to concrete is to increase its ductility, toughness and resistance to crack propagation. Several types of tests were performed. This paper will only provide some of the results of the wedge spit test (WST).

WST is a test method to perform stable fracture mechanics tests on concrete and concrete-like materials. It was proposed by Brühwiler and Wittman [10], and Linsbauer and Tschegg [11]. The method proposed by last authors [11] was used in discussed and previous [12-14] investigations in order to obtain load – CMOD curves. Equivalent strengths up to selected crack width (\( CW = 0.1, 0.2, \)
0.3 and 0.4 mm) are calculated by equation, in which parameters, derived from load-CMOD curve are used.

Tests in accordance with the WST method were carried out on cubes with an edge length of 150 mm and with initial notch depth of 50 mm, at ages of 28 days. The principle of the testing method is shown in Figure 5 [15].

![Figure 5. Principle of the WST method [15].](image)

Characteristic load – CMOD curves of SCC without fibres and SFR-SCC with 1 vol.% steel fibres with l/d = 30 are given in Figure 6.

![Figure 6. Characteristic load – CMOD curves of SCC without fibres and SFR-SCC with 1 vol.% steel fibres with l/d = 30.](image)
There is a very large difference between the areas under the curves, which represent the amount of absorbed energy SCC and SFR-SCC during the test. From such diagrams the following strengths are calculated: ultimate strength $f_{ct}$, strength at first crack $f_{FC}$ and equivalent strengths up to selected crack width (CW = 0,1, 0,2, 0,3 and 0,4 mm). For SCC, SFR-SCC with 1 vol.% steel fibres with l/d = 30 and 40, the average values of these strengths in Table 3 are given.

Table 3. The average results of strengths of SCC and SFR-SCC obtained by WST.

| Type of concrete               | $f_{FC}$ (MPa) | $f_{ct}$ (MPa) | $f_{0,1}$ (MPa) | $f_{0,2}$ (MPa) | $f_{0,3}$ (MPa) | $f_{0,4}$ (MPa) |
|-------------------------------|----------------|---------------|----------------|----------------|----------------|----------------|
| SCC                           | 2,8            | 3,2           | 2,7            | 2,2            | 1,8            | 1,5            |
| SFR-SCC with 1vol.% fibers with l/d = 30 | 4,9            | 5,7           | 4,5            | 4,9            | 4,9            | 4,8            |
| SFR-SCC with 1vol.% fibers with l/d = 40 | 5,2            | 6,1           | 5,0            | 5,2            | 5,4            | 5,5            |

The average ultimate strengths $f_{ct}$ are given in Figure 7 depending on the aspect ratios l/d (aspect ratio l/d = 0 has SCC because it has no fibres).

![Figure 7](image_url)

Figure 7. The average ultimate strengths $f_{ct}$ depending on the aspect ratios l/d.

The average strength at first crack $f_{FC}$ and equivalent strengths up to selected crack width $f_{CW}$ are given in Figure 8 depending on the crack width (CW = 0, 0,1, 0,2, 0,3 and 0,4 mm). For the crack width CW = 0 mm, the first cracking strengths $f_{FC}$ are applied.

From the average strength results (Table 3, and Figures 7 and 8), it is evident that they are much higher in SFR-SCC than in SCC. Fibres, of course have significant influence on post crack behaviour of concrete. Strain – softening response was obtained, when SCC without fibres were tested (Figure 8). On the other hand, strain - hardening response of SFR-SCC were gained up to the crack width of 0,4 mm (Figure 8). This is especially true when fibres with larger aspect ratio (l/d = 40) are used.
4. Conclusion
The SCC whose mix proportion has been developed as part of the development project for the LILW disposal container exhibits properties (in fresh state) that ensure good workability and denseness in the walls, bottom and container cover, despite the large amount of reinforcing bars. Similar behaviour was found in fresh SFR-SCC, despite the addition of fibres. Some results suggest that the presence of fibres in quantity up to 0.75vol.% even improves workability, as if the fibres increase the internal "sliding" of the fresh SFR-SCC mass and do not hinder its workability - the flow-ability.

The obtained results of measurements of autogenous shrinkage and shrinkage due to drying of SCC show that there is no risk of cracking, of course, provided that a good curing of placed SCC is carried out. However, based on the results of the preliminary experimental investigation into the shrinkage of high performance fibre reinforced concrete, it was found that total shrinkage of the fibre reinforced concrete was less than that of the comparable concrete without fibres. For the reduction of the early autogenous shrinkage of SFRC, the use of short steel fibres (with length of 16 mm) and with volumetric contents of 0.75% is more effective than the use of longer fibres (with length of 32 mm).

It is also one of the essential findings of the investigations is that strain-hardening response of SFR-SCC with 1 vol.% of fibres was obtained, while strain – softening response was obtained, when SCC without fibres were tested. This is especially true when fibres with larger aspect ratio are used.

On the basis of all the research results so far obtained, it can be concluded that there is a possibility to increase the resistance of SCC (for the construction of a LILW disposal container) to the crack propagation by adding a certain amount of steel fibres, without worsening the workability and place-ability of SCC.

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