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Finite Element Design and Analysis of Sustainable Mono-Reinforced and Hybrid-Reinforced Fibergeopolymers

Sergey V. Klyuev¹ , Alexander V. Klyuev¹ , Narman A. Ayubov² ,Roman S. Fediuk³ , Elena V. Levkina³ ¹ V.G. Shukhov Belgorod State Technological University, Belgorod, Russian Federation² Kh.I. Ibragimov Complex Research Institute of the Russian Academy of Sciences, Grozny, Russian Federation³ Far Eastern Federal University, Vladivostok, Russian Federation roman44@ya.ru

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Abstract

Introduction. Environmental improvement involves the recycling of man-made materials for product recovery with high performance characteristics. However, in general, energy-intensive and uneconomical materials have no alternative in construction. Literary information on the problem is insufficient and uncompiled. The presented article is intended to fill this gap. The research objective is to study mono-reinforced and hybrid-reinforced fibergeopolymers. For this purpose, two problems are solved: design of polymers and analysis of beams made from them using the finite element method.

Materials and Methods. The binding base for the production of fibergeopolymers was sintered particles (beads) extracted from basalt wool waste — technogenic fibrous materials (TFM). The fiber was made from metal cord, basalt wool waste and polypropylene. Beams made from hybrid-reinforced fibergeopolymers were studied under bending and shear in the ANSYS 16.1 software environment.

Results. Two types of geopolymers were obtained:

- mono-reinforced (fiber from metal cord, polypropylene fiber, and TFM – fiber from waste from basalt wool production);
- hybrid-fiber-reinforced (metal cord + polypropylene, metal cord + TFM, polypropylene + TFM).

High values of elastic modulus (more than 25 GPa), bending strength (up to 10.19 MPa) and compression strength (up to 46.67 MPa) were defined. The ratio of bending and compression strength for the studied and traditional materials was 1:4 and 1:10, respectively. The simulated and experimental indicators of beam deflections under loads from 5 to 72 kN were compared. It was found that finite element modeling allowed designing structures from the developed materials and predicting their performance characteristics.

Discussion. The cases of the smallest discrepancy between the modeling and experimental data were established. For FGP-1, it was 8% (load — 35 kN), for FGP-2 — 11% (50 kN), for FGP-3 — 7% (38 kN), for FGP-1 (1%) — 3% (30 kN). Among the hybrid-reinforced fibergeopolymers, the best compliance was that of HFGP-3. At a load of 55 kN, the discrepancy was 0.80% (theory — 4.98 mm, experiment — 5.02 mm). For HFGP-1, the best indicator was 1.85% (72 kN, 5.85 mm, 5.96 mm), for HFGP-2 — 9.12% (63 kN, 5.58 mm, 6.14 mm). The applied value of the results was confirmed by their visualization – the similarity and coincidence of the curves on the graphs.

Conclusions. The advantages of the proposed innovative components for the production of building materials are proved. They are environmentally friendly and show sufficient workability. Design of hybrid-reinforced fibergeopolymers makes it possible to obtain high values of bending and compression strength (significantly higher than that of unreinforced concrete). The modulus of elasticity of more than 25 GPa proves good resistance of the material to deformations. The results of the modeling are adequate to the results of the experiments.

Keywords: mono-reinforced fibergeopolymers, hybrid-reinforced fibergeopolymers, processing of technogenic raw materials, technogenic fibrous materials, technical properties of fibers, geopolymer concrete

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Оригинальное эмпирическое исследование

Проектирование и анализ методом конечных элементов экологически безопасных моноармированных и гибридноармированных фиброгеополимеров

С.В. Ключев¹ , А.В. Ключев¹ , Н.А. Аюбов² , Р.С. Федюк³  , Е.В. Левкина³ 

¹ Белгородский государственный технологический университет им. В.Г. Шухова, г. Белгород, Российская Федерация

² Комплексный научно-исследовательский институт им. Х.И. Ибрагимова Российской академии наук, г. Грозный, Российская Федерация

³ Дальневосточный федеральный университет, г. Владивосток, Российская Федерация

✉ roman44@ya.ru

Аннотация

Введение. Улучшение экологии предполагает переработку техногенных материалов для получения продукции с высокими эксплуатационными характеристиками. Однако в строительстве в целом безальтернативны энергоемкие и неэкономичные материалы. Литературные сведения по проблеме недостаточны и разрознены. Представленная статья призвана восполнить этот пробел. Цель работы — исследование моноармированных и гибридноармированных фиброгеополимеров. Для достижения цели решались две задачи: проектирование полимеров и анализ балок из них методом конечных элементов.

Материалы и методы. Вяжущей основой фиброгеополимеров служили спекшиеся частицы (корольки) из отходов техногенных волокнистых материалов (ТВМ), а именно из базальтовой ваты. Фибру изготавливали из металлокорда, отходов базальтовой ваты и полипропилена. Балки из гибридноармированных фиброгеополимеров изучали при изгибе и сдвиге в программной среде Ansys 16.1.

Результаты исследования. Получены два вида геополимеров:

– моноармированные (фибра из металлокорда, полипропиленовая фибра и ТВМ – фибра из отходов производства базальтовой ваты);

– гибриднофиброармированные (металлокорд + полипропилен, металлокорд + ТВМ, полипропилен + ТВМ).

Выявили высокие значения модуля упругости (более 25 ГПа), прочности при изгибе (до 10,19 МПа) и сжатии (до 46,67 МПа). Отношение прочности при изгибе и сжатии для исследуемых и традиционных материалов — 1:4 и 1:10 соответственно. Сравнили смоделированные и экспериментальные показатели прогибов балок при нагрузках от 5 до 72 кН. Выяснили, что конечноэлементное моделирование позволяет проектировать конструкции из разработанных материалов и прогнозировать их эксплуатационные характеристики.

Обсуждение. Установлены случаи наименьшего расхождения данных моделирования и опытов. Для ФГП-1 это 8 % (нагрузка — 35 кН), для ФГП-2 — 11 % (50 кН), для ФГП-3 — 7 % (38 кН), для ФГП-1 (1 %) — 3 % (30 кН). Среди гибридноармированных фиброгеополимеров наилучшее соответствие — у ГФГП-3. При нагрузке 55 кН расхождение — 0,80 % (теория — 4,98 мм, опыт — 5,02 мм). Для ГФГП-1 лучший показатель — 1,85 % (72 кН, 5,85 мм, 5,96 мм), для ГФГП-2 — 9,12 % (63 кН, 5,58 мм, 6,14 мм). Прикладную ценность результатов подтвердила их визуализация — схожесть и совпадение кривых на графиках.

Заключение. Доказаны преимущества предложенных инновационных компонентов для производства строительных материалов. Они экологичны, демонстрируют достаточную удобоукладываемость. Проектирование гибридноармированных фиброгеополимеров дает возможность получить высокие значения прочности при изгибе и сжатии (существенно выше, чем у неармированных бетонов). Модуль упругости более 25 ГПа доказывает хорошее сопротивление материала деформациям. Итоги моделирования адекватны результатам экспериментов.

Ключевые слова: моноармированные фиброгеополимеры, гибридноармированные фиброгеополимеры, переработка техногенного сырья, техногенные волокнистые материалы, технические свойства фибр, геополимерный бетон

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Introduction. One of the priorities of the strategy of scientific and technical development of the Russian Federation is to counteract man-made, biogenic, sociocultural and other sources of danger to society and the economy [1]. The most important task of environmental safety is the development of processes and techniques [2], resource conservation [3], and complex processing of man-made materials [4], obtaining products with high performance characteristics on their basis [5].

Transdisciplinary approaches provide a new level of development of building composite mixtures. For progress in this area, it is important to move away from the current templates of designing building materials [6]. To reduce the complexity of recipes and the cost of components, it is necessary to use data from various sciences: materials science, physics, chemistry, geology, nanotechnology, etc. In addition, certain operational characteristics can be assigned to the new composite [7].

Improvement of physical, mechanical, operational, protective and environmental properties of modern modified composites is based on:

- optimization of formulations and technologies;
- use of non-traditional types of natural and man-made raw materials [8].

It is known that the economic efficiency of projects is largely determined by the use of high-tech building materials [9]. Modern composites have good prospects in industrial and civil construction [9]. They are often used for unique projects and objects that are operated under various conditions [10].

When producing the materials described above, one of two innovative strategies is usually used:

- recycling for the production of so-called “green” materials [11];
- creation of “smart” concrete for monitoring the condition of building structures [12].

It should be noted that the regulatory framework governing construction design does not contain recommendations on the use of man-made waste as fillers for concrete. Promising approaches are discussed in the literature. As a rule, this concerns the comprehensive processing of used tires, as well as fibrous materials — man-made waste from the production of mineral wool [13]. However, both of these solutions have not been sufficiently studied and tested in practice.

The possibility of using carbon black and TFM waste should also be mentioned. However, even in this case there are no adequate scientific conclusions that would prove the practical feasibility of introducing such composites into construction practice [14].

The objective of the presented work was to study and design unreinforced and hybrid-reinforced fibergeopolymers using the FEM. Within the framework of this study, two problems were solved: design of hybrid-reinforced fibergeopolymers and analysis of beams made from them by the FEM. This was required to reach the stated goal, as well as in general for the creation of sustainable building materials.

Materials and Methods. The binding base for the production of fibergeopolymers was sintered particles (beads) extracted from waste basalt wool — technogenic fibrous materials (TFM). A combination of sodium silicate and sodium hydroxide solution was used as an alkaline activating liquid. Polyfractionated quartz sand with a specific gravity of 2.67 acted as a fine filler. The maximum size of the coarse aggregate used in this study did not exceed 12 mm, which increased the workability of concrete. The fiber from the metal cord of waste tires was heat-treated and cut. The fiber from TFM was obtained through grinding basalt wool. The authors found that sometimes the actual technical properties of the fibers differed from those declared by the manufacturers, and these actual parameters are given in Table 1.

Table 1

Properties of Different Types of Fiber

Properties	Metal cord	Polypropylene	TFM
Diameter, mm	0.75	0.002	0.013
Length, mm	60–75	12.0	40–70
Length to diameter ratio	80–100	6,000	3,077–5,385
Tensile strength, MPa	2,500	3.50	2,000
Modulus of elasticity, MPa	210	3.45	75,000
Specific gravity	8	0.90	2.6

The behavior of 1,000×200×100 mm beams made from hybrid-reinforced fiber-geopolymers was studied. They were analyzed by the FEM in bending and shear. The deflection of geopolymer concrete beams was calculated to prevent unacceptable deformations and provide normal operation of structures. The FEM is suitable for computer processing, it can be used to solve problems in solid mechanics, fluid mechanics, heat transfer and vibrations.

Research Results. Compositions of sustainable fibergeopolymer mixtures have been developed, which show satisfactory workability characteristics (Table 2). Workability provides high-quality, safe transportation of the geopolymer mixture to the place of installation.

Table 2

Developed Compositions and Cone Slump Measurement Results

Composition	Fiber content, % by volume	Slump, mm	Workability
Cement concrete	–	112.1	High
Unreinforced geopolymer (GP)	–	103.5	High
Fibergeopolymer (FGP-1), metal cord	0.5	80.3	Average
FGP-2, polypropylene	0.5	78.4	Average
FGP-3, TFM	0.5	76.5	Average
Hybrid fibergeopolymer (HFGP-1), metal cord + polypropylene	0.25 + 0.25	65.4	Average
HFGP-2, metal cord + TFM	0.25 + 0.25	70.2	Average
HFGP-3, TFM + polypropylene	0.25 + 0.50	68.7	Average

The composites were cured for 28 days under normal, unintentionally specified conditions. Their final mechanical properties were summarized in Table 3. High values of compressive strength (up to 46.67 MPa) and bending strength (up to 10.19 MPa) were shown. An extremely important difference in the ratio of bending and compressive strength for the studied and traditional materials was established — 1:4 and 1:10, respectively. High modulus of elasticity (more than 25 GPa) is especially important for designers and engineers, since it determines the ability of the material to resist deformation, i.e., the strength and stability of building structures. In Table 3, the compositions with the best characteristics are highlighted in color.

Table 3

Mechanical Properties of Composite Materials after Curing for 28 Days

Composition	Strength, MPa		Modulus of elasticity, GPa
	compressive	bending	
Cement concrete	40.89	4.60	19.24
Unreinforced geopolymer (GP)	41.33	4.40	19.32
Fibergeopolymer (FGP-1)	46.67	8.79	25.01
FGP-2	45.78	8.60	24.57
FGP-3	34.67	8.00	20.02
Hybrid fibergeopolymer (HFGP-1)	46.67	8.39	25.03
HFGP-2	44.44	10.19	23.49
HFGP-3	40.44	9.50	20.11

The statics problems were solved by the FEM. The sequence of analysis in the Ansys software environment is described below.

1. Setting the algorithm.
2. Specifying the geometry.
3. Specifying and determining the material properties (modulus of elasticity and Poisson's ratio).

For the modeling, a geopolymer beam with three degrees of freedom at each node was used. It moved and was elastically deformed in x , y , z directions.

Modulus of elasticity of concrete:

$$E_c = 5000\sqrt{R_{cж.}}, \quad (1)$$

where E_c — short-term static modulus of elasticity, MPa; $R_{cж.}$ — compressive strength, MPa.

Poisson's ratio is usually less than 0.5. In [15], the values from 0.18 to 0.24 are given, while in [16], the figures are from 0.23 to 0.32.

Meshing is based on the geometry of the structure. Visualization of the bending analysis in Ansys is shown in Figures 1–11.

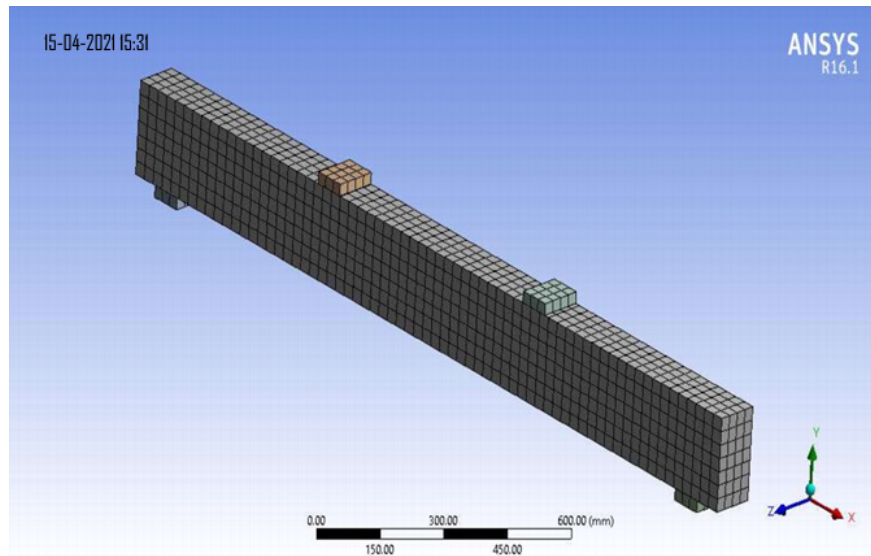


Fig. 1. Beam discretization

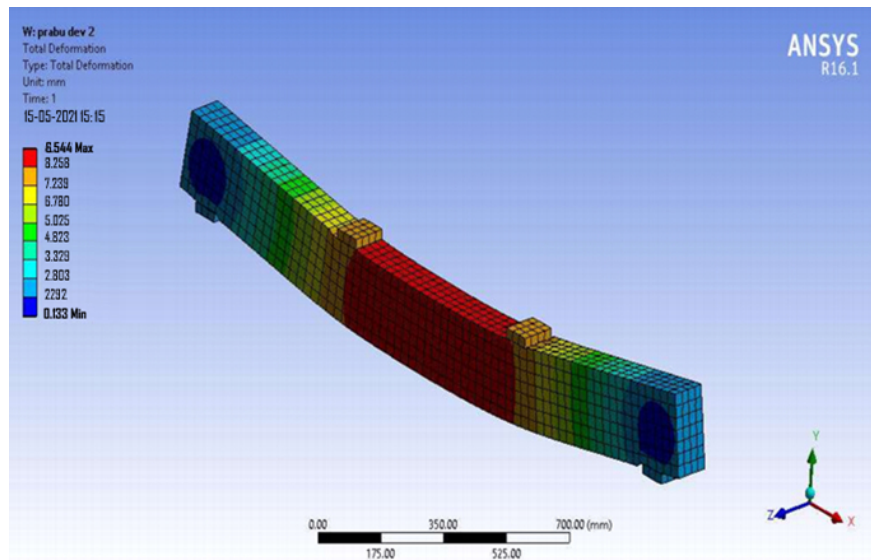


Fig. 2. Deformation of beam FGP-1

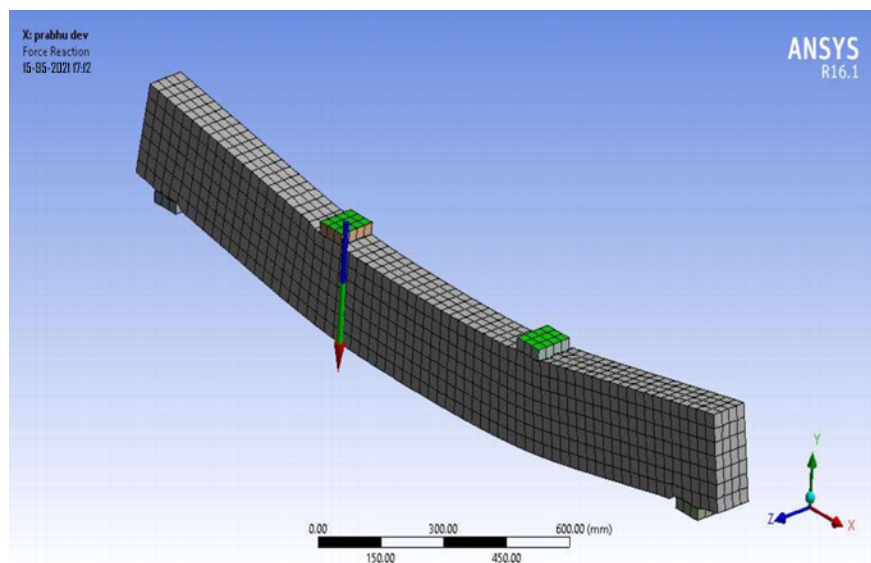


Fig. 3. Deflection of beam FGP-1

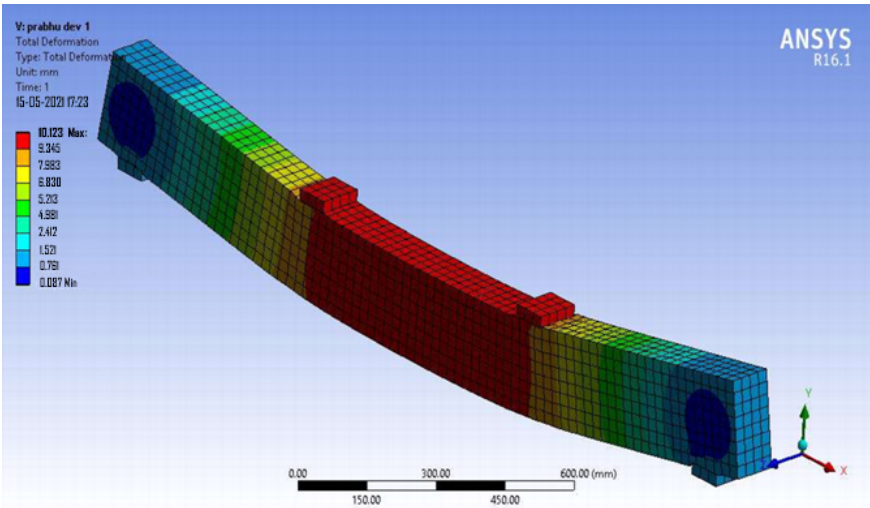


Fig. 4. Deformation of GP beam

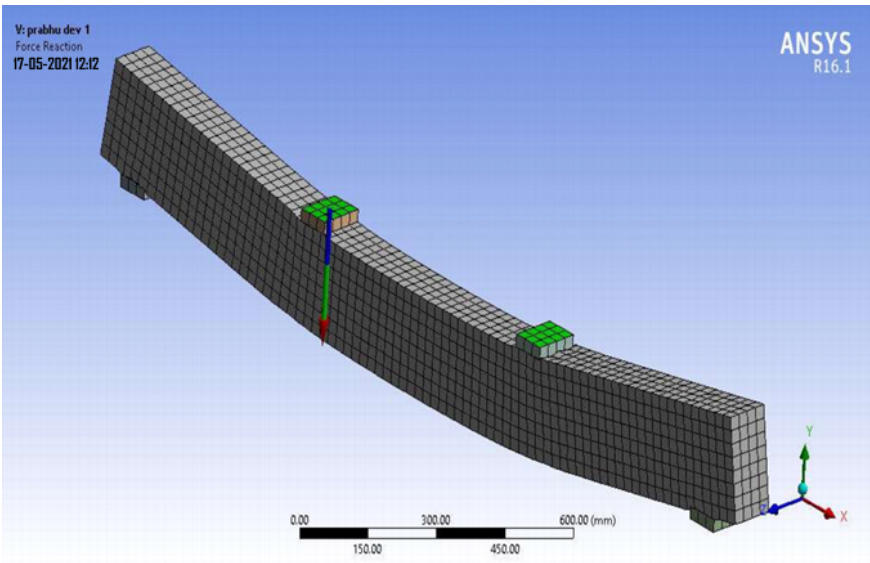


Fig. 5. Deflection of GP beam

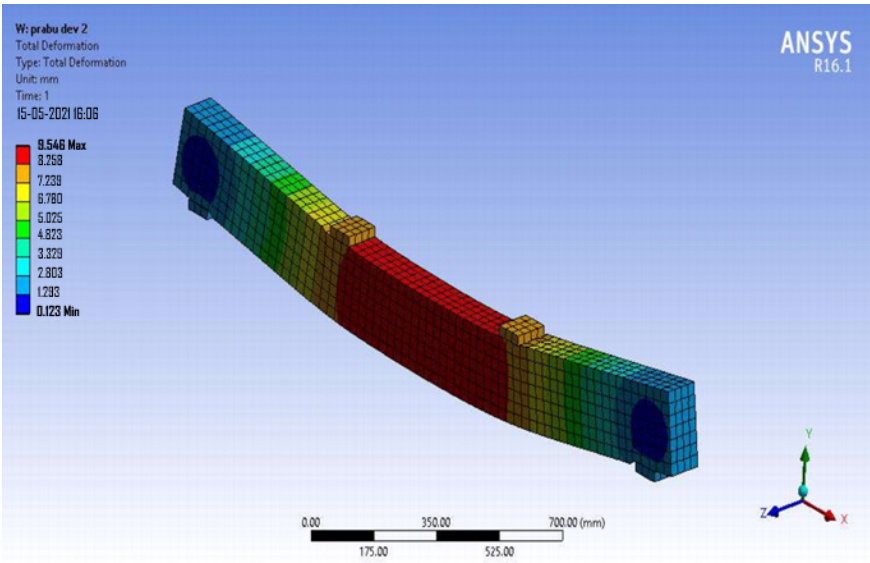


Fig. 6. Deformation of beam HFGP-1

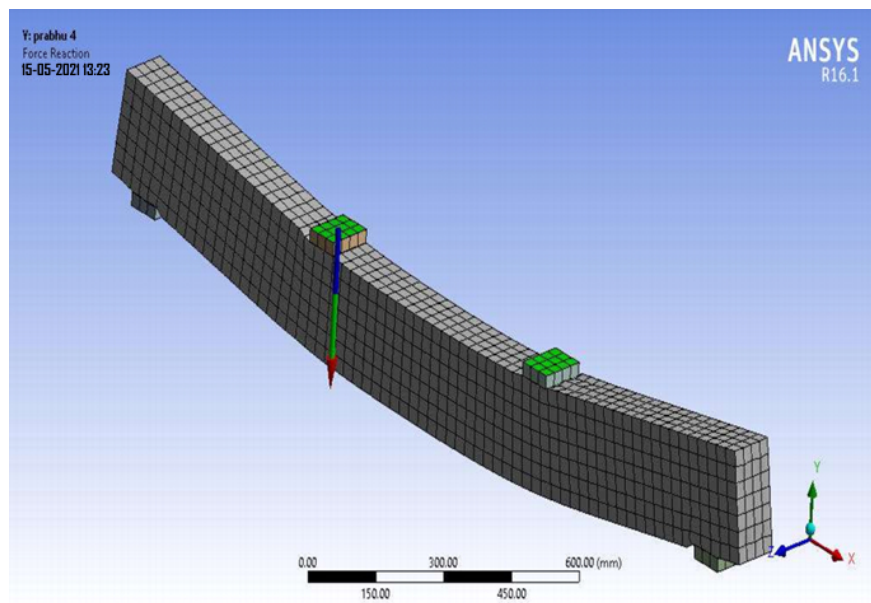


Fig. 7. Deflection of beam HFGP-1

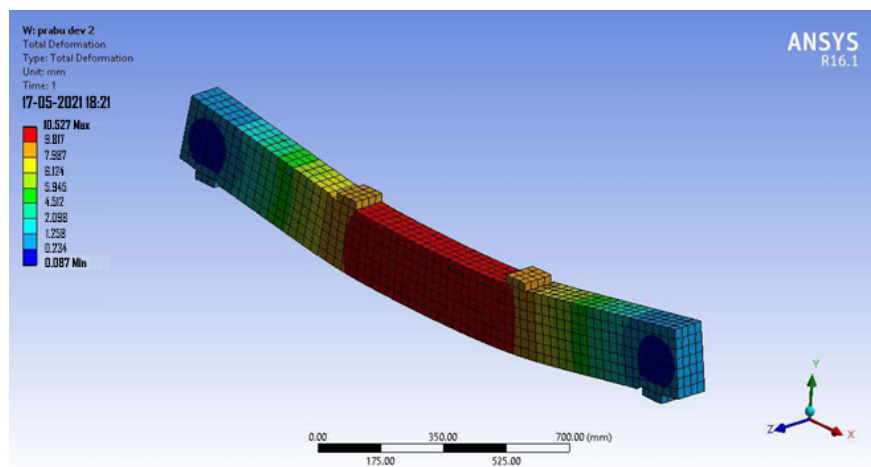


Fig. 8. Deformation of beam HFGP-2

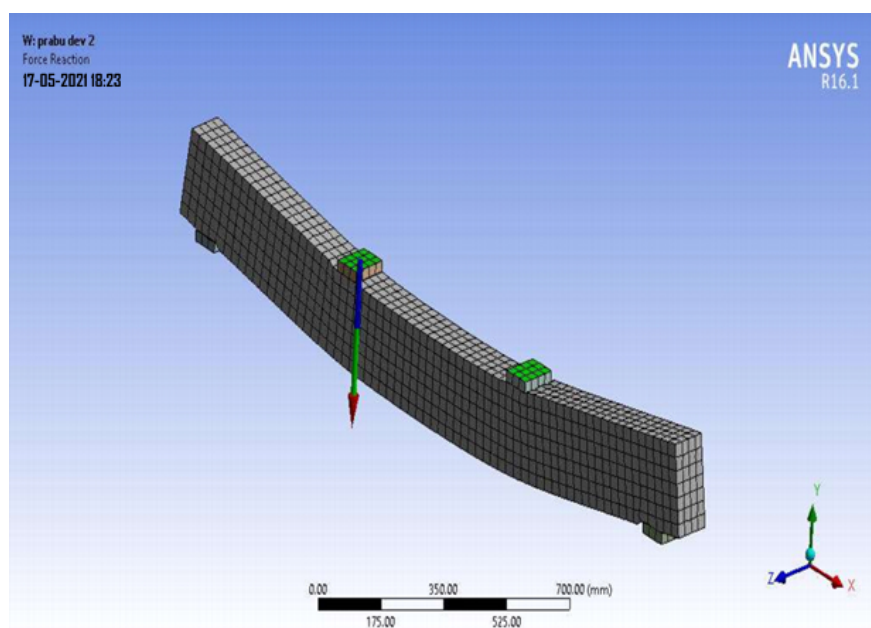


Fig. 9. Deflection of beam HFGP-2

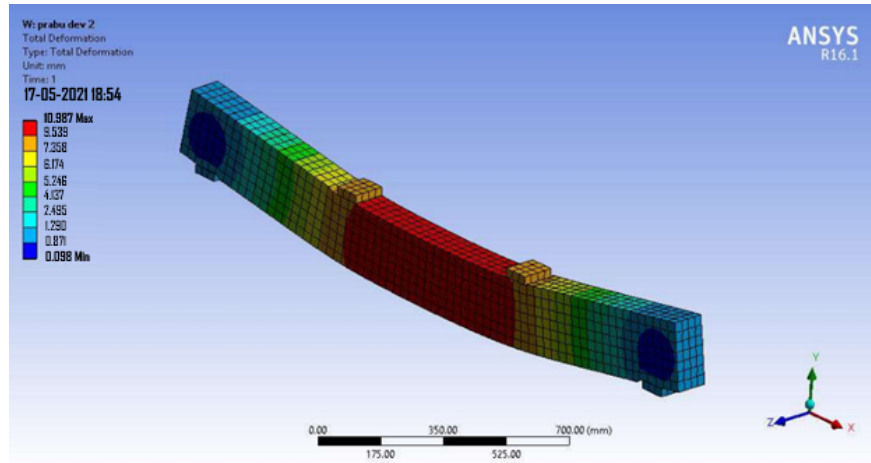


Fig. 10. Deformation of beam HFGP-3

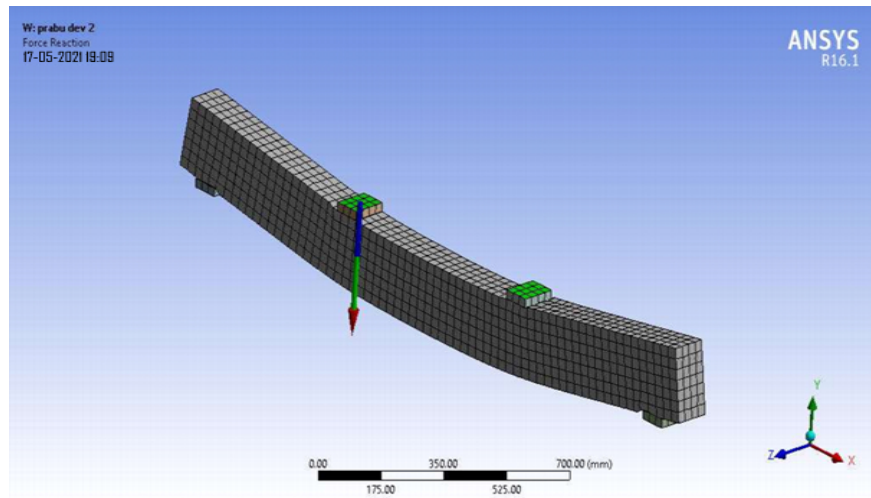


Fig. 11. Deflection of beam HFGP-3

Comparison of the experimental and theoretical results of deflection is given in Tables 4, 5 and Figures 12–17. Geopolymer concrete is an elastic-plastic material, therefore the stress-strain graph is nonlinear.

Table 4

Comparison of Experimental and Theoretical Results of Deflection

Load, kN	Cement concrete			GP			FGP-1			FGP-2			FGP-3			FGP-1(1 %)		
	Deflection, mm		Difference, %	Deflection, mm		Difference, %	Deflection, mm		Difference, %	Deflection, mm		Difference, %	Deflection, mm		Difference, %	Deflection, mm		Difference, %
	exper.	calc.		exper.	calc.		exper.	calc.		exper.	calc.		exper.	calc.		exper.	calc.	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0.85	0.65	24	0.74	0.58	22	0.48	0.35	27	0.55	0.43	22	0.70	0.42	40	0.64	0.47	27
10	1.72	1.45	16	1.52	1.58	4	1.28	1.14	11	1.28	0.98	23	1.56	0.95	39	1.44	1.05	27
15	2.45	2.35	4	2.35	2.14	9	1.96	1.56	20	1.84	1.14	38	2.18	1.47	33	2.02	1.87	7
20	2.54	3.05	20	2.96	3.05	3	2.38	2.02	15	2.64	1.45	45	2.89	2.04	29	2.74	2.43	12
25	4.35	3.96	9	3.70	3.65	1	2.96	2.48	16	3.04	2.02	34	3.34	2.90	13	3.64	3.05	16
30	5.04	4.57	9	4.20	4.14	1	3.43	3.05	11	3.78	2.75	27	4.10	3.47	15	3.98	3.85	3
35	6.25	5.43	13	4.75	4.56	4	4.14	3.81	8	4.21	3.24	23	4.98	4.25	15	4.64	4.00	14
38	7.12	6.85	4	5.20	5.10	2	4.97	4.26	14	5.02	3.75	25	5.47	5.07	7	5.08	4.56	10
44	—	—	—	5.35	5.15	4	5.14	4.58	11	5.28	4.33	18	6.76	5.48	19	5.38	4.95	8
50	—	—	—	6.75	5.45	19	5.48	4.97	9	5.58	4.98	11	—	—	—	6.57	5.50	16
52	—	—	—	—	—	—	6.03	5.05	16	6.42	5.52	14	—	—	—	—	—	—
63	—	—	—	—	—	—	6.12	5.55	9	—	—	—	—	—	—	—	—	—

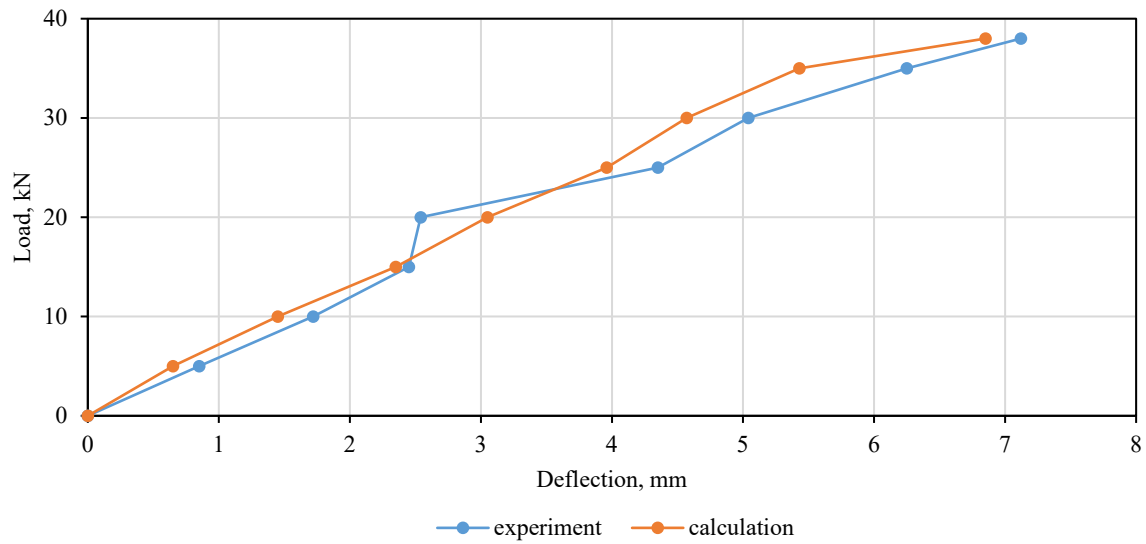


Fig. 12. Deflection of a cement concrete beam

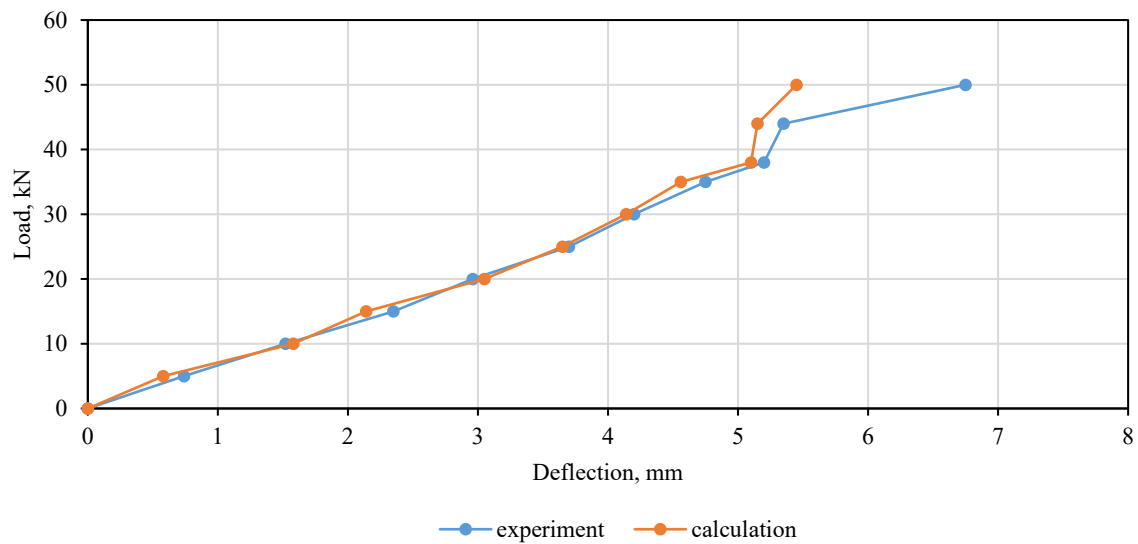


Fig. 13. Deflection of GP beam

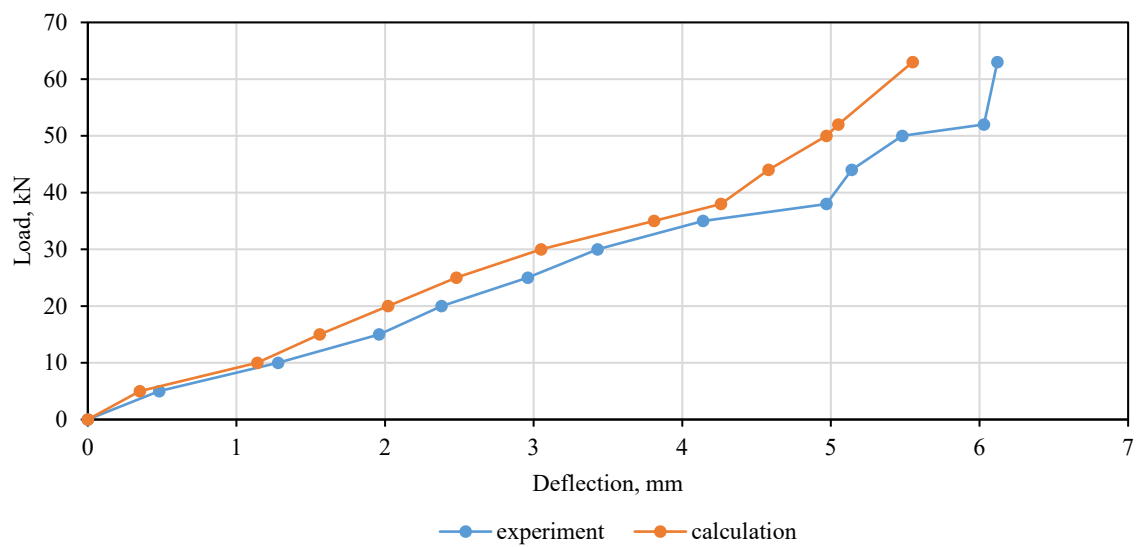


Fig. 14. Deflection of beam FGP-1

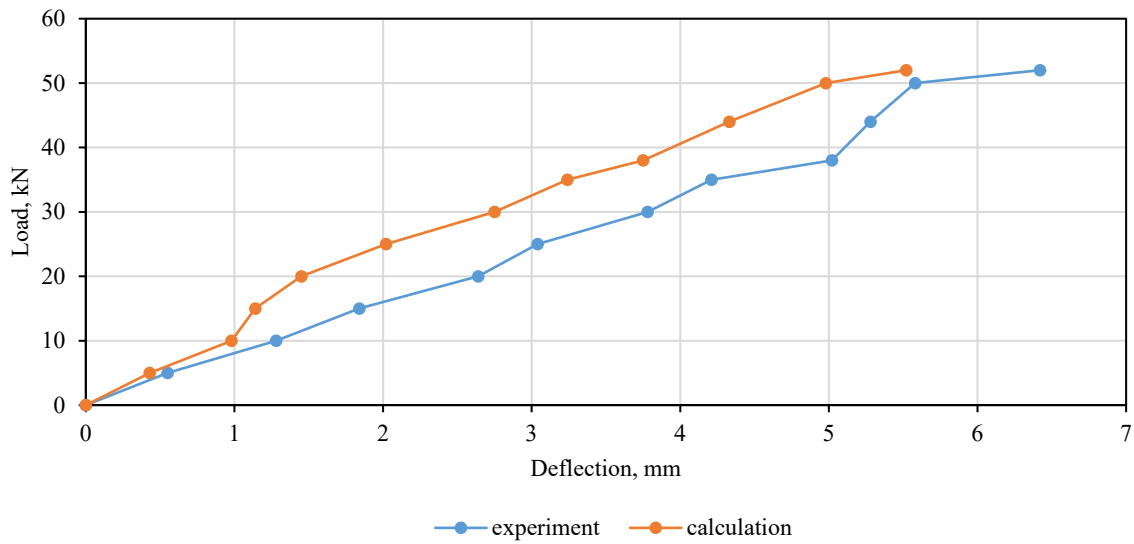


Fig. 15. Deflection of beam FGP-2

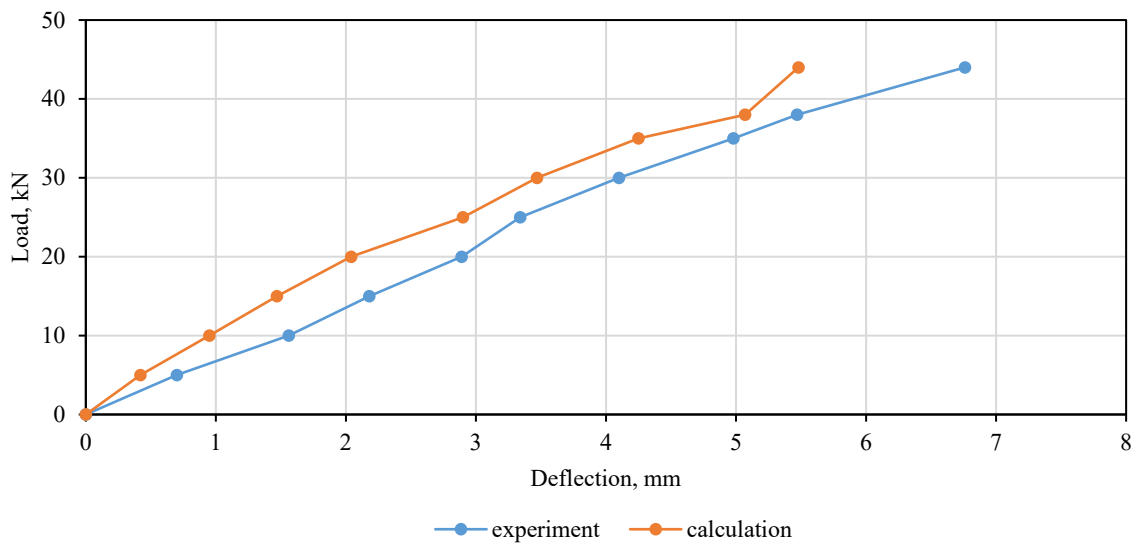


Fig. 16. Deflection of beam FGP-3

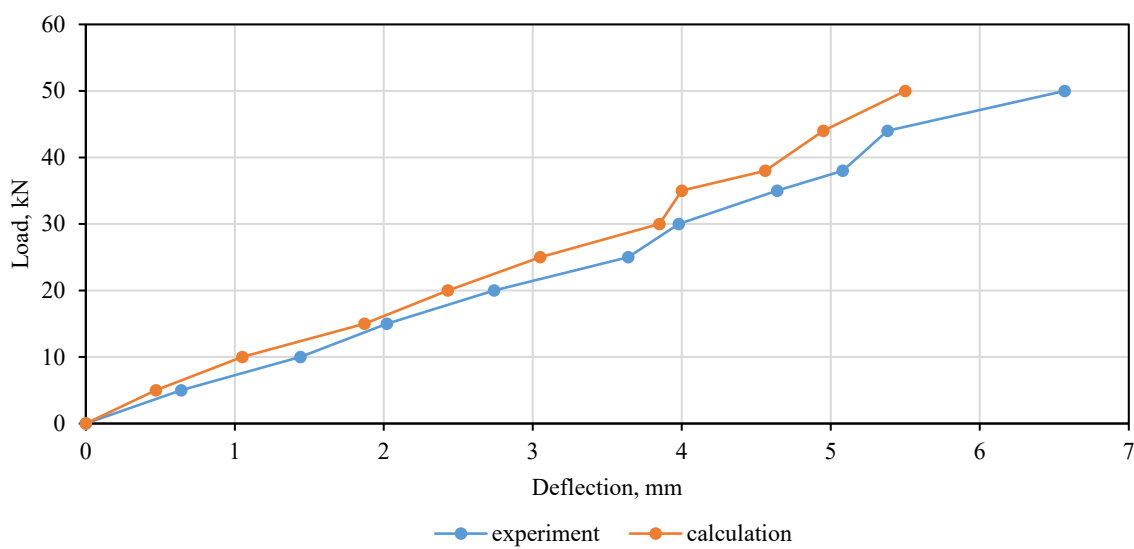


Fig. 17. Deflection of beam FGP-1 with 1% of metal cord fiber

Table 5

Comparison of Experimental and Theoretical Deflection Results for Hybrid-Reinforced Fibergeopolymers

Load, kN	Deflection, mm					
	HFGP-1		HFGP-2		HFGP-3	
	exper.	calc.	exper.	calc.	exper.	calc.
0	0	0	0	0	0	0
5	0.26	0.14	0.32	0.18	0.30	0.17
10	0.55	0.37	0.67	0.42	0.58	0.37
15	0.97	0.64	1.18	0.71	1.05	0.82
20	1.28	0.99	1.64	1.07	1.54	1.02
25	1.86	1.14	2.03	1.84	2.07	1.71
30	2.04	1.86	2.85	2.04	2.48	2.10
35	2.74	2.41	3.12	2.26	3.99	2.89
40	3.04	2.74	3.98	3.24	4.29	3.12
45	3.65	3.24	4.26	3.75	4.54	3.92
50	3.98	3.74	5.24	4.36	4.96	4.26
55	4.18	4.08	6.05	5.05	5.02	4.98
63	4.86	4.66	6.14	5.58	5.64	5.21
64	5.26	4.89	–	–	6.03	5.74
70	5.77	5.14	–	–	–	–
72	5.96	5.85	–	–	–	–

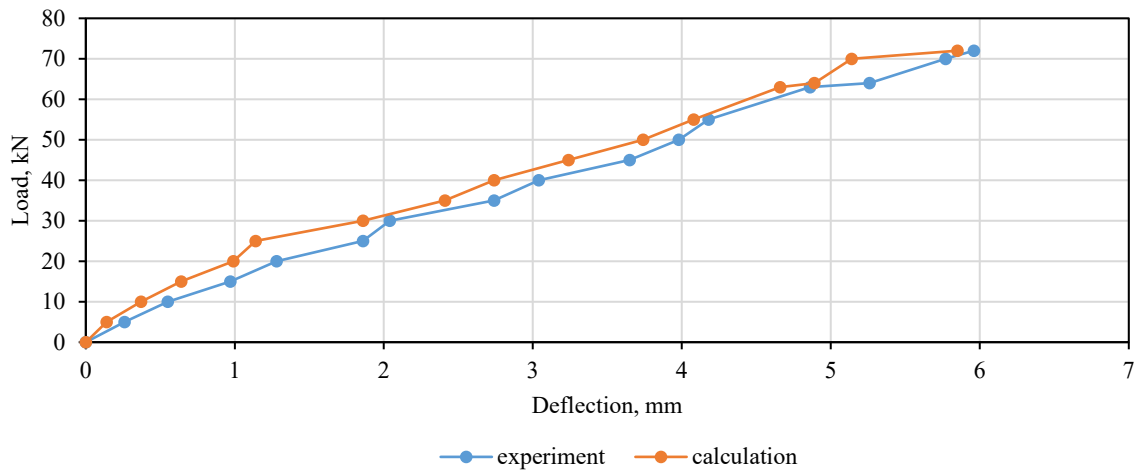


Fig. 18. Deflection of beam HFGP-1

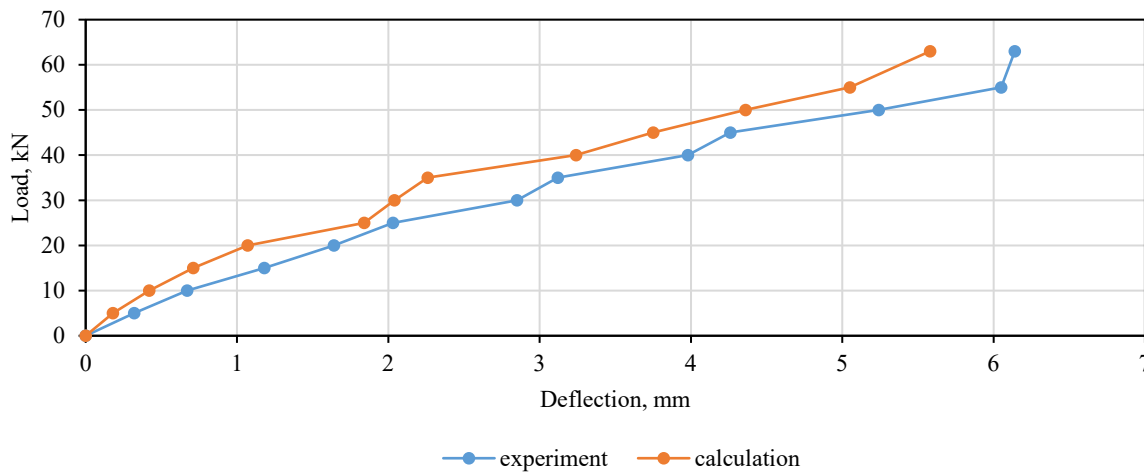


Fig. 19. Deflection of beam HFGP-2

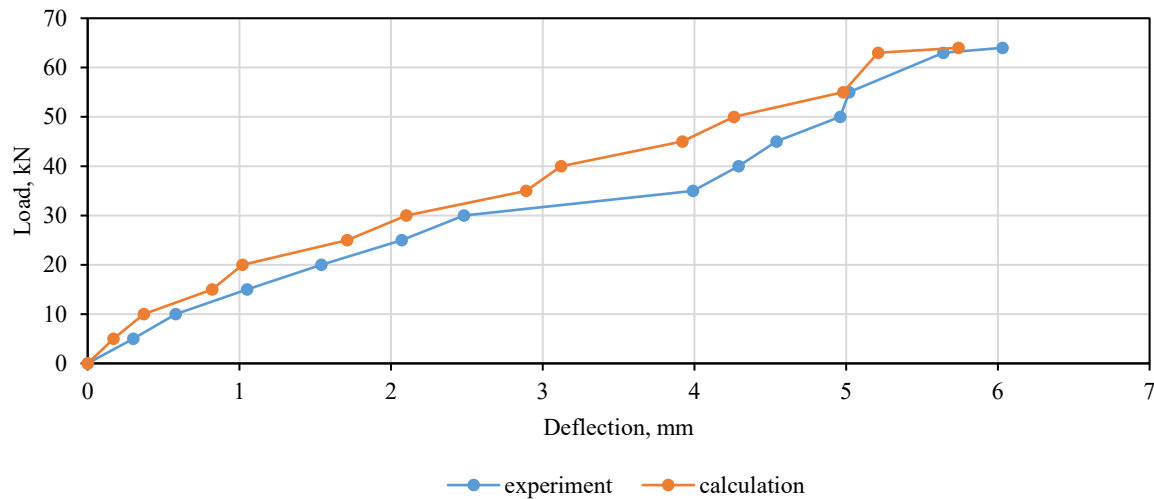


Fig. 20. Deflection of beam HFPG-3

Thus, the finite element modeling of beams made from mono-reinforced and hybrid-reinforced fibergeopolymers has shown good convergence of experimental and theoretical results, which allows for the efficient design of structures from the developed materials and the prediction of their operational characteristics.

Discussion. The most noticeable discrepancy between the results of experiments and calculations (45%) was found for FGP-2 at a load of 20 kN. At 15 kN, the difference was 38%. However, in this and the following cases, it is important to emphasize the low absolute values. At 20 kN, a deflection of 1.45 mm was theoretically assumed, but the experiment showed 2.64 mm. The corresponding data at 15 kN were 1.14 and 1.84. At other loads, the difference was significantly smaller. For FGP-3, the maximum discrepancy was recorded at minimum loads: 40% at 5 kN and 39% at 10 kN. If we are talking about absolute figures, then in the first case, the calculation is 0.42 mm, the experiment is 0.70 mm. In the second case, 0.95 mm and 1.56 mm, respectively. For FGP-1 and FGP-1 (1%), the maximum discrepancy did not exceed 27%, and at low loads. At loads of 5 kN, the theoretically obtained deflection indicator for FGP-1 is 0.35 mm, established empirically — 0.48 mm. The difference is 27%. At a load of 5 kN for FGP-1 (1%), the calculation shows a deflection of 0.47 mm, the experiment — 0.64 mm. The corresponding data for 10 kN are 1.05 and 1.44. The difference in both cases is 27%. For other loads, it is significantly less.

Let us also note the cases of the best convergence of the calculation and experimental data. For FGP-1, this is 8% (load — 35 kN), for FGP-2 — 11% (50 kN), for FGP-3 — 7% (38 kN), for FGP-1 (1%) — 3% (30 kN).

The results of the study of hybrid-reinforced fibergeopolymers allow us to state that the most significant discrepancy between theory and experiments is recorded at minimum loads (in this case, 5 kN). Thus, for HFPG-1, it is 46.2% (calculation shows a deflection of 0.14 mm, experiment — 0.26 mm). The corresponding difference for HFPG-2 is 43.8% (0.18 mm and 0.32 mm), for HFPG-3 — 43.3% (0.17 and 0.30). At other loads, the discrepancies are smaller.

The best agreement between calculations and experimental results for HFPG-1 is 1.85%. This figure is recorded at a load of 72 kN (theory — 5.85 mm, experiment — 5.96 mm). The smallest discrepancy, obtained when modeling the deflection for HFPG-2, is 9.12% (63 kN, 5.58 mm and 6.14 mm, respectively). For HFPG-3 — 0.80% (55 kN, 4.98 mm and 5.02 mm). As noted above, extremely minor discrepancies in absolute figures should be taken into account. Both individual and generalized data are of interest for design and engineering practice. This is confirmed by the visualization of the results of the work — the curves in Figures 12-20 are similar or coincide in numerous cases.

Conclusion. Innovative components for the production of sustainable building materials have been obtained [17]. Ecological compatibility is due to the fact that an alternative to cement is used [18], and this provides a significant reduction in greenhouse gas emissions. The design of hybrid-reinforced fibergeopolymers makes it possible to obtain high strength values — both in compression (from 46 MPa) and in bending (from 10 MPa). When using hybrid fiber, it is possible to reach bending and compression strength at the level of 1:4, and this is several times higher than for unreinforced Portland cement concrete [19]. The modulus of elasticity of more than 25 GPa shows good resistance of the material to deformations, which has a positive effect on the strength and stability of building structures [20]. The finite element analysis of hybrid-reinforced fibergeopolymer beams confirmed the experimental results obtained [21].

The three main research results are described below.

1. Two types of geopolymers were obtained:

- mono-reinforced (fiber from metal cord, polypropylene fiber, and fiber from waste from basalt wool production — TFM);
- hybrid fiber-reinforced (metal cord+polypropylene, metal cord+TFM, polypropylene+TFM).

2. Fiber-reinforced geopolymer concrete mixtures have standard workability characteristics that allow them to be efficiently transported to the place of use and placed in formwork.

3. Finite component modeling of beams made from mono-reinforced and hybrid-reinforced fibergeopolymers show good agreement between experimental and theoretical results, which allows for efficient design of structures made from the developed materials and prediction of their performance characteristics [22].

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About the Authors:

Sergey V. Klyuev, Dr.Sci. (Engineering), Professor, Leading Researcher of the Scientific Research Laboratory of Resource and Energy-Saving Technologies, Equipment and Complexes, V.G. Shukhov Belgorod State Technological University (46, Kostyukov Str., Belgorod, 308012, Russian Federation), [SPIN-code](#), [ORCID](#), [ScopusID](#), [ResearchGate](#), klyuyev@yandex.ru

Alexander V. Klyuev, Cand.Sci. (Engineering), Associate Professor, Senior Researcher of the Scientific Research Laboratory of Resource and Energy-Saving Technologies, Equipment and Complexes, V.G. Shukhov Belgorod State Technological University (46, Kostyukov Str., Belgorod, 308012, Russian Federation), [SPIN-code](#), [ORCID](#), [ScopusID](#), klyuyevav@yandex.ru

Narman A. Ayubov, Cand.Sci. (Economics), Senior Researcher of the Kh.I. Ibragimov Complex Research Institute, Russian Academy of Sciences (21a, Staropromyslovskoe shosse, Grozny, 364906, Russian Federation), [SPIN-code](#), [ORCID](#), yrekly@mail.ru

Roman S. Fediuk, Dr.Sci. (Engineering), Professor of the Military Training Center, Far Eastern Federal University (10, Ajax Bay, Russky Island, Vladivostok, 690922, Russian Federation), [SPIN-code](#), [ORCID](#), [ScopusID](#), [ResearchGate](#), [ResearcherID](#), roman44@yandex.ru

Elena V. Levkina, Cand.Sci. (Economics), Associated Professor, Head of the Department for Work with Dissertation Councils, Far Eastern Federal University (10, Ajax Bay, Russky Island, Vladivostok, 690922, Russian Federation), [SPIN-code](#), [ORCID](#), levkina.ev@dvfu.ru

Claimed Contributorship:

SV Klyuev: conceptualization, writing – original draft preparation.

AV Klyuev: data curation, writing – original draft preparation.

NA Ayubov: formal analysis, writing – original draft preparation.

RS Fediuk: investigation, writing – original draft preparation.

EV Levkina: methodology, writing – original draft preparation.

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All authors have read and approved the final version of manuscript.

Об авторах:

Сергей Васильевич Ключев, доктор технических наук, профессор, ведущий научный сотрудник Научно-исследовательской лаборатории ресурсо-энергосберегающих технологий, оборудования и комплексов Белгородского государственного технологического университета им. В.Г. Шухова (308012, Российская Федерация, г. Белгород, ул. Костюкова, 46), [SPIN-код](#), [ORCID](#), [ScopusID](#), [ResearchGate](#), klyuyev@yandex.ru

Александр Васильевич Ключев, кандидат технических наук, доцент, старший научный сотрудник Научно-исследовательской лаборатории ресурсо-энергосберегающих технологий, оборудования и комплексов Белгородского государственного технологического университета им. В.Г. Шухова (308012, Российская Федерация, г. Белгород, ул. Костюкова, 46), [SPIN-код](#), [ORCID](#), [ScopusID](#), klyuyevav@yandex.ru

Нарман Аюбович Аюбов, кандидат экономических наук, старший научный сотрудник Комплексного научно-исследовательского института им. Х.И. Ибрагимова Российской академии наук (364906, Российская Федерация, г. Грозный, Старопромысловское шоссе, 21 а), [SPIN-код](#), [ORCID](#), yrekly@mail.ru

Роман Сергеевич Федюк, доктор технических наук, профессор военного учебного центра при Дальневосточном федеральном университете (690922, Российская Федерация, г. Владивосток, о. Русский, п. Аякс, 10), [SPIN-код](#), [ORCID](#), [ResearchGate](#), [ScopusID](#), [ResearcherID](#), roman44@yandex.ru

Елена Владимировна Левкина, кандидат экономических наук, доцент, начальник отдела по работе с диссертационными советами Дальневосточного федерального университета (690922, Российская Федерация, г. Владивосток, о. Русский, п. Аякс, 10), [SPIN-код](#), [ORCID](#), [ScopusID](#), levkina.ev@dvfu.ru

Заявленный вклад авторов:

С.В. Ключев: разработка концепции, написание черновика рукописи.

А.В. Ключев: курирование данных, написание черновика рукописи.

Н.А. Аюбов: формальный анализ, написание черновика рукописи.

Р.С. Федюк: проведение исследования, написание черновика рукописи.

Е.В. Левкина: разработка методологии, написание черновика рукописи.

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