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Fine-grained concrete with recycled polyvinyl chloride fiber

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ABSTRACT

Introduction. Polymer fiber is widely used in the production of structural concrete components, in shotcrete for tunnels, concrete slabs, blast-resistant concrete, and solid road pavements. Recently, numerous studies have been devoted to the use of fibers derived from recycled polymers in fiber-reinforced concrete. Most of these studies address the effect of fiber on the compressive, flexural and tensile strength properties of concrete. Fibers of various lengths based on nylon, aramid, polyester, polyethylene terephthalate, polypropylene, polyvinyl alcohol, and polyvinyl chloride are used in concrete. However, the insufficient amount of data, or its complete absence, regarding the effect on the properties of concrete with polymer fibers based on recycled PVC necessitates further research, which is particularly relevant given the generation of significant volumes of PVC waste during the production of plastic windows. **Materials and methods.** The electron microscopy and thermomechanical analyses (TMA) were used to investigate the properties of PVC-based polymer fibers. The effect of the polymer fiber on properties of fine-grained concrete mixtures and hardened concrete, the standard testing methods were used, including the determination of workability by flow table test diameter on a vibrating plate, the average density of concrete mixtures and concrete, and tensile strength under flexural and compressive loading. **Results.** It is shown the positive effect of the grinding process determined by electron microscopy, which produces a rough surface and fibers of 2.5–4 cm in length, 1.75–4 mm in width, and 0.2–0.3 mm in thickness. It is established that the PVC-based fiber belongs to amorphous polymers of linear structure with a crystallization temperature of 86.4 °C and a destruction temperature of 208.91 °C. It is determined that the optimal fiber content in concrete does not impair the workability of concrete mixtures or affect their cohesion. It is shown that the addition of PVC-based fiber to fine-grained concrete in amount up to 1.2% increases the concrete density of 1.6 times, increases flexural tensile strength by 22%, and has no effect on compressive strength. **Conclusion.** Conducted studies confirm the feasibility of using polyvinyl chloride-based fiber as a component of fine-grained concretes. However, there is the lack of sufficient data of fiber introduction method in concrete which requires additional scientific research to prevent fiber clumping, establish its compatibility with chemical additives added to the concrete mixture and the effect of curing conditions.

KEYWORDS: Portland cement, fiber-reinforced concrete, fiber, recycled polyvinyl chloride, workability, strength

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Мелкозернистые бетоны с фиброй из переработанного поливинилхлорида

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АННОТАЦИЯ

Введение. Широкое применение полимерная фибра получила при производстве конструкционных бетонных элементов, в торкрет-бетонировании туннелей, бетонных перекрытиях, взрывостойком бетоне и жестких дорожных покрытиях. Вопросам применения в дисперсно-армированных бетонах фибры на основе вторичной переработки полимеров в последнее время посвящено множество исследований. Большинство из них затрагивает влияние фибры на прочностные свойства бетона на сжатие, при изгибе и на растяжение. Применяются различные по длине волокна в бетонах на основе нейлона, арамида, полиэстера, полиэтилентерефталата, полипропилена, поливинилового спирта и поливинилхлорида. Однако недостаточное количество данных либо их полное отсутствие о влиянии на свойства бетона с полимерной фиброй на основе переработанного ПВХ вызывает необходимость дополнительных исследований, что особенно актуально ввиду образования значительных объемов отходов ПВХ при производстве пластиковых окон. **Материалы и методы.** В работе применены методы электронной микроскопии и термомеханического анализа для исследования свойств полимерной фибры на основе ПВХ. Для исследования влияния полимерной фибры на свойства мелкозернистых бетонных смесей и затвердевшего бетона применялись стандартные методы исследования, включающие определение диаметра расплыва на встряхивающем столике, среднюю плотность бетонных смесей и бетонов, прочность на растяжение при изгибе и при сжатии. **Результаты исследования.** Методом электронной микроскопии установлено положительное влияние процесса измельчения, позволяющего получить шероховатую поверхность и фибру с длиной 2,5–4 см, шириной 1,75–4 мм и толщиной 0,2–0,3 мм. Установлена принадлежность фибры на основе ПВХ к аморфным полимерам линейного строения с температурой стеклования 86,4 °С и температурой деструкции 208,91 °С. Установлено оптимальное содержание фибры, которое не ухудшает подвижность бетонных смесей и не нарушает их связность и удобообрабатываемость. Показано, что введение фибры на основе ПВХ в состав мелкозернистого бетона в количестве до 1,2% обеспечивает рост плотности бетона в 1,6 раз, повышение прочности при растяжении с изгибом на 22% и не оказывает влияния на прочность при сжатии. **Заключение.** Проведенные исследования подтвердили возможность применения фибры на основе поливинилхлорида в составе мелкозернистых бетонов. Однако недостаточное количество данных о порядке введения для предотвращения ее комкования, совместимости с химическими добавками, вводимыми в бетонную смесь, а также влиянии условий твердения и дальнейшей области применения бетонов, в состав которых она входит, вызывает необходимость дальнейшего научного поиска.

КЛЮЧЕВЫЕ СЛОВА: портландцемент, дисперсно-армированный бетон, фибра, рециклинг поливинилхлорида, подвижность, прочность

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INTRODUCTION

Enhancing concrete efficiency involves not only improving its mechanical and operational characteristics but also producing innovative composite materials, such as fiber-reinforced concretes [1]. The development of fiber-reinforced concrete compositions with enhanced strength, crack resistance, frost resistance, water permeability, as well as abrasion and impact resistance, represents the most promising direction in the field of building materials science. Fibers of various origins exert a positive influence on concrete properties. Polymeric, glass, carbon, hybrid, and vegetable fibers of different shapes and sizes can be utilized as reinforcement. Currently, the use of steel fibers has become the most widespread, both domestically and internationally.

Polymeric fibers have gained widespread application in the production of structural concrete elements, shotcrete for tunnels, concrete slabs, explosion-resistant concrete, and solid pavements [2]. In recent years, preference has been given to the use of secondary fibrous materials derived from industrial waste as reinforcing fibers. However, over 90% of polymers are still manufactured from virgin materials, with only a small fraction undergoing recycling [3, 4]. It is noted [5, 6] that only 32% of plastic waste is recycled, the rest is either incinerated (43%) or disposed in landfills (25%), causing significant environmental harm.

Plastic production has currently reached a massive scale, leading to a simultaneous surge in the volume of plastic-based waste. From 1950 to 2017, the total volume of plastic waste reached 8.3 billion tons. In 2021, annual production hit approximately 400 million tons, with only 9% being fully recycled and successfully reused. According to [5], global plastic production reached 413.8 million tons in 2023, of which only 8.9% was sent for recycling, and a mere 0.5% was actually utilized in the manufacturing of new products.

The service life of plastic products averages about 10 years, whereas their decomposition spans many decades, depending on composition and disposal methods [6].

In recent years, there has been a surge of interest in studying the impact of recycled polymeric fibers on the static and dynamic mechanical properties of concrete [7], fatigue characteristics [8, 9], and durability-related parameters. It has been found that incorporating recycled polymer fibers can reduce early-age concrete shrinkage, thereby enhancing mechanical properties and longevity [10]. Alongside polypropylene fibers, recycled polymer fibers effectively prevent crack propagation and increase freeze-thaw resistance [10]. Fiber-reinforced concrete (FRC) is widely utilized for airport pavements, highways, bridge decks, tunnel linings, and offshore platforms [11] — structures subjected to repetitive cyclic loading throughout their service life. Furthermore, polymeric fibers are effectively used in Ultra-High Performance Concrete (UHPC) for repairing and strengthening bridge columns exposed to chloride-rich waters. The addition of fibers significantly minimizes crack formation and limits crack width resulting from shrinkage during hardening and subsequent curing, which also enhances the impact strength of the concrete.

Extensive experience exists in utilizing fibers derived from waste Polyethylene Terephthalate (PET) bottles, as well as polyethylene-based fibers and aggregates sourced from recycled low and high-density plastic bags. Furthermore, recycled Polyvinyl Chloride (PVC) has been employed as aggregates from pipe waste and as both aggregates and fibers from electrical cable insulation. Fiber obtained from recycled electrical cables is also used in concrete. Fibers of various lengths based on nylon [12], aramid [13], polyester [14], polyethylene terephthalate [15], polypropylene [16], polyvinyl alcohol [17], and polyvinyl chloride [18] are used.

There is established practice in using recycled PVC fibers in fiber-reinforced concrete with lengths ranging from 30 to 50 mm and diameters up to 4 mm. Research on the influence of recycled PVC fiber on the technological and mechanical properties of concrete mixtures revealed that incorporating 1% by mass of cement reduces the mixture's workability (slump) by 6.67% [21]. An increase in compressive, flexural, and tensile strengths was observed when fibers were added at dosages of 0.6%, 0.8%, and 1.0%. Specifically, it was established that an 0.8% fiber content leads to a 30.8% increase in compressive strength and a 9.11% increase in flexural strength. However, it was found that increasing the fiber content beyond 0.8% results in a decrease in concrete strength.

According to [22], the incorporation of recycled PVC fibers with a length of 40 mm and a thickness of 0.5 mm and a dosage of 0.5% by volume of the concrete contributes to increase in flexural tensile strength of 14.28%.

The recycling of PVC window profiles is a complex technological process. Thermal processing of PVC is accompanied by the release of hydrogen chloride (HCl), which necessitates strict safety protocols for personnel and specific conditions to ensure high-quality PVC regranulate. The profile recycling sequence includes pretreatment, mechanical shredding, sorting and fractionation, washing, and extrusion with melt filtration. There is only a limited number of studies have been conducted on the influence of recycled fibers derived from various polymers on concrete properties.

Numerous studies have recently focused on the application of recycled polymer fibers in fiber-reinforced concrete, mostly addressing their influence on compressive, flexural, and tensile strengths. However, there is no specific data of influence of recycled PVC-based fibers on concrete properties. This creates an urgent need for additional research, as a significant amount of PVC waste is generated during the production of plastic window profiles.

2. MATERIALS AND METHODS

In this work the following materials were used:

– Heidelberg Cement Rus manufactured Portland cement CEM I 52.5N in accordance with GOST 31108-2020, "General-purpose construction cements," and used it as the binder. Its water demand was 30.2%, with an initial settingtime of 150 min, a final setting time of 175 min, a specific surface area of 377.3 m^2/kg, and a strength of 76 MPa at 28 days. The mineralogical and chemical composition of Heidelberg Cement Rus Portland cement CEM I 52.5N is presented in Table 1 and 2;
– quartz sand, Class I, with a Fineness modulus of 2.75, manufactured by "Bolars" with a true density of 2.65 g/cm^3. Particle size distribution is shown in Fig. 1;

Table 1. Mineralogical composition of Portland cement CEM I 52.5N "HeidelbergCement Rus"

Component content, %			
C_3S	C_2S	C_3A	C_4AF
64	14	7	11

Table 2. Chemical composition of Portland cement CEM I 52.5N "HeidelbergCement Rus"

Component content, %											
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	MnO	TiO_2	P_2O_5	LOI
21.23	4.78	3.31	62.95	1.65	3.22	0.66	0.12	0.08	0.28	0.06	1.60

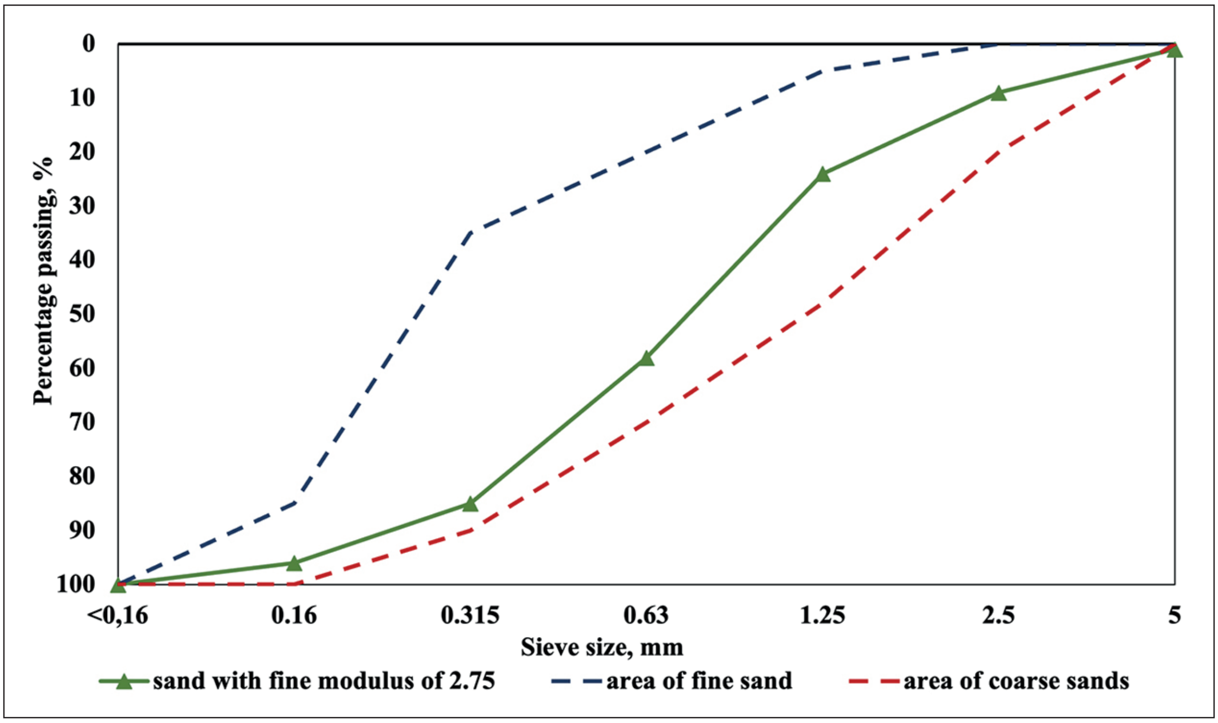

Fig. 1. Particle size distribution of fine aggregate

– recycled polyvinyl chloride (PVC) fiber was obtained by shredding of the window profile in a shredder machine, and it is shown in Fig. 2.

3. RESULTS AND DISCUSSION

The technological scheme is presented in Fig. 3. The production of polymer fibers based on recycled waste from polyvinyl chloride (PVC) window profiles was carried out by shredding in a chipping machine and included the separation of the glass unit and rubber seals from the window profile (Fig. 4). In the case of recycling waste from the cutting and trimming of window frames, it is necessary to remove the protective film from the surface. Single-stage shredding of the profile in a chipping machine allows for obtaining polymer fibers with a rough surface, ranging from 2.5 to 4 cm in length, 1.75 to 4 mm in width, and 0.2 to 0.3 mm in thickness (Fig. 5).

The phase and relaxation states of PVC-based fiber properties, and deformations under mechanical and thermal loads, was conducted by using the equipment (Fig. 6). A TMA Q400 thermomechanical analyzer manufactured by TA Instruments was used to determine the glass transition and degradation temperatures, as well as to determine the linear thermal expansion coefficient (LTEC). The polymer fiber test specimen is presented in Fig. 7.

Thermomechanical properties of polymers generally characterize their mechanical behavior under varying temperatures [23]. Thermomechanical Analysis (TMA) is employed to identify the polymer's nature, crystallization,

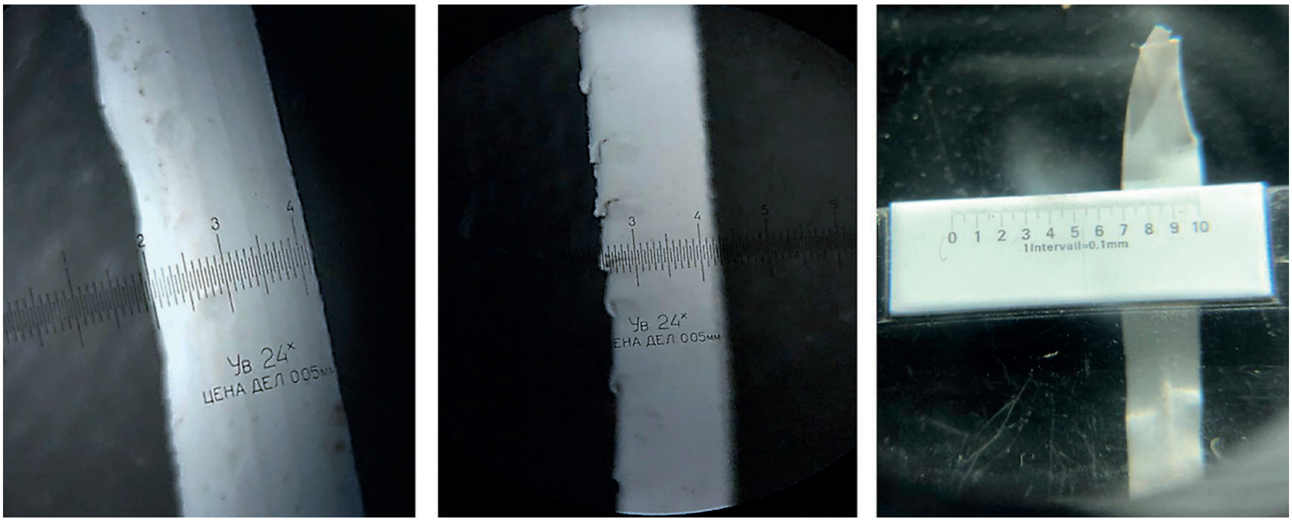

Fig. 2. Recycled polyvinyl chloride (PVC) fiber

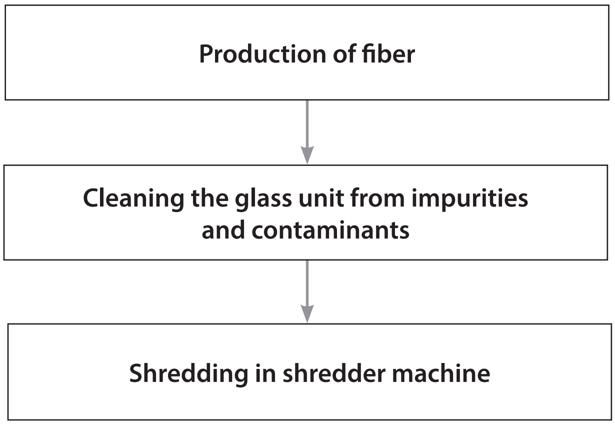

Fig. 3. Production of PVC fiber from window profile

Fig. 4. Fibre production in a shredder machine

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Fig. 5. Equipment for measuring the geometric dimensions of fiber

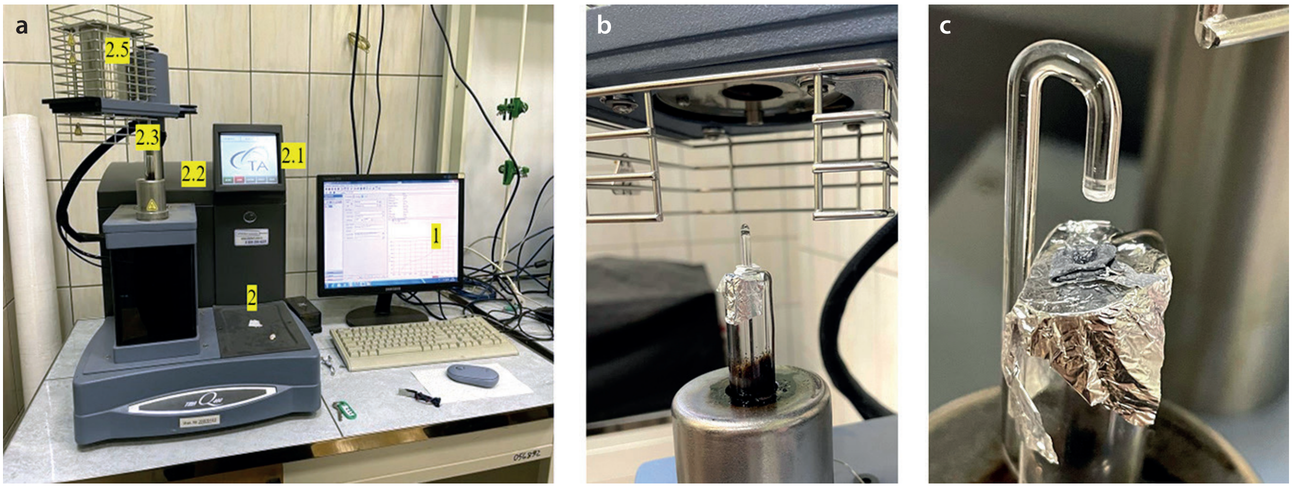

Fig. 6. Study of the thermomechanical properties of PVC-based fiber: a) 1 – Computer; 2 – TMA device: 2.1 – Display; 2.2 – Stage (Sample platform); 2.3 – Probe; 2.4 – Thermocouple; 2.5 – Furnace; b) Fiber specimen before testing; c) Specimen after testing

glass transition, and melting temperatures, as well as to evaluate its thermal operating ranges. Experimental results indicate that the obtained data are significantly influenced by testing conditions, the prior processing of the PVC profiles, and the applied mechanical and thermal loading regimes. For the thermomechanical curve plotting, a load of 1 N was applied to the specimen with a heating rate of 5 °C/min. The TMA data analysis (Fig. 7) confirmed that the PVC-based fiber is an amorphous polymer with a linear structure. The analysis of frea 1, during heating from 0 to 86.4°C, corresponds to the glass transition temperature (T_g), indicating the polymer's glassy state and its linear amorphous nature. The area 2 corresponds to the high-elastic (rubbery) state, while the area 3 represents the viscous-flow state, leading to a degradation temperature (T_d) of 208.91 °C. The heating rate of 5 °C/min and a minimal load of 0.01 N to determine the linear thermal expansion coefficient were used. The thermomechanical curve also allowed to determine the values of linear thermal expansion coefficient at the range of 21.49 up to 80.96 °C with a step of 10 °C.

Various surface modification methods are applied, including polymer coating, chemical etching, and mechanical treatment to improve the bond strength between the cement matrix and the fiber. The microstructure of the PVC fiber surface was investigated using a Quanta 650 FEG field emission scanning electron microscope (FE-SEM). Electron microscopy revealed that after shredding in shredder machine, the fiber surface undergoes changes and becomes rough (Fig. 8).

The influence of PVC-based fiber on the properties of fine-grained concrete was investigated with content of the fiber from 0 up to 3% by mass of concrete mixture. The compositions of the mixture are presented in Table 3. The fine-grained concrete mixtures were prepared in accordance with Кгыышфт ыефтвфкв GOST 30744. The

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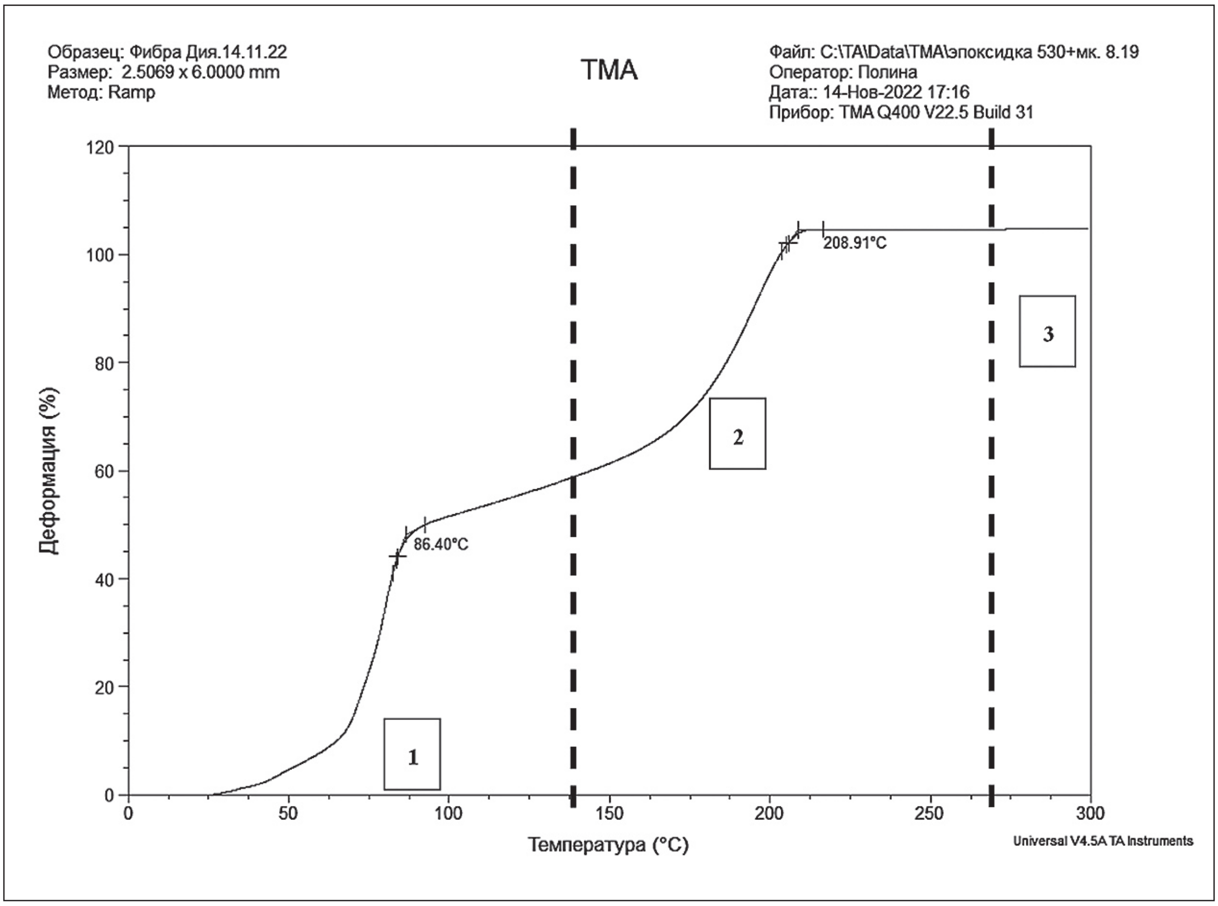

Fig. 7. Study of the thermomechanical properties of PVC-based fiber

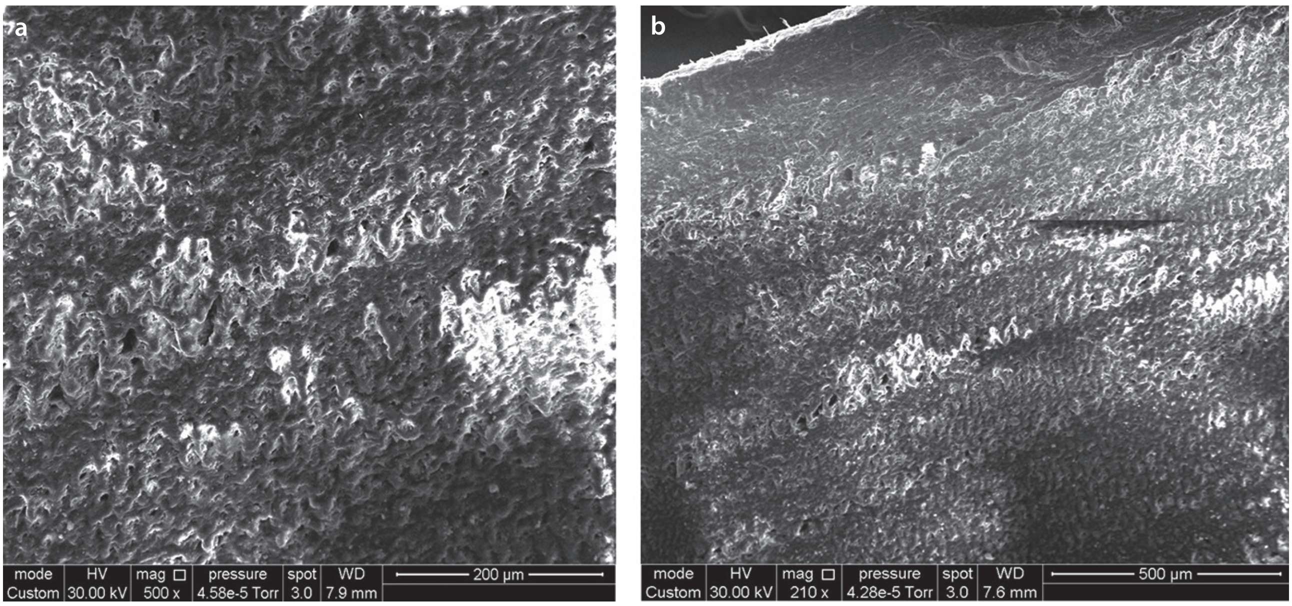

Fig. 8. Surface of recycled polyvinyl chloride fiber after shredding: a) x500 magnification; b) x210 magnification

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Table 3. Mix designs of fine-grained concrete with various contents of PVC-based fiber

Components, g	Fiber content, %					
	0	0.3	0.4	0.6	1.2	1.8
Portland cement	655	655	655	655	655	655
Sand	1310	1310	1310	1310	1310	1310
Fiber	0	5.65	11.0	13.8	27.6	41.4
Water	295	295	295	295	295	295

gradual mixing of dry components was followed with addition of mixing water. The addition of the PVC fiber was carried out at the final stage with mixing time of 3 min.

The effect of PVC-based polymer fiber on the flow diameter of fine-grained concrete, measured with by the use of flow table, demonstrated the decrease of workability of the mixture. The minimum reduction in workability was observed with fiber contents at the range of 0.3 up to 0.6%. The average density of the mixture maintained between 2262 and 2265 kg/m³ (Fig. 9). The significant decrease in workability and average density of the concrete mixture was established with increase of the fiber content up to 1.2%. This can be explained of the high water demand to the fiber and its highly developed surface area. A further increase in fiber content up to 1.8% reduced the average density decreased to 2247 kg/m³, the flow diameter from 245 mm to 143 mm (Fig. 9), resulting in loss of cohesion and workability. These findings are consistent with the results reported by other authors [24, 25, 26].

The influence of PVC fiber on the mechanical properties of fine-grained concrete was investigated at 28 days of standard curing in accordance with Russian standard GOST 310.4. It was found that the strength remains at the range of 8.7 MPa with fiber content of 0.4–1.2%. This behavior can be attributed to the strength provided by cement binder and the positive effect of the fiber on the structure formation process. The fiber may act as nucleation center in cement paste, organizing and densifying its microstructure [27, 28]. The formation of such a structure, consisting of randomly distributed fibers, occurs along the entire fiber surface, enhancing the interfacial transition zone between cement paste and aggregate and forming a micro frame [26]. However, the increase of the fiber content up to 1.8% leads to a decrease in average

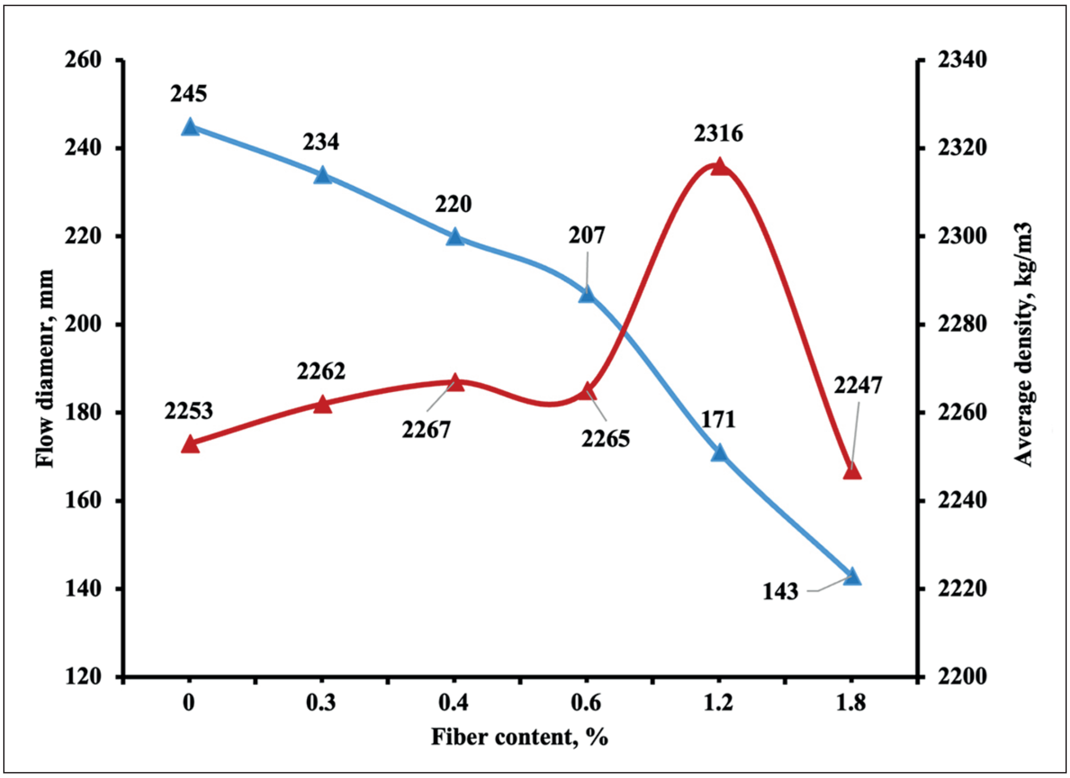

Fig. 9. Effect of PVC-based fiber on the flow table diameter of fine-grained concrete

density (Fig. 10) and the strength at the range of 8.3 MPa (Fig. 11). This reduction is explained by the weakening of the cement matrix and the fact that the low-modulus fiber occupies a portion of the cross-sectional area within the cement stone, thereby weakening it due to a deficiency in the matrix component and composite stratification [26].

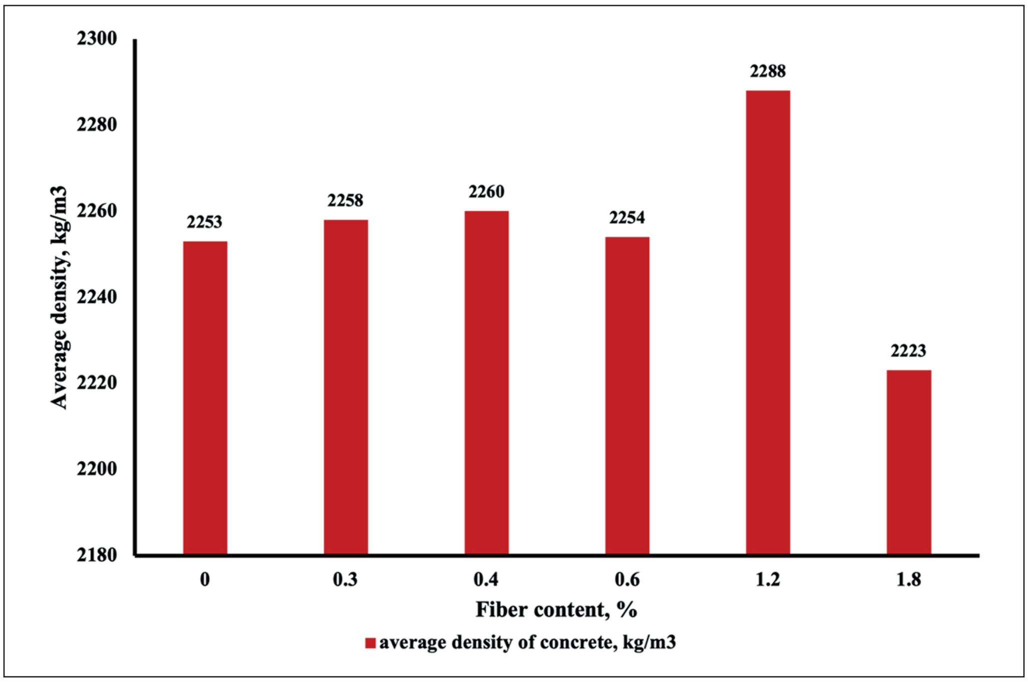

Fig. 10. Effect of polymer fiber on average density of the concrete

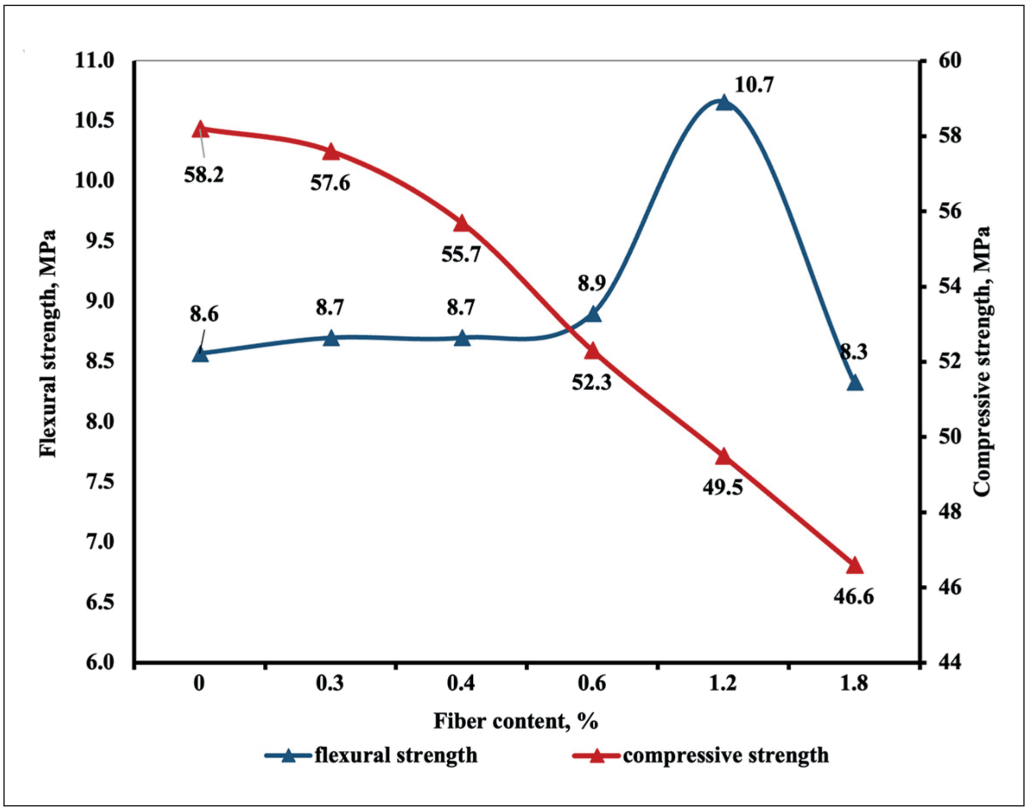

Fig. 11. Effect of PVC fiber on the compressive and flexural strengths at the age of 28 days

CONCLUSIONS

Based on the obtained results, the following conclusions can be drawn:

1.It was established that recycled PVC-based fiber can be used in fiber-reinforced concrete to enhance mechanical properties, which contributes the expandance the raw material base. This approach promotes the conservation of raw material resources, reduces negative environmental impacts, and decreases the volume of PVC-based waste.

2. It was shown that the fiber obtained from the mechanical shredding of PVC window profiles possesses a rough surface, has a length of 2.5–4 cm, a width of 1.75–4 mm, and a thickness of 0.2–0.3 mm.

3. It was established that the PVC-based fiber is an amorphous polymer with a linear structure, characterized by a glass transition temperature of 86.4 °C and a degradation temperature of 208.91 °C. These properties ensure the load-bearing capacity of the fiber within the fiber-reinforced concrete under elevated temperature operating conditions.

4. It was established the remain of workability of the fine-grained concrete with fiber content of 0.3–0.6%. However, increase of the fiber content up to 1.8% by mass of fine-grained concrete leads to 1.7 times decrease in workability, a slight decrease in the average density of the mixture, and a loss of cohesion.

5. It was established the decrease in compressive strength, that can be explained by low-modulus of PVC-based fiber. The compressive strength decreases in 1.2 times if the content is 1.8% by mass of the concrete.

6. It was determined that the optimal content of PVC-based fiber in fine-grained concrete is 1.2% which results the increase of concrete density in 1.6 times and of 22% enhancement in flexural strength.

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ADDITIONAL INFORMATION

The authors declare that generative artificial intelligence technologies and technologies based on artificial intelligence were not used in the preparation of the article.

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