Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Impact of Polypropylene, Steel, and PVA Fibre Reinforcement on Geopolymer Composite Creep and Shrinkage Deformations

To cite this article: Rihards Gailitis *et al* 2023 *J. Phys.: Conf. Ser.* **2423** 012030

IMST 2022 IOP Publishing
Journal of Physics: Conference Series **2423** (2023) 012030 doi:10.1088/1742-6596/2423/1/012030

Impact of Polypropylene, Steel, and PVA Fibre Reinforcement on Geopolymer Composite Creep and Shrinkage Deformations

Rihards Gailitis [1*], Andina Sprince [1], Tomass Kozlovksis [1], Leonids Pakrastins [1], Viktorija Volkova [2]

[1] Institute of Structural Engineering, Riga Technical University, Riga, Latvia, rihards.gailitis@rtu.lv
[2] Department of Civil Engineering, Building Technologies and Environmental Protection, Dnipropetrovsk State Agrarian and Economic University, Dnipro, Ukraine

Corresponding author's institutional e-mail address (rihards.gailitis@rtu.lv)

Abstract. For the last 40 years, there has been increased interest in geopolymer composite development and its mechanical properties. In the last decades, there have been cases when geopolymer composites have been used for civil engineering purposes, such as buildings and infrastructure projects. The main benefit of geopolymer binder usage is that it has a smaller impact on the environment than the Portland cement binder. Emissions caused by geopolymer manufacturing are at least two times less than emissions caused by Portland cement manufacturing. As geopolymer polymerization requires elevated temperature, it also has a significant moisture evaporation effect that further increases shrinkage. It can lead to increased cracking and reduced service life of the structures. Due to this concern, for long-term strain reduction, such as plastic and drying shrinkage and creep, fibre reinforcement is added to constrain the development of stresses in the material. This research aims to determine how different fibre reinforcements would impact geopolymer composites creep and shrinkage strains. Specimens for long-term property testing purposes were prepared with 1% of steel fibres, 1% polypropylene fibres (PP), 0.5% steel and 0.5% polyvinyl alcohol fibres, 5% PP fibres, and without fibres (plain geopolymer). The lowest creep strains are 5% PP fibre specimens, followed by 1% PP fibre, plain, 0.5% steel fibre and 0.5% PVA fibre, and 1% steel fibre specimens. The lowest specific creep is to 5% PP fibre reinforced specimens closely followed by 1% PP fibre followed by 0.5% steel and 0.5% PVA fibre, plain and 1% steel fibre reinforced composites. Specimens with 0.5% steel and 0.5 PVA fibre showed the highest compressive strength, followed by 1% PP fibre specimens, plain specimens, 1% steel fibre, and 5% PP fibre reinforced specimens. Only specimens with 1% PP fibre and 0.5% steel, and a 0.5% PVA fibre inclusion showed improved mechanical properties. Geopolymer concrete mix with 1% PP fibre inclusion and 0.5% steel and 0.5% PVA fibre inclusion have a 4.7% and 11.3% higher compressive strength. All the other fibre inclusion into mixes showed significant decreases in mechanical properties.

1. Introduction

For the last 4 decades, there has been much research focusing on a three-dimensional inorganic material group called geopolymer. For the last 15 years, the interest in research regarding geopolymers (GP/GPC) has increased more than 20 times. Geopolymer composites promise multiple benefits and are claimed to partially replace ordinary Portland cement (OPC). In some applications, it has been claimed to replace OPC completely. The main benefits of GP usage are reduced CO_2 emissions and increased resistance to harsh environmental impacts such as exposure to increased temperature and acids [1]–[4]. According to some research [5], [6], the most CO_2 emission-effective geopolymer is based on caolin. It has been evaluated that 1 ton of caolin-based geopolymer binder manufacturing has up to 6 times lower CO_2 emissions than OPC binder manufacturing. It has to be mentioned that this kind of binder manufacturing is from 7% to 39% more expensive than OPC-based binders.

Creep and shrinkage, which are time-dependent properties, have a significant effect on concrete structures. The main concerns are regarding the serviceability and durability of structures. Only in the last decade have there been studies looking into long-term properties, specifically creep. It has been determined that in most cases OPC based composites and concrete exhibits larger creep strains than geopolymer composites [7]–[10].

Shrinkage especially drying shrinkage, also influences long-term strains. Drying shrinkage is caused by water travel between the specimen and the environment. As it is closely linked together with capillary pressure in the pore walls, it is necessary to reduce the pore amount to reduce drying shrinkage, according to capillary tension theory. It can be achieved by pore structure change or significantly reducing water loss while curing. Also, inert or reactive fillers can give similar gains. Fibre introduction can also reduce shrinkage [11]–[13]. Fibre addition significantly reduces and, in some cases, can take out shrinkage altogether. In studies [14]–[16], the addition of 0.5 vol% of polypropylene (PP) fibres or steel fibres (SF) reduced shrinkage significantly. Furthermore, by introducing two vol% of ST fibres into the matrix, the shrinkage strains are insignificant.

Fibre reinforcement is frequently used to enhance OPC-based material mechanical properties and structural application accordingly. According to [17]–[23] all fibre reinforcement is highlighted into two groups – ones with high elongation properties and, therefore, low modulus of elasticity and ones with just a high modulus of elasticity. In the first group are such fibres as polypropylene, nylon, polyethylene, etc. In the second group, mostly are carbon, steel, and glass fibres. All in all, fibres from the first group are not used for load-bearing functions. Their main task is to increase fracture toughness and resistance to impact and explosion loads, overcome plastic shrinkage, and reduce cracks in the OPC. The second group effectively enhances cementitious composites strength and stiffness properties.

The most used fibre is Polypropylene (PPF). The main factors are their relatively low cost to steel fibre and their corrosion resistance [24]. These fibres also are superior to other synthetic fibres due to their low density and cost contrast to other synthetic fibres, low thermal conductivity, and significant chemical resistance; in other words, the alkali environment of concrete does not affect them [17], [18]. Furthermore, raw polypropylene fibres are likely to decompose in nature, unlike the same fibre fabric that places ecological challenges to be decomposed [25]. Some studies [26], [27] have shown that PPF usage increases splitting tensile strength and flexural strength. Also, creep and shrinkage strains are reduced. According to research, the optimal amount of polypropylene fibres to increase splitting and flexural performance is 1%. It has been claimed that the addition of PPF of 0.10, 0.15, 0.20, 0.25, and 0.30% results in 32, 53, 78, 91, and 100% crack limitation. In these cases, PPF reinforcement bridges the cracks and disallows crack growth. When fibre incorporation is above 3%, the workability is decreased [17].

Steel fibres are being increasingly used as additional reinforcement in constructions exposed to temporary load cases. In some cases, they act as a partial replacement for conventional steel reinforcement. In certain cases, like overall compression, SF can replace traditional reinforcement. Concrete structures reinforced with SF overall show good durability and mechanical performance. Conventional reinforcement replaced by SF has particular popularity in statically indeterminate structures [28]. Frequently steel fibres are used in structures with a great risk of cracking [17]. Industrial pavements and different structural linings as well as cooling towers, various silos and different wastewater and sewage treatment plants. The seismic resistance of concrete structures is also increased as well as the deformation capability, and ductility capacity of these fibres [28]–[30]. There has been some research where it was revealed that steel fibre incorporation in concrete mixture decreased the structural ductility of the reinforced concrete beams. Results show that it was very visible in the case of reinforcement ratio [31]. It has been known that steel fibre orientation and distribution throughout concrete structure cross-section significantly affects the strength. Furthermore, the aggregate is not allowed to be more than ¾ of the length of fibre or 25mm [32].

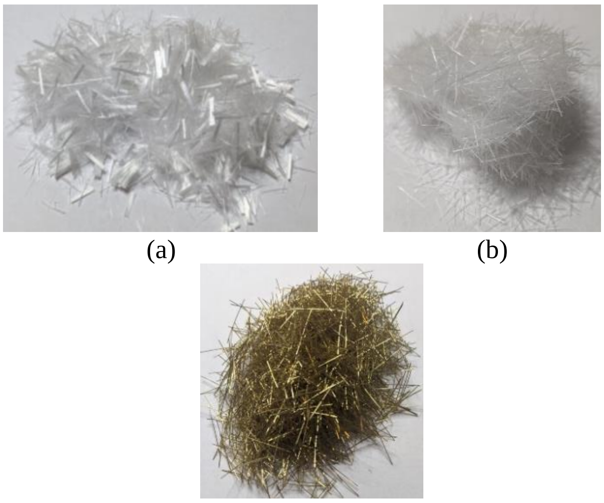
Because environmental concerns and the apparent benefits of geopolymer usage instead of regular OPC and fibre reinforcement undoubtedly significantly impact the mechanical and long-term properties of OPC, there is a necessity to evaluate fibre reinforcement impact on geopolymer composite mechanical and long-term properties as well as to determine optimal fibre incorporation amount.

2. Materials and methods

The matrix of the prepared samples and the alkali solution was the same as in [33]. As it is mentioned previously, the used fly ash contains spherical alumino-silicate particles and is rich with oxides such as SiO_2 (47.81%), Al_2O_3 (22.80%), which makes it suitable for polymerization.

The geopolymer mix preparation is done according to the [33]. When the sand and matrix mix is prepared in the mixer fibres are added. For 20% of specimens, 1% (by mass) short PP fibres (approximately 3mm in length) are added. For the next 20% of the specimens, 5% of the same PP fibres are added. The third 20% portion of the specimens are reinforced with 1% of steel fibres (approximately 18mm in length). The next 20% of the specimens are reinforced with 0.5% of steel fibres and 0.5% of PVA. The last 20% of the specimens are left without fibre reinforcement as a reference mix. Fibre reinforcement types are shown in Figure 1. The technical properties of the fibres are compiled in Table 1.

All of the specimen pouring and setting is done as it is described in [34], [35].



(a) (b)

(c)

Figure 1. Polypropylene (PP) fibres (a), polyvinyl alcohol (PVA) fibres (b), and steel fibres (c) were used as reinforcement

Table 1. Used fibre reinforcement basic properties

	Polypropylene fibres (PP)	**Polyvinyl alcohol fibre (PVA)**	**Steel fibre (SF)**
Length, mm	12.00	18.00	20.00
Diameter, mm	0.034	0.16	0.30
Tensile strength, MPa	300-400	790-1160	2635-3565

Specimens that were meant for long-term tests as well as for the mechanical property assessment were prepared according to RILEM TC 107-CSP recommendations [36]. The dimensions of the specimens were Ø 46 x 190 mm. For creep and shrinkage specimens, six aluminium plates (10 x 15 mm) were glued in pairs to each specimen. It is done so that strain gauges can be attached. The strain gauge attachment is shown in Figure 2 (a). Hereupon, shrinkage specimens were placed in the same laboratory near the creep test stands, as shown in Figure 2 (b), to get accurate and representative shrinkage strains. Long-term tests of the specimens are done simultaneously in the laboratory with a temperature of 24±1˚C and relative humidity of 30±3%.

(a) (b)

Figure 2. Specimens intended for creep tests (a) and shrinkage tests (b)

Shrinkage and creep strains were monitored daily for the first two weeks, later – every second day. The creep specimens were subjected to constant load throughout all testing time. They were subjected to load equivalent with 20% of the compressive strength. Compressive strength was determined prior to the long-term tests using the same shape specimens as the loaded specimens for creep testing. Initial loading is done within 5 minutes in steps equal to 25% of the applicable amount of load.

3. Results and discussions

The compressive strength test was done at the age of 28 days. To determine compressive strength values for each mix four specimens were used. The results are shown in Figure 3.

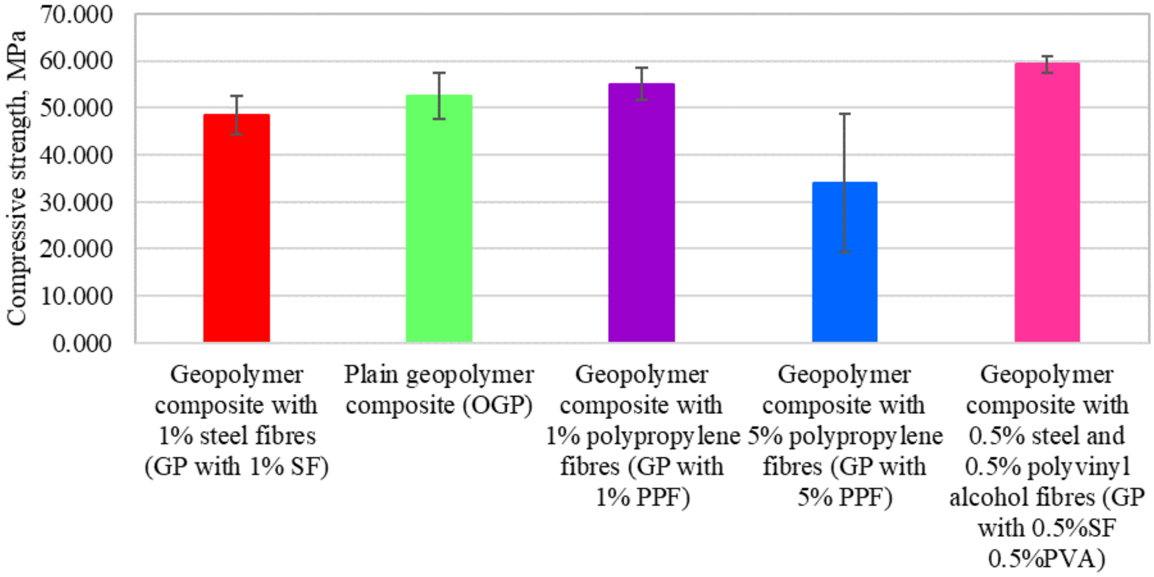
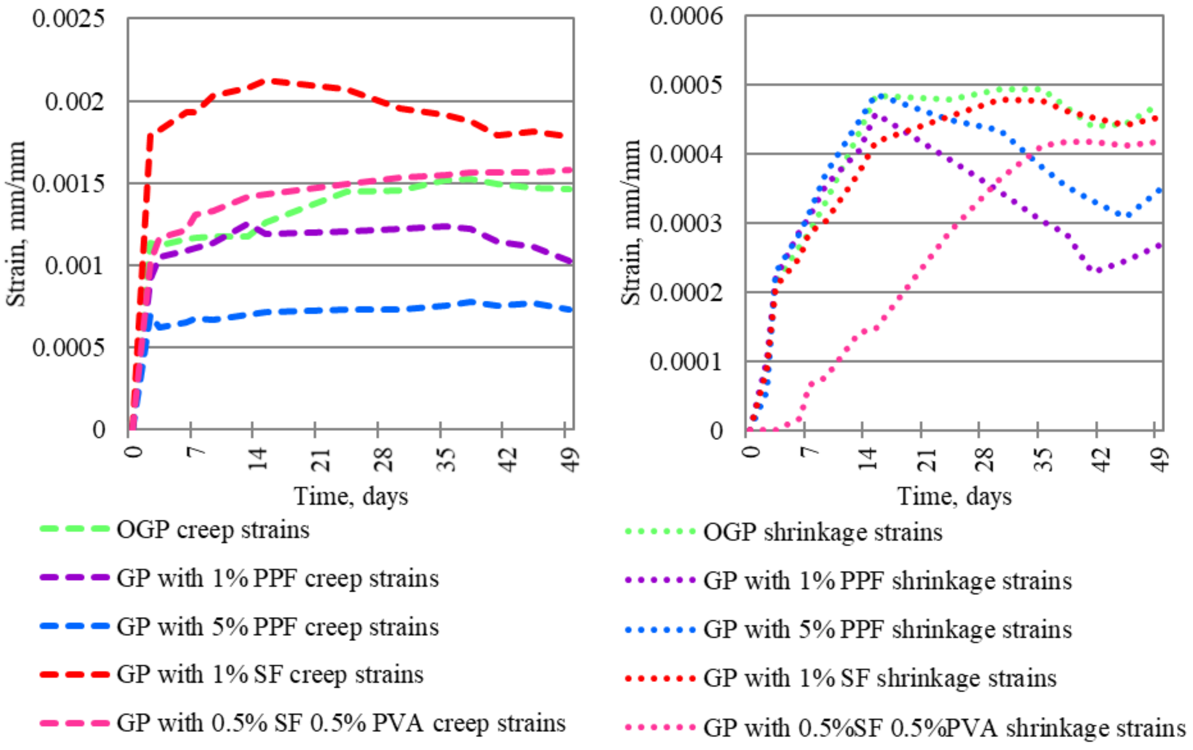


Figure 3. Geopolymer composite compressive strength

The calculations of applicable load for creep tests were based on compressive strength values shown in Figure 3. As it is stated in [37], the increase in compressive strength to fibre-reinforced cement composite is not significant. In some research, a decrease in compressive strength due to fibre incorporation has been observed [38]–[41]. It is also visible here, where although, with 5% polypropylene fibre and 1% steel fibre inclusion, the compressive strength in contrast to plain geopolymer specimens is significantly lower. Furthermore, the error of compressive strength values of 5% polypropylene fibre reinforced specimens is two times larger than specimens without reinforcement. At the end, it can be concluded that at some point high amount fibre incorporation would significantly reduce composite workability, and consequently, the inner structure is distorted, which leads to significant effects on compressive strength values. It becomes apparent that as [18] states in their review that using two different material fibre mixes as reinforcement can improve mechanical properties much more than just one type of fibre used. Also, Figure 1 is shown that the error margin for 0.5% SF and 0.5% PVA fibre-reinforced composite is significantly less than all other tested specimens. Still, compressive strength is at least 7% higher than all other specimens compressive strength.

As the compressive strength tests were concluded, the 50-day long creep and shrinkage tests were done.

Measured long-term strains are shown in Figure 4.



(a) (b)

Figure 4. Plain and reinforced geopolymer composite creep (a) and shrinkage strains (b)

From Figure 4 (a) and Figure 4 (b), it becomes apparent that the shrinkage strain amount is around 20 to 25% from creep strains for all of the tested specimens. Furthermore, curves representing creep strain curves show less activity in strain development in the first 14 days than shrinkage curves. They show huge gains in the first 14 days. Here, in Figure 4 (a), the strain peak on the first day is from the elastic strains. Figure 5 shows that all geopolymer composites, except geopolymer composite with 1% steel fibre reinforcement, have lower creep strain development in contrast to shrinkage strain. From the Figure 4 curves it is evident that geopolymer specimens with 5% of polypropylene fibres exhibit lowest amount of creep. As for the shrinkage strains, the lowest amount of it is for the 1% PP fibres reinforced geopolymer composite. Unfortunately, the 1% steel fibre addition shows no noticeable improvement in restraining creep and shrinkage. Steel fibre incorporation has made the creep and shrinkage curves larger than those of specimens without any reinforcement. On average, the creep strains of steel fibre-reinforced specimens are 40% higher than specimens without any reinforcement. It is remarkable that geopolymer composite with 0.5% steel fibres and 0.5% PVA fibres, even though it does not have the lowest shrinkage strains, has significantly more significant stress development delay than all other tested composites. On average, this composite shows 41% fewer shrinkage strains than OGP specimens.

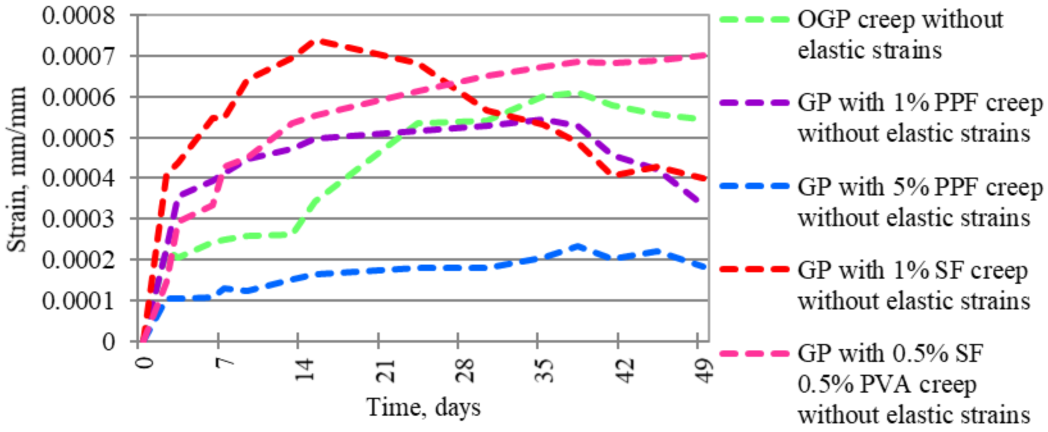


Figure 5. Tested geopolymer composite creep strains without elastic strains

When the creep strains elastic strains are removed, then in the first 28 days, the strain rising relation represented in Figure 4 (a) is also visible in Figure 5. The shrinkage strains of 1% steel fibre-reinforced geopolymer specimens decrease irrelevantly. The highest creep strains show composite specimens reinforced with SF. The specimens, which are reinforced with 5% of PP fibre show the lowest creep strains of all specimens. Also, geopolymer composite specimens with 5% PP fibre incorporation show the poorest compressive strength.

Still, Figure 5 does not give full closure on which of the tested geopolymer composite mixes have greater creep properties. Even though all of the creep specimens are subjected to the same stress level, the stress values still are different. For this aspect, it is necessary to determine specific creep. The equation for this is shown down below. Determining specific creep makes it possible to take away the differences in the subjected stress amount to the specimens. The specific creep is determined using equation 1.

The determined specific creep values are shown in Figure 6.

$$\chi_{cr}(t,t_0) = \frac{\varepsilon_{cr}(t,t_0)}{\sigma} = \frac{\varepsilon_{kop}(t)-\varepsilon_{sh}(t)-\varepsilon_{el}(t,t_0)}{\sigma} = \frac{1}{E_{cr}(t,t_0)} \tag{1}$$

$\chi_{cr}(t,t_0)$ - specific creep,

$\varepsilon_{cr}(t,t_0)$ - creep strain,

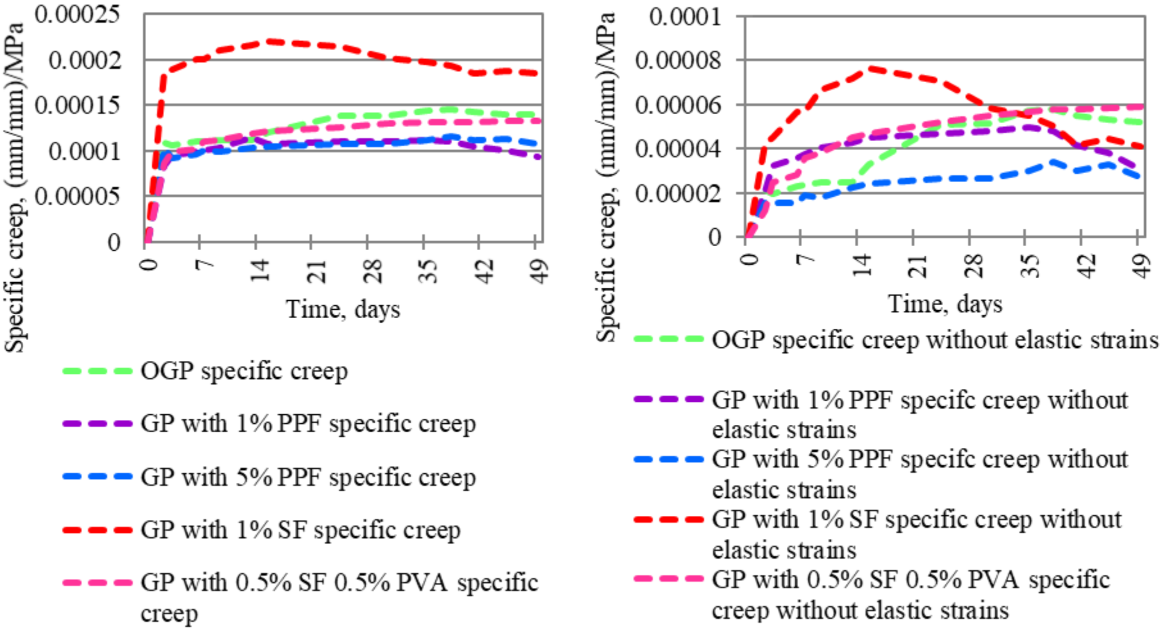
$\varepsilon_{kop}(t)$ - total strain,

$\varepsilon_{sh}(t)$ - shrinkage strain,

$\varepsilon_{el}(t, t_0)$ - elastic strain,

σ - compressive stress,

$E_{cr}(t, t_0)$ - modulus of creep



(a) (b)

Figure 6. Tested geopolymer composite specific creep with (a) and without (b) elastic strains

As visible from Figure 6 (a) curves, both the PP fibre-reinforced geopolymer composite mixes show superior specific creep properties. Therefore, there are less likely to creep in contrast to all of the other mixes. If the curves from Figure 6 (a) and Figure 6 (b) are cross-referenced, there is an interesting characteristic regarding how specific creep reduces whether the elastic strains are included or absent in creep strains. On average, the specific creep calculated from creep strains without elastic strains is 50% less than the specific creep calculated from creep strains with elastic strains. The 0.5% steel fibre and 0.5% PVA fibre reinforced composite shows the same specific creep strains with and without elastic strain partition as the OGP specimens.

4. Conclusions

Fifty-day-long creep and shrinkage tests were done on the geopolymer specimens based on fly ash matrix with different kinds and amounts of fibre reinforcement to determine long-term properties. Prior to the long-term tests also, compressive strength was determined. Summarizing gained data and measurements, the conclusions from this study are as follows:

- Geopolymer composite with 5% polypropylene fibre inclusion has the lowest creep strains of all specimens. They are followed by specimens with 1% polypropylene fibre, plain geopolymer, and specimens with 1% steel fibre reinforcement. When the strains are at the highest point, specimens with 1% of polypropylene fibre have 1.4 times higher creep strains. For instance, the difference of creep strains between geopolymer without reinforcement, with 0.5% steel fibre and 0.5% polyvinyl alcohol fibres, and with 1% of steel fibre, is correspondingly 1.99, 2.04 and 2.44 times higher.

- Also, when elastic strains are removed from strain curves, the 5% polypropylene fibre reinforced geopolymer is the one with the smallest creep strains and is followed by the 1% PP fibre reinforced, 1% steel fibre reinforced, plain, and 0.5% steel and 0.5% polyvinyl alcohol fibre geopolymer specimens. The creep strain difference of the corresponding specimens to the 5% polypropylene fibre reinforced specimens are 1.84, 2.19, 2.99, and 3.03 times.

- The specimens with 1% and 5% polypropylene fibre reinforcement have significantly better specific creep properties than all of the rest tested geopolymer composite mixes. Plain geopolymer composite has on average 19.4% higher specific creep, 0.5% steel fibre and 0.5% polyvinyl alcohol fibre reinforced geopolymer composite has on average 19.6% higher specific creep, and 1% steel fibre reinforced geopolymer composite shows 49.6% higher specific creep.

- Without elastic strains, 5% polypropylene fibre reinforced specimens show superior specific creep over all other tested specimens. For example, the specimens with 1% polypropylene fibre have, on average, 32.1% higher specific creep, and plain and 1% steel fibre reinforced specimens show, on average, 31.1% and 49.8% higher specific creep correspondingly.

- Fibre reinforcement mix containing 0.5% steel fibre and 0.5% polyvinyl alcohol fibre does not affect creep and shrinkage strain development compared to plain geopolymer composite. Still, it helps to increase compressive strength by 11.4%.

- Each type of reinforcement has its optimal amount, which ensures that the mechanical as well as long-term properties increases. For example, a geopolymer composite made using 10M NaOH solution and reinforced with 1% polypropylene fibres not only improves compressive strength but also leads to low creep and shrinkage and, accordingly, low specific creep. On the other hand, specimens with 5% polypropylene fibre reinforcement correspond to the lowest creep and have 2nd lowest shrinkage strains, while they appear with the lowest compressive strength and the highest elastic strains from all of the tested specimens.

Acknowledgment(s)

This work has been supported by the European Regional Development Fund within the Activity 1.1.1.2 “Post-doctoral Research Aid” of the Specific Aid Objective 1.1.1 “To increase the research and innovative capacity of scientific institutions of Latvia and the ability to attract external financing, investing in human resources and infrastructure” of the Operational Programme “Growth and Employment” (No.1.1.1.2/VIAA/3/19/401);
This work has been supported by the Latvian Council of Science within the scope of the project “Foamed Geopolymer Made by Additive Manufacturing for the Construction Technology Applications (3D-FOAM)” No. ES RTD/2022/8;
This publication was supported by Riga Technical University's Doctoral Grant programme.

References

[1] P. Zhang, Y. Zheng, K. Wang, and J. Zhang, “A review on properties of fresh and hardened geopolymer mortar,” *Compos. Part B Eng.*, vol. 152, no. June, pp. 79–95, 2018, doi: 10.1016/j.compositesb.2018.06.031.
[2] M. Said, A. A. Abd El-Azim, M. M. Ali, H. El-Ghazaly, and I. Shaaban, “Effect of elevated temperature on axially and eccentrically loaded columns containing Polyvinyl Alcohol (PVA)

fibers," *Eng. Struct.*, vol. 204, no. December 2019, p. 110065, 2020, doi: 10.1016/j.engstruct.2019.110065.

[3] B. C. Lippiatt and S. Ahmad, *Measuring the Life-Cycle Environmental and Economic Performance of Concrete: the Bees Approach*. 2004.

[4] W. Lokuge, A. Wilson, C. Gunasekara, D. W. Law, and S. Setunge, "Design of fly ash geopolymer concrete mix proportions using Multivariate Adaptive Regression Spline model," *Constr. Build. Mater.*, vol. 166, pp. 472–481, 2018, doi: 10.1016/j.conbuildmat.2018.01.175.

[5] K. T. Nguyen, T. A. Le, and K. Lee, "Evaluation of the mechanical properties of sea sand-based geopolymer concrete and the corrosion of embedded steel bar," *Constr. Build. Mater.*, vol. 169, pp. 462–472, 2018, doi: 10.1016/j.conbuildmat.2018.02.169.

[6] L. Sele, D. Bajare, G. Bumanis, and L. Dembovska, "Alkali Activated Binders Based on Metakaolin," vol. 1, pp. 200–204, 2015, doi: 10.17770/etr2015vol1.204.

[7] S. Liang and Y. Wei, "Methodology of obtaining intrinsic creep property of concrete by flexural deflection test," *Cem. Concr. Compos.*, vol. 97, no. April 2018, pp. 288–299, 2019, doi: 10.1016/j.cemconcomp.2019.01.003.

[8] K. Sagoe-Crentsil, T. Brown, and A. Taylor, "Drying shrinkage and creep performance of geopolymer concrete," *J. Sustain. Cem. Mater.*, vol. 2, no. 1, pp. 35–42, Mar. 2013, doi: 10.1080/21650373.2013.764963.

[9] S. Chen, C. Wu, and D. Yan, "Binder-scale creep behavior of metakaolin-based geopolymer," *Cem. Concr. Res.*, vol. 124, no. July, p. 105810, 2019, doi: 10.1016/j.cemconres.2019.105810.

[10] I. Khan, T. Xu, A. Castel, R. I. Gilbert, and M. Babaee, "Risk of early age cracking in geopolymer concrete due to restrained shrinkage," *Constr. Build. Mater.*, vol. 229, p. 116840, 2019, doi: 10.1016/j.conbuildmat.2019.116840.

[11] T. A. Nizina and A. S. Balykov, "Experimental-statistical models of properties of modified fiber-reinforced fine-grained concretes," *Mag. Civ. Eng.*, vol. 62, no. 2, pp. 13–25, 2016, doi: 10.5862/MCE.62.2.

[12] N. K. Lee, J. G. Jang, and H. K. Lee, "Shrinkage characteristics of alkali-activated fly ash/slag paste and mortar at early ages," *Cem. Concr. Compos.*, vol. 53, pp. 239–248, 2014, doi: 10.1016/j.cemconcomp.2014.07.007.

[13] C. Kuenzel, L. Li, L. Vandeperre, A. R. Boccaccini, and C. R. Cheeseman, "Influence of sand on the mechanical properties of metakaolin geopolymers," *Constr. Build. Mater.*, vol. 66, pp. 442–446, 2014, doi: 10.1016/j.conbuildmat.2014.05.058.

[14] N. Ranjbar, S. Talebian, M. Mehrali, C. Kuenzel, H. S. Cornelis Metselaar, and M. Z. Jumaat, "Mechanisms of interfacial bond in steel and polypropylene fiber reinforced geopolymer composites," *Compos. Sci. Technol.*, vol. 122, pp. 73–81, 2016, doi: 10.1016/j.compscitech.2015.11.009.

[15] N. Ranjbar, M. Mehrali, M. Mehrali, U. J. Alengaram, and M. Z. Jumaat, "High tensile strength fly ash based geopolymer composite using copper coated micro steel fiber," *Constr. Build. Mater.*, vol. 112, pp. 629–638, 2016, doi: 10.1016/j.conbuildmat.2016.02.228.

[16] N. Ranjbar and M. Zhang, "Fiber-reinforced geopolymer composites: A review," *Cem. Concr. Compos.*, vol. 107, no. December 2019, p. 103498, 2020, doi: 10.1016/j.cemconcomp.2019.103498.

[17] C. S. Das, T. Dey, R. Dandapat, B. B. Mukharjee, and J. Kumar, "Performance evaluation of polypropylene fibre reinforced recycled aggregate concrete," *Constr. Build. Mater.*, vol. 189, pp. 649–659, 2018, doi: 10.1016/j.conbuildmat.2018.09.036.

[18] J. Blazy and R. Blazy, "Polypropylene fiber reinforced concrete and its application in creating architectural forms of public spaces," *Case Stud. Constr. Mater.*, vol. 14, p. e00549, 2021, doi: 10.1016/j.cscm.2021.e00549.

[19] S. Yin, R. Tuladhar, F. Shi, M. Combe, T. Collister, and N. Sivakugan, "Use of macro plastic fibres in concrete : A review," *Constr. Build. Mater.*, vol. 93, pp. 180–188, 2015, doi: 10.1016/j.conbuildmat.2015.05.105.

[20] T. Transactions and C. Techniczne, “POLYOLEFIN FIBRES USED IN CEMENTITIOUS COMPOSITES – MANUFACTURING , PROPERTIES AND APPLICATION WŁÓKNA POLIOLEFINOWE STOSOWANE W KOMPOZYTACH CEMENTOWYCH – METODY WYTWARZANIA , WŁAŚCIWOŚCI I ZASTOSOWANIE,” 2016, doi: 10.4467/2353737XCT.16.223.5972.

[21] A. Mohajerani, S. Hui, M. Mirzababaei, and A. Arulrajah, “Amazing Types, Properties, and Applications of Fibres in Construction Materials,” pp. 1–45.

[22] M. Amran *et al.*, “Fibre-reinforced foamed concretes: A review,” *Materials (Basel).*, vol. 13, no. 19, pp. 1–36, 2020, doi: 10.3390/ma13194323.

[23] S. Klyuev, A. Klyuev, and N. Vatin, “Fine-grained concrete with combined reinforcement by different types of fibers,” in *MATEC Web of Conferences*, Dec. 2018, vol. 245. doi: 10.1051/matecconf/201824503006.

[24] C. L. Xin, Z. Z. Wang, J. M. Zhou, and B. Gao, “Shaking table tests on seismic behavior of polypropylene fiber reinforced concrete tunnel lining,” *Tunn. Undergr. Sp. Technol.*, vol. 88, no. July 2018, pp. 1–15, 2019, doi: 10.1016/j.tust.2019.02.019.

[25] Y. Qin, X. Zhang, J. Chai, Z. Xu, and S. Li, “Experimental study of compressive behavior of polypropylene-fiber-reinforced and polypropylene-fiber-fabric-reinforced concrete,” *Constr. Build. Mater.*, vol. 194, pp. 216–225, 2019, doi: 10.1016/j.conbuildmat.2018.11.042.

[26] J. Yang, R. Wang, and Y. Zhang, “Influence of dually mixing with latex powder and polypropylene fiber on toughness and shrinkage performance of overlay repair mortar,” *Constr. Build. Mater.*, vol. 261, p. 120521, 2020, doi: 10.1016/j.conbuildmat.2020.120521.

[27] G. M. S. Islam and S. Das, “Evaluating plastic shrinkage and permeability of polypropylene fiber reinforced concrete,” *Int. J. Sustain. Built Environ.*, vol. 5, no. 2, pp. 345–354, 2016, doi: 10.1016/j.ijsbe.2016.05.007.

[28] V. Marcos-Meson, G. Fischer, C. Edvardsen, T. L. Skovhus, and A. Michel, “Durability of Steel Fibre Reinforced Concrete (SFRC) exposed to acid attack – A literature review,” *Constr. Build. Mater.*, vol. 200, pp. 490–501, 2019, doi: 10.1016/j.conbuildmat.2018.12.051.

[29] G. Ruiz, Á. de la Rosa, and E. Poveda, “Relationship between residual flexural strength and compression strength in steel-fiber reinforced concrete within the new Eurocode 2 regulatory framework,” *Theor. Appl. Fract. Mech.*, vol. 103, no. July, p. 102310, 2019, doi: 10.1016/j.tafmec.2019.102310.

[30] K. Wu, F. Chen, J. Lin, J. Zhao, and H. Zheng, “Experimental study on the interfacial bond strength and energy dissipation capacity of steel and steel fibre reinforced concrete (SSFRC) structures,” *Eng. Struct.*, vol. 235, no. March, p. 112094, 2021, doi: 10.1016/j.engstruct.2021.112094.

[31] M. Gümüş and A. Arslan, “Effect of fiber type and content on the flexural behavior of high strength concrete beams with low reinforcement ratios,” *Structures*, vol. 20, no. February, pp. 1–10, 2019, doi: 10.1016/j.istruc.2019.02.018.

[32] J. Han, M. Zhao, J. Chen, and X. Lan, “Effects of steel fiber length and coarse aggregate maximum size on mechanical properties of steel fiber reinforced concrete,” *Constr. Build. Mater.*, vol. 209, pp. 577–591, 2019, doi: 10.1016/j.conbuildmat.2019.03.086.

[33] R. Gailitis, A. Sprince, T. Kozlovskis, L. Radina, and L. Pakrastins, “Long-Term Properties of Different Fiber Reinforcement Effect on Fly Ash-Based Geopolymer Composite,” pp. 1–8, 2021.

[34] K. Korniejenko, “Geopolymers for Increasing Durability for Marine Infrastructure,” *Spec. Publ.*, vol. 326.

[35] M. Łach, J. Mikuła, and M. Hebda, “Thermal analysis of the by-products of waste combustion,” *J. Therm. Anal. Calorim.*, vol. 125, no. 3, pp. 1035–1045, 2016, doi: 10.1007/s10973-016-5512-9.

[36] P. Acker *et al.*, “RILEM TC 107-CSP: CREEP AND SHRINKAGE PREDICTION MODELS: PRINCIPLES OF THEIR FORMATION Recommendation Measurement of time-dependent

strains of concrete," *Mater. Struct.*, vol. 31, pp. 507–512, Oct. 1998.
[37] R. Ravinder, V. Kumar, C. Kumar, A. Prakash, and P. V. V. S. S. R. Krishna, "Strength Characteristics of Fibrous Self Curing Concrete Using Super Absorbent Polymer Strength Characteristics of Fibrous Self Curing Concrete Using Super Absorbent Polymer," no. July, pp. 5–10, 2019.
[38] Z. H. Mahdil, B. H. Maula, A. S. Ali, and M. R. Abdulghani, "Influence of Sand Size on Mechanical Properties of Fiber Reinforced Polymer Concrete," pp. 554–560, 2019.
[39] S. S. K. H.R. Tavakoli, O.L. Omran, M.F. Shiade, "Prediction of combined effects of fibers and nano- silica on the mechanical properties of self-compacting concrete using artificial neural network," vol. 11, pp. 1906–1923, 2014.
[40] H. Tanyildizi, "Statistical analysis for mechanical properties of polypropylene fiber reinforced lightweight concrete containing silica fume exposed to high temperature," *Mater. Des.*, vol. 30, no. 8, pp. 3252–3258, 2009, doi: 10.1016/j.matdes.2008.11.032.
[41] M. M. M.G. Chorzepa, "Performance of multiscale, including nanoscale, fibres in concrete," *Mater. Res.*, vol. 6, pp. 198–209, 2017, doi: 10.1680/jemmr.16.00020.