IOP Conference Series: Materials Science and Engineering

**PAPER** • **OPEN ACCESS**

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To cite this article: R Gailitis *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **660** 012007

# Mechanical Properties of Geopolymer Concretes Reinforced with Waste Steel Fibers

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**Abstract**. The article presents the research that try to determinate the possibilities of utilization the waste came from used tires to create the composites based on geopolymer matrix. The tire is multicomponent construction. It mainly consists of elastomer (rubber), metal and textile fibres such called textile cord. A lot of components causes difficulties in the tire recycling process. The main aim of the research was determinate the possibilities of recycling the waste steel from used tires in geopolymer composites and develop the eco-friendly material for construction industry. The matrix based on fly ash from power station located in city named Skawina (Poland) and fine sand at a ratio of 1:1. The process of activation was made by 10M sodium hydroxide solution combined with the sodium silicate solution. In order to manufacture these composites the addition of 2% and 3.5% of waste steel fibres by mass was applied. Also specimen without steel fiber reinforcement were made to get reference specimens. The waste steel fibres came from recycling company from Argentina – 'Regomax'. The specimens were prepared according to the methodology described in the standard EN 12390-1. The research methods used were: microstructure research, tensile strength and compressive strength tests as well as analysis of breakthroughs.

## 1. Introduction

Cement is categorized as indispensable material in the construction industry all over world, special in developing countries. Due to this increased cement consumption there are intense negative effects, such as release of carbon dioxide into the atmosphere [1]. In comparison to the traditional materials, such as Portland concrete, geopolymers have a number of advantages, especially connected with reduction of footprint and eco-friendly character. Manufacturing of this class of materials compared to the traditional concretes is economically more beneficial including the low energy consumption.

Additional environmental benefit is connected with using to production process waste materials: for example, fly ashes and mine tailings. Coal power stations contributes to 25-30% of world's energy production. Consequences to this is 800 million tons of fly ash generated worldwide every year by power stations. Only half of this amount is recycled. This recycled amount can be increased by manufacturing environmentally friendly binders such as geopolymer [2]. Also it has to be acknowledged that production of Portland cement causes significant amount of $CO_2$ emissions. Portland cement production every year causes around 5-7% of the total $CO_2$ anthropogenic emissions. Cement production reached a distressing value of about 4200 million tons in 2016 that contributes approximately to 3570 million tons of $CO_2$ [3].

Geopolymer is comparable in performance to ordinary Portland cement [4]. Geopolymer concrete main advantage is its contribution to the environment. It is estimated that carbon footprint made by geopolymer concrete manufacturing is 26 to 46% less than Portland cement concrete if in concrete mix Portland cement is replaced completely [4, 5]. It is reckoned that production of 1 tonne of caolin geopolymer contributes to 0.180 tonnes of $CO_2$, that is 6 times less than manufacturing of Portland cement concrete [6].

Geopolymer belongs to a group of novel three-dimensional inorganic materials. This novel material got multiple beneficial properties such as low density, low cost, environmentally friendly nature and high mechanical performance. However like traditional brittle materials, geopolymer shows poor tensile and flexural properties and appalling fracture behavior [7]. As a composite material geopolymer concrete is two or more constituent material arrangement. A continuous called matrix and the dispersed phase or phases, either fibers or particulates, in order to develop another material with desired combination of properties [5, 8]. A significant increase of tensile strength fracture energy can be achieved by adding fibers to geopolymer matrix [9, 10].

In terms of sustainable raw material management, it is crucial to recycle industrial waste as much as possible and also to develop new technologies that not only reduces industrial waste landfills but also produce materials with new added value [2, 11]. Contemporary, every year approximately 17 million tons of waste tires, which have no further use [12, 13]. This waste is categorized as serious contaminant to environment, therefore, recycling of tires is extremely important [14, 15].

This study shows how two secondly used components interacts with each other and what kind of properties has got developed material. The aim of this study is to show how different amount of reused steel fiber reinforcement can improve or disapprove material properties in compression and tensile loads.

## 2. Materials and methods

Cubic (70x70x70 mm) and prismatic (50x50x200 mm) specimens were prepared with 2% and 3,5% by mass steel fibers from recycled car tire cords and without steel fiber reinforcement. The matrix was based on fly ash from power plant located in Skawina city (Poland). This kind of fly ash is suitable for manufacturing geopolymers because of proper physical properties and chemical composition. The fly ash contains of spherical aluminosilicate particles in different sizes: > 0.0039 in. [>100 µm] – ca.3%, 0.0028 – 0.0039 in. [71-100 µm] – ca. 12%, 0.0025 – 0.0028 in. [63-71 µm] – ca. 10%, 0.0022 – 0.0025 in. [56-63 µm] – ca. 15% and <0.0022 in. [<56 µm] – ca. 60%. This fly ash is rich in oxides such as $SiO_2$ (47.81%), $Al_2O_3$ (22.80%). High value of $SiO_2$ and $Al_2O_3$ is advantageous for geopolymerization.

Steel fibers were obtained from Argentinian company "Regomax", that recycles old tires to get milled rubber for synthetic grass and other rubber produce production. Steel cords from tires are recycling process byproduct that has no particular market as reusable material so they have scrap value - http://www.regomax.com/.

Specimens were prepared using sodium promoter, fly ash, sand (ratio sand and fly ash – 1:1) and steel fibers (2% and 3.5%). The process of activation has been made by 10M sodium hydroxide solution combined with the sodium silicate solution (liquid glass at a ratio of 1:2.5). In order to manufacture the composites the technical sodium hydroxide in flakes were used and water solution of sodium silicate R–145 (modulus 2.5, density 0.052 lb/in.$^3$ - 1.45 g/cm$^3$). Tap water was used instead of the distilled one. The alkaline solution was prepared by means of pouring the aqueous solution of sodium silicate and water over solid sodium hydroxide. The solution was mixed and left until its temperature became stable and the concentrations equalized about 2 hours. The fly ash, sand, alkaline solution and steel fibers were mixed about 15 minutes by using low speed mixing machine (to receive the homogenous paste). Next, it was poured into two sets of plastic molds. The specimens were hand-formed and then subjected to vibratory removal of air bubbles. Tightly closed molds were heated in the laboratory dryer for 24h at 75 °C. Then, the specimens were unmolded. The prepared specimens had following dimensions: per each testing batch 3 cubes 70x70x70 mm and prisms 50x50x200 mm.

## 3. Results and discussion

### *3.1. Microstructure research*

The SEM observations were made for plain samples (figure 1) as well as for composition reinforced by fibres (figure 2 and figure 3). The images were made at various magnifications - between 20 – 220x. The different magnification allows to observe of microstructure of composites, including fibres distribution as well as it gives a preliminary information about the coherency of fibres (reinforcement) with the geopolymer matrix.

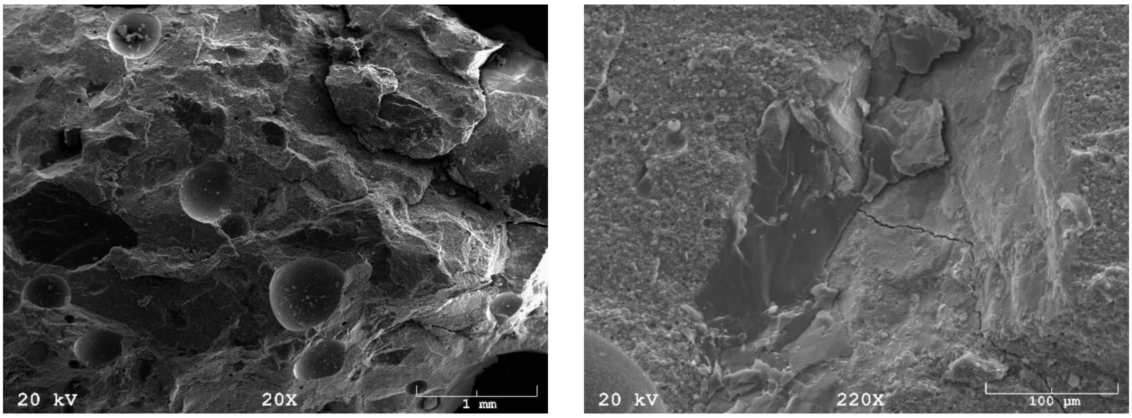


**Figure 1.** SEM scan of non-reinforced geopolymer sample.

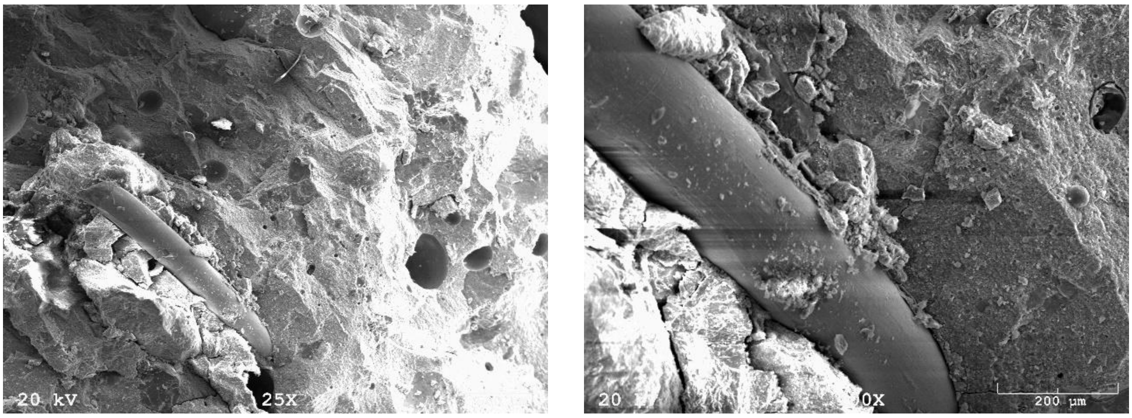


**Figure 2.** SEM scan of geopolymer sample reinforced with 2% steel fibers.

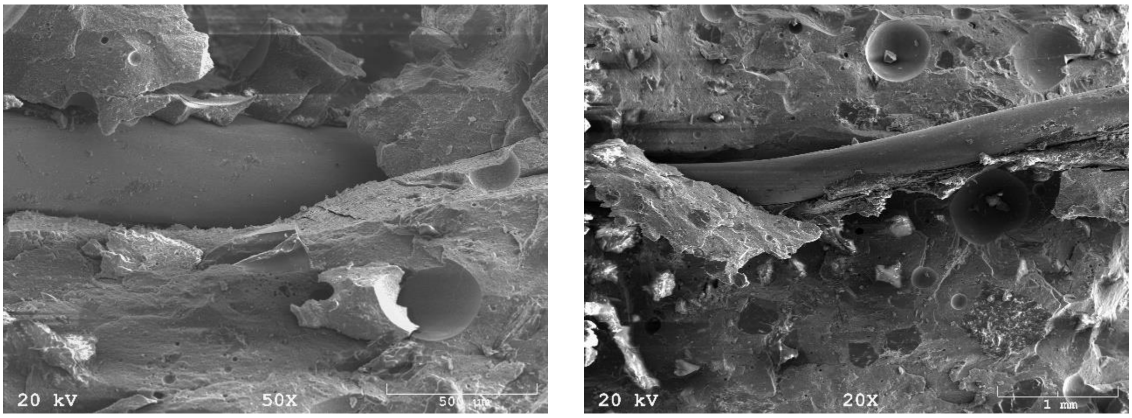


**Figure 3.** SEM scan of geopolymer sample reinforced with 3.5% steel fibers.

The microstructural observation allow to notice that the structure is coherent - good adhesion the steel fibres to the matrix. The contact zone are visible on figure 3.

### *3.2. Compressive strength*

Table 1 and figure 4 show the compressive strength for geopolymer concrete cubes 28 days after they were made.

**Table 1.** Compressive strength of geopolymer concrete.

| Specimen type | Specimen number | Specimen size | | | Compressive strength, kN | Compressive strength, MPa |
|---|---|---|---|---|---|---|
| | | Width, mm | Height, mm | Length, mm | | |
| Geopolymer with 3.5% steel fibers | 1 | 71.55 | 71.20 | 70.86 | 581.7 | 114.7 |
| | 2 | 72.17 | 71.42 | 71.38 | 605.0 | 117.4 |
| | 3 | 71.19 | 71.26 | 71.98 | 562.7 | 109.8 |
| Geopolymer with 2% steel fibers | 1 | 71.54 | 71.53 | 71.15 | 398.0 | 78.2 |
| | 2 | 71.48 | 71.18 | 71.30 | 407.6 | 80.0 |
| | 3 | 71.44 | 71.65 | 71.16 | 431.9 | 85.0 |
| Geopolymer without steel fibers | 1 | 70.22 | 71.58 | 71.12 | 362.0 | 72.5 |
| | 2 | 72.38 | 71.08 | 71.34 | 475.2 | 92.0 |
| | 3 | 71.62 | 71.20 | 71.70 | 467.7 | 91.1 |

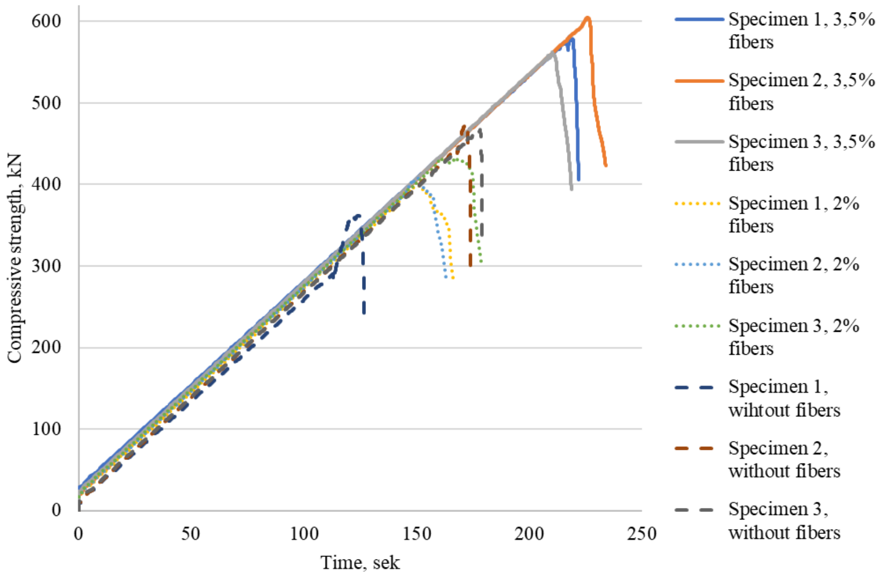


**Figure 4.** Geopolymer cubic specimen compressive strength loading graph.

For specimens with largest amount of steel fiber reinforcement compressive strength is considerably higher than all other specimens. Furthermore it is interesting that compressive strength of specimens without steel fiber reinforcement is not the lowest.

### *3.3. Tensile strength*

Table 2 shows the tensile strength for geopolymer concrete spherical specimens 28 days after they were made. For specimens with largest amount of steel fiber reinforcement compressive strength is considerably higher than all other specimens. As well as in for cubes the tensile strength of specimens without steel fiber reinforcement is not the lowest.

Also in figure 5 it is shown that specimens with 3.5% steel fiber reinforcement after first crack development in bended part still holds and increases load capacity after it breaks.

**Table 2.** Tensile strength of geopolymer concrete.

| Specimen type | Specimen number | Specimen size | | | Compressive strength, kN | Compressive strength, MPa |
|---|---|---|---|---|---|---|
| | | Width, mm | Height, mm | Length, mm | | |
| Geopolymer with 3,5% steel fibers | 1 | 50.46 | 50.03 | 206.67 | 5.8 | 10.2 |
| | 2 | 50.56 | 50.37 | 203.33 | 5.9 | 10.4 |
| | 3 | 50.21 | 51.56 | 206.67 | 6.5 | 11.3 |
| Geopolymer with 2% steel fibers | 1 | 50.84 | 50.14 | 210.00 | 4.7 | 8.4 |
| | 2 | 51.45 | 50.16 | 205.00 | 4.3 | 7.5 |
| | 3 | 50.23 | 50.21 | 210.00 | 3.6 | 6.4 |
| Geopolymer without steel fibers | 1 | 50.08 | 50.22 | 210.00 | 4.2 | 7.5 |
| | 2 | 49.69 | 50.25 | 208.30 | 4.8 | 8.6 |
| | 3 | 49.54 | 50.22 | 208.30 | 5.6 | 10.1 |

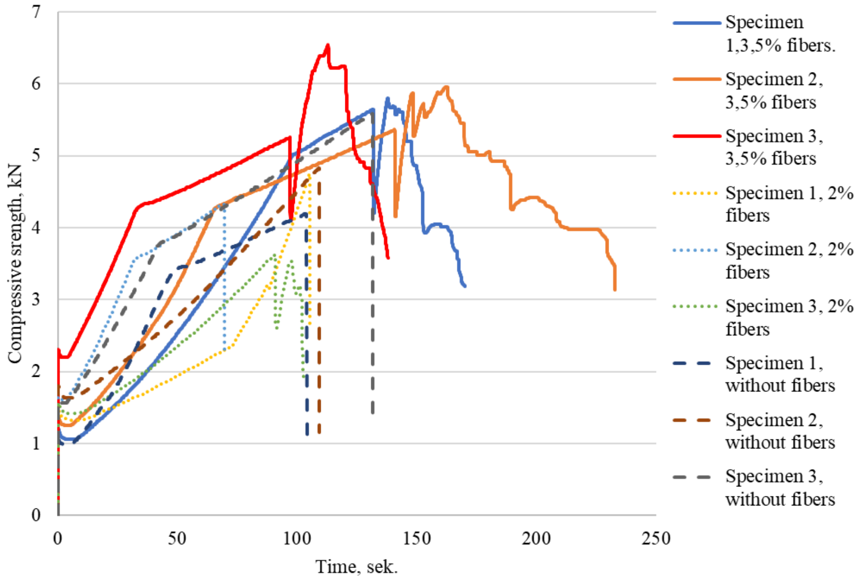


**Figure 5.** Geopolymer spherical specimens tensile loading graph.

As it is visible in figure 6, figure 7 and figure 8 only specimens with 3.5% steel fiber reinforcement keeps carrying load after crack appearance. All other specimens (with 2% fiber reinforcement and without fibers) fail after crack appearance.

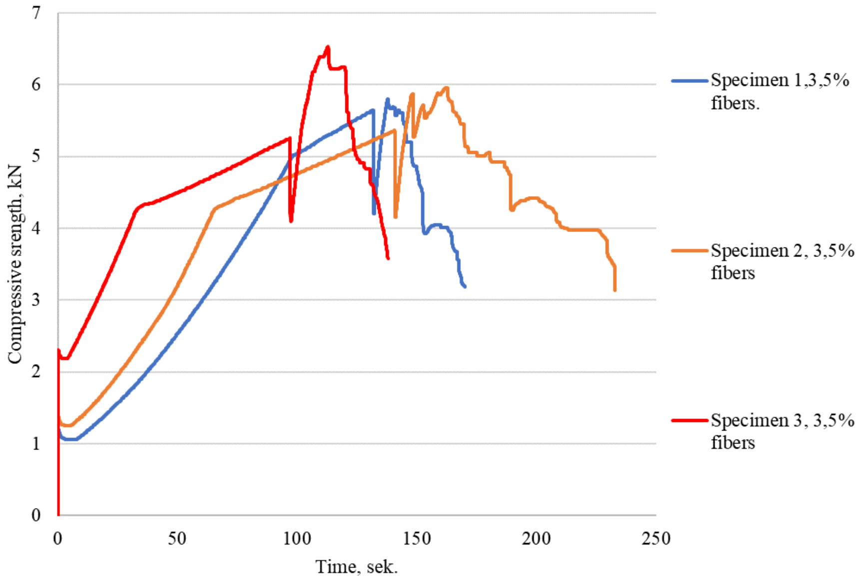


**Figure 6.** Geopolymer spherical specimens with 3.5% steel fiber reinforcement tensile loading graph.

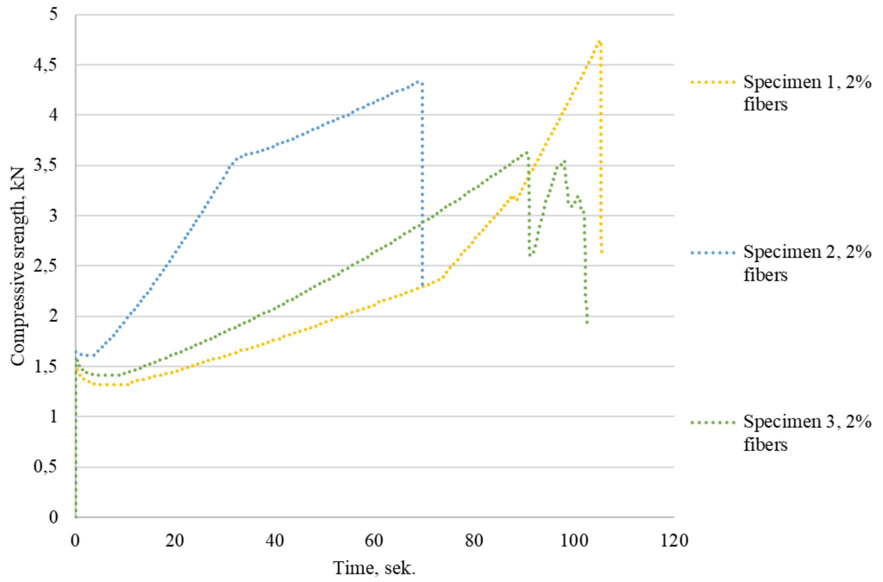


**Figure 7.** Geopolymer spherical specimens with 2% steel fiber reinforcement tensile loading graph.

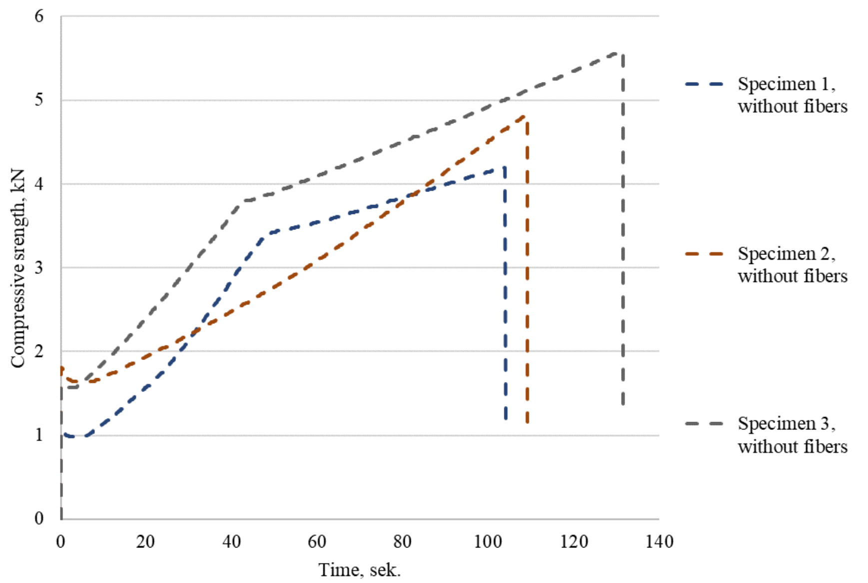


**Figure 8.** Geopolymer spherical specimens without steel fiber reinforcement tensile loading graph.

## 4. Conclusions

Regarding tensile strength specimens with fiber reinforcement of 3.5% has further load capacity even if some of geopolymer matrix has failed in stretched part of specimen. For specimens with 2% fiber reinforcement there are not enough fibers in stretched part so they could not carry all the load and specimen fails. In compressive strength cubic specimens with steel fiber reinforcement fails without significant late increase in load capacity as the specimens without fiber reinforcement do.

The load-bearing capacity of geopolymer cubes with 3.5% steel fiber reinforcement is 29% higher than specimens with 2% steel fiber reinforcement and 26% higher than specimens without reinforcement. Furthermore it can be aknowladge that for geopolymer cubes steel reinforcement gives increase in compressive strength when steel reinforcement is 3.5%. For less reinforcement amount there is decrease in specimen compressive strength.

For tensile strength there is similar conclusion. Specimens with 3.5% steel fiber reinforcement has got 30% higher tensile strength than specimens with 2% steel fiber reinforcement and 18% higher tensile strength than specimens without fibers. Furthermore specimens without fibers has got 15% higher tensile strength than specimens with 2% steel fiber reinforcement. It could only mean, that for geopolymer matrix reinforced with waste tire steel cord fibers has to be at least 3.5% from mass of the mix to contribute to specimen strength increase.

The decrease in tensile and compression strength for geopolymer concrete with 2% steel fiber reinforcement can be because the fibers could be surfaced to specimens top not bottom side where tensile loads are. Due to this the reinforcement has not worked as it should have and most on tensile load was carried by geopolymer matrix not steel fiber reinforcement with geopolymer matrix together. Furthermore, the collapse of specimens with 2% steel fiber reinforcement and specimens without reinforcement (Fig.5, Fig.7 and Fig.8) is similar and could indicate, that for specimen with 2% steel fiber reinforcement the steel fibers have not been arranged evenly through the cross section of specimen.

**Acknowledgments**

1. This work has been supported by the Latvian Council of Science within the scope of the project ‘Long-term properties of innovative cement composites in various stress-strain conditions’ No. lzp-2018/2-0249.
2. This work has been supported by the ERANet-LAC 2nd Joint Call (http://www.eranet-lac.eu) and funded by Ministry of Science, Technology and Productive Innovation (MINCYT) in Argentina and the National Centre for Research and Development in Poland, within the framework of the grant: ‘Development of eco-friendly composite materials based on geopolymer matrix and reinforced with waste fibers’.

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