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RESEARCH ARTICLE

IMPROVING EFFICIENCY IN 3D PRINTING THROUGH MODIFICATION OF FINE-GRAINED CONCRETE COMPOSITION

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Abstract. *Additive manufacturing, also known as three-dimensional printing (3D printing), has many advantages over traditional construction technologies, including high construction efficiency, less construction waste, and significantly reduced labor costs. Nowadays, additive technologies are becoming increasingly popular in various fields, including the construction industry. One of the most effective ways to regulate and ensure the required technological and construction properties of concrete mixtures in concrete technology, including 3D printing, is by using various modifying additives. The introduction of active mineral additives into concrete mixes allows for reduced cement consumption, increased cement stone density, improved water resistance, and decreased permeability. This article presents the results of a study on the effect of mineral additives on the properties of cement paste, shape stability, and physicomechanical characteristics of fine-grained concrete in additive manufacturing technology, aiming to select the most effective mineral components for the production of cement materials for 3D printing. The optimization of the structure to form a dense and hermetic high-quality concrete structure based on cement binders can be achieved by introducing finely dispersed mineral additives of various compositions. The study examines the effect of mineral additives on the normal density and setting time of Portland cement, the kinetics of plastic strength gain in cement systems over time depending on the type and concentration of additives and the type of Portland cement, the ultimate shear stress of the concrete mixture, the formability of the mixture, the dimensional stability of the layers, and the physicomechanical characteristics of the hardened composites.*

Keywords: *3D printing, Portland cement, fine-grained concrete, mineral additives, modifying additives.*

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ҒЫЛЫМИ МАҚАЛА

ҰСАҚ ТҮЙІРШІКТІ БЕТОННЫҢ ҚҰРАМЫН ӨЗГЕРТУ АРҚЫЛЫ 3D БАСЫП ШЫҒАРУДАҒЫ ТИІМДІЛІКТІ АРТТЫРУ

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Аңдатпа. *Үш өлшемді басып шығару (3D басып шығару) аддитивті өндіріс дәстүрлі құрылыс технологияларына қарағанда көптеген артықшылықтарға ие, яғни құрылыс тиімділігі жоғары, құрылыс қалдықтары аз және еңбек шығындары айтарлықтай төмен болады. Қазіргі уақытта аддитивті технологиялар әр түрлі салаларда, соның ішінде құрылыс индустриясында танымал бола бастады. Бетон технологиясында, соның ішінде 3D басып шығаруда бетон қоспаларының қажетті технологиялық және құрылыс-техникалық қасиеттерін реттеу мен қамтамасыз етудің тиімді әдістерінің бірі әртүрлі модификациялық қоспаларды қолдану болып табылады. Бетон қоспаларына белсенді минералды қоспаларды енгізу цемент шығынын үнемдеуге, цемент тасының тығыздығын, суға төзімділігін арттыруға және өткізгіштігін төмендетуге мүмкіндік береді. Бұл мақалада 3D басып шығару технологиясында цемент материалдарын өндіруге арналған ең тиімді минералды компоненттерді таңдау мақсатында минералды қоспалардың цемент қоспасының қасиеттеріне, пішінге төзімділігіне және аддитивті өндіріс технологиясындағы ұсақ түйіршікті бетонның физикалық-механикалық сипаттамаларына әсерін зерттеу нәтижелері келтірілген. Цемент байланыстырғыштарында жоғары сапалы бетонның тығыз және герметикалық құрылымын қалыптастыру үшін құрылымды оңтайландыру әр түрлі құрамдағы ұсақ дисперсті минералды қоспаларды енгізу арқылы жүзеге асырылуы мүмкін. Сондай-ақ, минералды қоспалардың портландцементтің қалыпты тығыздығы мен қатаю уақытына әсері, қоспалардың түрі мен концентрациясына және портландцемент түріне байланысты уақыт бойынша цемент жүйелерінің пластикалық беріктігі жиынтығының кинетикасы, бетон қоспасының шекті ығысу кернеуі, қоспаның қалыптылығы, қабаттардың пішінге төзімділігі, қатайтылған композиттердің физика-механикалық сипаттамалары зерттелді.*

Түйін сөздер: *3D басып шығару, портландцемент, ұсақ түйіршікті бетон, минералды қоспалар, модификациялық қоспалар.*

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НАУЧНАЯ СТАТЬЯ

ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ В 3D ПЕЧАТИ ПУТЕМ МОДИФИКАЦИИ СОСТАВА МЕЛКОЗЕРНИСТОГО БЕТОНА

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Аннотация. *Аддитивное производство, также известное как трехмерная печать (3D печать), имеет множество преимуществ перед традиционными строительными технологиями, включая высокую эффективность строительства, меньшее количество строительных отходов и значительное сокращение трудозатрат. В настоящее время аддитивные технологии становятся все более популярными в различных областях, в том числе и в строительной отрасли. Одним из эффективных способов регулирования и обеспечения, требуемых технологических и строительно-технических свойств бетонных смесей в технологии бетонов, в том числе при 3D-печати, является применение различных модифицирующих добавок. Введение активных минеральных добавок в состав бетонных смесей позволяет экономить расход цемента, повышать плотность цементного камня, водостойкость, снижать проницаемость. В этой статье представлены результаты исследования влияния минеральных добавок на свойства цементного теста, формоустойчивость и физико-механические характеристики мелкозернистого бетона в технологии аддитивного производства, с целью выбора наиболее эффективного минеральные компоненты для изготовления цементных материалов для 3D-печати. Оптимизация структуры с целью формирования плотной и герметичной структуры высококачественного бетона на цементных вяжущих может быть осуществлена путем введения мелкодисперсных минеральные добавки различного состава. А также исследовано влияние минеральных добавок на нормальную густоту и сроки схватывания портландцемента, кинетику набора пластической прочности цементных систем во времени в зависимости от вида и концентрации добавок и вида портландцемента, предельное напряжение сдвига бетонной смеси, формуемость смеси, формоустойчивость слоев, физико-механические характеристики затвердевших композитов.*

Ключевые слова: *3D печати, портландцемент, мелкозернистый бетон, минеральные добавки, модификационные добавки.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің гранттық қаржыландыру шеңберінде жүргізілді (грант № «BR21882278 Аккредиттелген мамандардың толық циклін қамтамасыз ету үшін құрылыс-техникалық инженерлік орталық құру» Қазақстан Республикасының құрылыс, жол құрылысы саласындағы қызметтері»).

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан (грант № BR21882278 «Создание строительного инженерно-технического центра для обеспечения полного цикла аккредитованных специалистов» в сфере строительства и дорожного строительства Республики Казахстан).

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

3D printing technology is currently one of the most advanced technologies that help increase the efficiency of construction and save all types of resources.

3D printing is an additive construction technology that allows for the creation of a complete building structure of any complexity using a digital model and a 3D printer that uses various materials in a short time (**Lesovik, 2021**).

The main problem with the widespread adoption of such technologies is the lack of integrated solutions for designing printable walls that meet structural and thermal requirements, as well as the lack of available materials that enable the production of mixtures for building printing that are optimized for the features of a 3D printer. At the same time, an important condition for the economic attractiveness of 3D technologies is the minimization of initial costs, as well as the availability of the raw material base, which is currently a key driver of innovation.

To date, mixtures based on Portland cement have received significant scientific study and practical application in the field of building printing. There are well-known studies aimed at finding ways to increase their effectiveness through the use of chemical and mineral additive complexes (**Lin et al., 2017**), modification of the cement binder base (**Slavcheva et al., 2021**), and the use of special technological techniques for their production (**Reiter et al., 2018**). At the same time, cement types themselves are characterized by high energy consumption during production, and concrete based on them often has suboptimal rheological properties for building printing and a tendency toward increased early strength.

Despite the attractiveness of the new technological solution for the construction of building structures and judging by existing international experience in implementing this process, there are many problems that must be addressed before the potential of 3D printing in construction can be fully realized. Fine-grained concrete based on cement binders, being the most common and affordable construction material, forms the basis for the adoption of 3D printing technology in construction (**Duballet et al., 2019**), both in Kazakhstan and in other countries.

A wealth of theoretical and practical experience, as well as expert knowledge, has been accumulated worldwide in the field of fine-grained concrete. This knowledge can be used to formulate requirements for cement-based 3D printing materials and to optimize and standardize their formulations to improve quality. One of the key characteristics of high-quality and high-strength concretes, unlike traditional ones, is the presence of a highly dispersed mineral additive in the composition. This additive modifies the structure of the mixture, regulating its mobility and affecting the density and strength of the composite (**Verian et al., 2020**).

This can be achieved using mineral additives of natural or artificial origin. The use of these additives, also known as supplementary binders, not only reduces environmental damage but also lowers the cost of concrete and improves some of its properties (**Chernysheva, 2019**).

This article presents the results of experimental studies on modifying the basic composition of fine-grained concrete used in 3D printing to enhance the efficiency of additive manufacturing in construction by improving its formability, shape stability, and physical-mechanical properties.

2 LITERATURE REVIEW

One of the most effective ways to regulate and ensure the required technological and construction properties of concrete mixtures in concrete technology, including 3D printing, is the use of various modifying additives. The introduction of active mineral additives into concrete mixes allows for reduced cement consumption, increased density of cement stone, improved water resistance, and decreased permeability.

An analysis of classifications of mineral additives in cements, concretes, and mortars according to regulatory sources indicates the absence of their differentiation based on their influence on the rheological properties of mixtures. This is an important factor for the effective use of mineral additives in 3D printing technology.

A review of the literature allows us to consider composition and rheological properties of molding mixtures based on composite gypsum binder (**Chernysheva, 2021**) which, to a certain extent, takes into account their influence on rheological properties.

Considering the experience of using groups of additives, it should be noted that finely ground lime flour (with a particle size of 2.9 microns) is used as a rheologically active additive when ground together with cement and a 1% plasticizing additive. The authors obtained a concrete mix with a mobility of 12.5 cm, which does not meet the requirements for the use of such mixtures in 3D printing. Additionally, the strength characteristics of concrete slightly decreased in the samples obtained by the authors.

Regarding reactive additives, it is important to highlight the effectiveness of silica in increasing the strength of fine-grained concrete-based products (**Chen, 2020**). Its introduction in an amount of 12% increases compressive strength by 55% and bending strength by 14%, due to the binding of free calcium hydroxide into low-base calcium hydrosilicates, which have high durability. It is also known that clay calcined at a specific temperature and ground to 250-800 m^2/kg can be used as a reactive additive (**Shinkevich, 2019**), allowing for an increase in the average density and softening coefficient of cement stone.

Several studies indicate the effectiveness of using various mineral additives in cement systems for 3D printing technology, including metakaolin (**Chen, 2020**), clay in the form of bentonite (**Mendoza Reales, 2019**), diatomite, microcrystalline silicon (**Han, 2021**), and others. Additionally, kaolin and wollastonite are used to regulate the plastic properties of molded masses (**Zareei, 2019**).

However, when developing concrete mixes for 3D printing, particular attention should be paid to rheological properties, which directly affect geometric changes caused by the spreading of underlying layers. This factor largely determines the quality of the molded product.

Currently, no standardized criterion exists for assessing the effectiveness of 3D printing that accounts for geometric changes in construction products due to the spreading of underlying layers, depending on the presence of modifying additives, particularly mineral additives.

Numerous studies have examined the effects of mineral additives on the structure and properties of composites based on cements of various mineralogical compositions in combination with different chemical additives (**Ibragimov, 2023**). Several authors have proposed classifications of mineral additives based on various criteria, which is highly useful for their application and effectiveness analysis. However, the impact of different types of mineral additives on the formation of structure and properties of 3D-printed concrete, as well as on achieving optimal rheological properties of concrete mixtures and physicomechanical properties of the hardened composite, remains insufficiently studied. This underscores the necessity for further experimental research in this field.

3. MATERIALS AND METHODS

The effects of mineral additives with different mineralogical compositions and hydraulic activities on the normal density, setting time, kinetics of cement dough strength gain, ultimate shear stress of fine-grained concrete mixtures at the boundary of gravitational spreading, and the physicomechanical characteristics of fine-grained concrete printed using a 3D printer were investigated.

Table 1 presents the results of determining the hydraulic activity of mineral additives.

Table 1
Activity of the studied mineral additives [author's materials]

№	Name of mineral additives	Activity, mg/g	Content SiO_2,%	Content Al_2O_3, %
1	**2**	**3**	**4**	**5**
1	Diatomite	1653,8	93,00	4,60
2	Microsilica	1617,3	92,40	0,60
3	Biosilicon	1500,6	88,20	5,10
4	Metakaolin	1343,8	49,36	32,25

According to **Table 1**, diatomite, microsilicon, biosilicon, and metakaolin exhibit the highest hydraulic activity (in descending order).

The results of studies on changes in the normal density and setting time of Portland cement CEM I 42.5N, depending on the amount of additives with various mineral compositions, are presented in **Table 2**.

Table 2

The effect of mineral additives on the normal density and setting time of Portland cement CEM I 42.5N

Name of mineral additives	The content of mineral additives, %	Setting time		Normal density, %
		beginning	end	
1	2	3	4	5
-	-	3 h 30 min	4 h 48 min	32,39
Diatomite	20	3 h 36 min	5 h 09 min	42,08
	30	3 h 43 min	4 h 55 min	48,05
	40	4 h 08 min	5 h 14 min	55,11
	50	4 h 23 min	5 h 58 min	58,33
Microsilica	20	3 h 45 min	4 h 43 min	33,36
	30	4 h 34 min	5 h 45 min	36,73
	40	5 h 00 min	5 h 53 min	39,56
	50	5 h 03 min	5 h 55 min	39,77
Biosilicon	20	2 h 39 min	4 h 12 min	38,19
	30	4 h 07 min	4 h 57 min	42,08
	40	4 h 00 min	5 h 15 min	47,35
	50	3 h 41 min	5 h 11 min	52,66
Metakaolin	20	3 h 06 min	4 h 30 min	37,46
	30	3 h 38 min	5 h 02 min	43,08
	40	3 h 57 min	5 h 22 min	48,24
	50	3 h 43 min	5 h 30 min	51,77
Kaolin	20	4 h 12 min	5 h 15 min	38,93
	30	4 h 22 min	5 h 16 min	42,39
	40	4 h 38 min	6 h 05 min	45,16
	50	4 h 39 min	6 h 06 min	48,65
Wollastonite	20	3 h 34 min	4 h 31 min	35,29
	30	3 h 43 min	4 h 45 min	37,45
	40	4 h 18 min	5 h 21 min	40,53
	50	3 h 50 min	5 h 04 min	42,24

As seen in **Table 2**, all the studied mineral additives lead to an increase in the normal binder density by 3.2–85.4% compared to the additive-free composition. The smallest increase in normal binder density is observed when using a microsilicon additive (3.2–24.9%, depending on its content), while the largest increase is recorded with the addition of diatomite (32.3–85.4% compared to the additive-free composition). The use of silica at a 10% concentration by weight of Portland cement reduces the setting time by 5 minutes compared to the additive-free composition. The introduction of 10% biosilicon reduces the initial and final setting times by 51 minutes and 36 minutes, respectively. Similarly, 10% metakaolin reduces these times by 36 minutes and 18 minutes. Wollastonite, when added at 10–20% by weight of Portland cement, decreases the setting time by 4–17 minutes compared to the additive-free composition.

Conversely, the remaining additives in the studied concentrations lead to an increase in the setting time compared to the additive-free composition: initial setting time increases by 6–67 minutes, final setting time increases by 71–79 minutes.

To assess the effect of mineral additives on the rheological properties of fine-grained concrete mixtures, experimental studies were conducted on the maximum shear stress of concrete mixtures containing the studied mineral additives, based on Portland cement CEM I 42.5N and sand with a grain Finenes modulus FM 2.3 and FM 2.4.

According to the results of trial 3D printing of fine-grained concrete with different mobility levels, it was found that concrete mixtures with mineral additives but without Portland cement of mobility grade Dc 2 exhibited defect formation, such as tears, due to changes in rheological properties affecting extrusion. In this regard, a concrete mix with mobility grade Dc 3 (corresponding to a cone immersion depth of 8.9 cm) was selected for further research. Mineral additives were introduced as a partial replacement for quartz sand. The research results are presented in **Tables 3** and **4.**

Table 3
Effect of Mineral Additives on the Ultimate Shear Stress of Concrete Mixtures with Portland Cement CEM I 42.5N and Sand with a Grain Size Modulus of FM 2.4

Type of mineral additives	The content of mineral additives, %	The density of the concrete mix, kg/m^3	Maximum shear stress, Pa
1	**2**	**3**	**4**
-	-	2227	81
Diatomite	20	2186	57
	30	2115	55
	40	2056	48
	50	1968	51
Microsilica	20	2203	45
	30	2150	43
	40	2074	47
	50	1991	44
Biosilicon	20	2174	71
	30	2133	56
	40	2080	69
	50	2050	61
Wollastonite	20	2197	63
	30	2180	56
	40	2177	70
	50	2174	68

Table 4
The effect of mineral additives on the ultimate shear stress of concrete mixtures in Portland cement CEM I 42.5N and sand with a grain size modulus FM 2.3

Type of mineral additives	The content of mineral additives, %	The density of the concrete mix, kg/m^3	Maximum shear stress, Pa
1	**2**	**3**	**4**
-	-	2191	99
Kaolin	20	2174	78
	30	2127	75
	40	2086	74
	50	2066	73
Metakaolin	20	2133	94
	30	2139	69
	40	2121	67
	50	2101	64

As shown in **Table 3,4** all the studied mineral additives reduce the limiting shear stress by 6.7–49.3% to varying degrees compared with the additive-free composition. This reduction is caused by an increase in the water demand of the modified formulations (**Table 2**) to achieve the required mobility. As a result, the density of the mixture decreases, and its ability to spread increases. However, the obtained data do not fully allow for assessing changes in the viscoplastic properties of fine-grained concrete mixtures due to the limitations of this methodology (which considers only the boundary of gravitational spreading). This approach does not account for the shear stress values of the system while considering the viscosity of the mixture at different shear rates.

Therefore, further studies on the shape stability of the mixture were conducted during layer-by-layer extrusion, as the values of limiting shear stress and shear rate are closer to the actual conditions in 3D printing technology.

At the next stage, the influence of the type and content of mineral additives (MD) on the shape stability of the mixture was studied. The assessment was based on the maximum number of layers of the concrete mixture printed without technological interruption under the following conditions: Portland cement CEM I 42.5N; Sand with a grain size modulus FM 2.3 and FM 2.4; Mobility grade Dc 3 (corresponding to a cone immersion depth of 8.9 cm). The research results are shown in **Figures 1–6**.

During the 3D printing process, it was observed that fine-grained concrete mixes with mineral additives exhibited better formability during layer-by-layer extrusion compared to both: the base unmodified composition; compositions containing plasticizing additives. This improvement was reflected in the uniformity of the extruded mixture and a reduced number of defects during molding.

As seen in **Figures 1–6**, the introduction of the studied mineral additives significantly affects the shape stability of the fine-grained concrete mixture. Despite the decrease in the maximum shear stress at the boundary of gravitational spreading, the maximum number of printed layers without technological interruption increases.

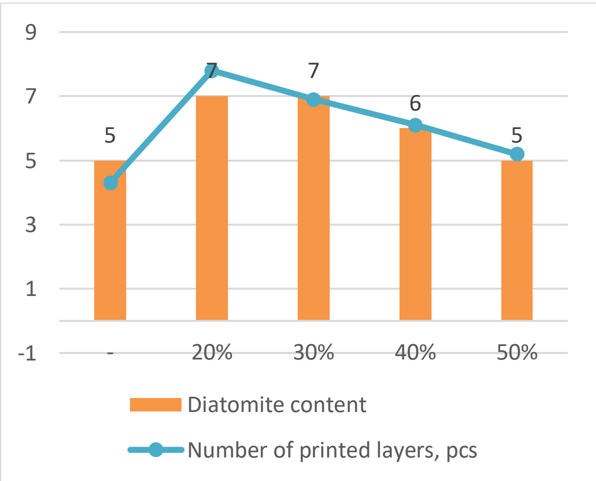

Figure 1 – The effect of the diatomite content on the shape stability of a fine-grained concrete mixture based on cement CEM I 42.5N and sand with FM 2.4

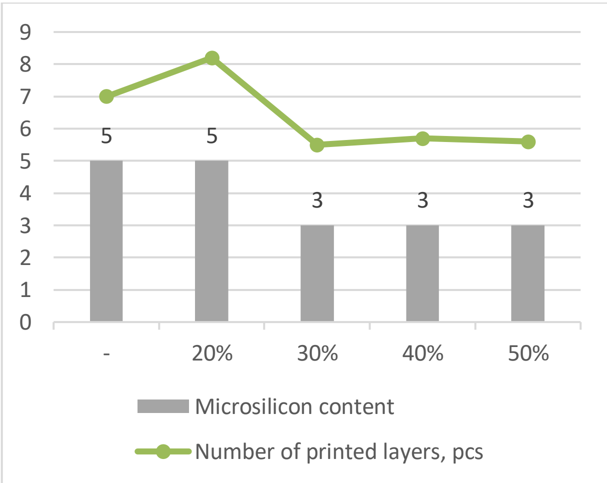

Figure 2 – The effect of the silica content on the shape stability of a fine-grained concrete mixture based on cement CEM I 42.5N and sand with FM 2.4

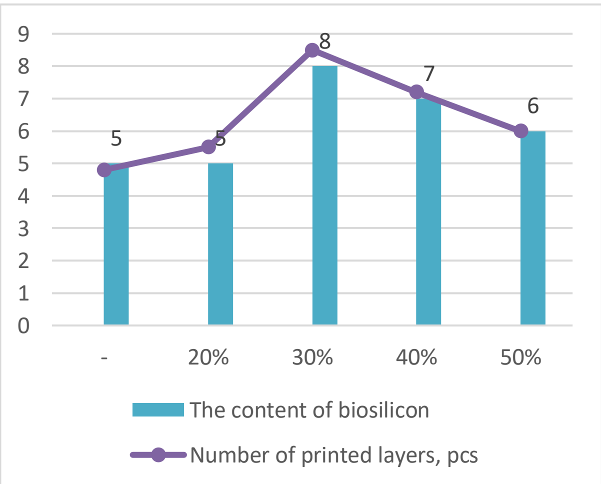

Figure 3 – The effect of the biosilicon content on the shape stability of a fine-grained concrete mixture based on Portland cement CEM I 42.5N and sand with FM 2.4

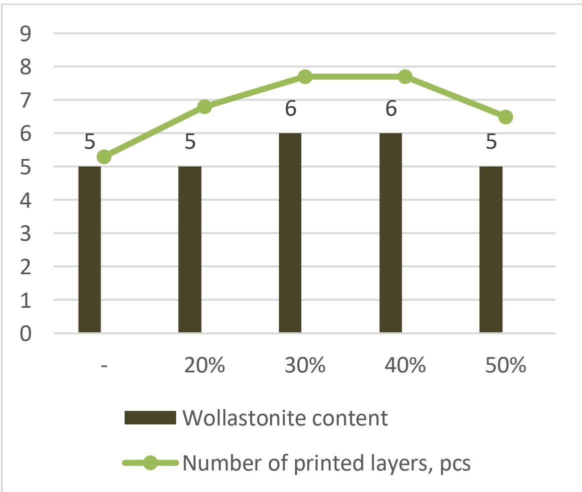

Figure 4– The effect of the wollastonite content on the shape stability of a fine-grained concrete mixture based on cement CEM I 42.5N and sand with FM 2.4

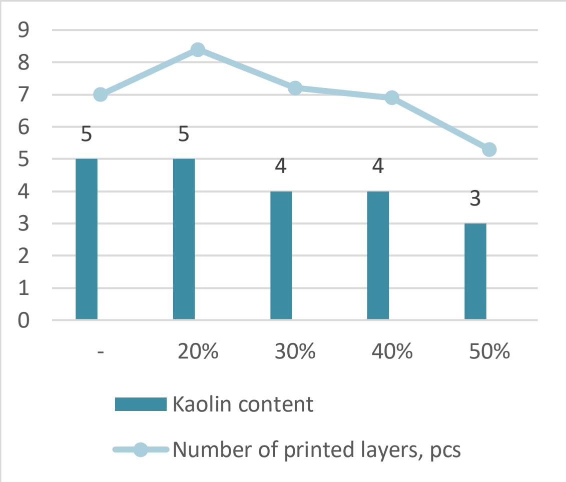

Figure 5 – Effect of kaolin content on the shape stability of fine-grained concrete mix on Portland cement CEM I 42.5N and sands with FM 2.3

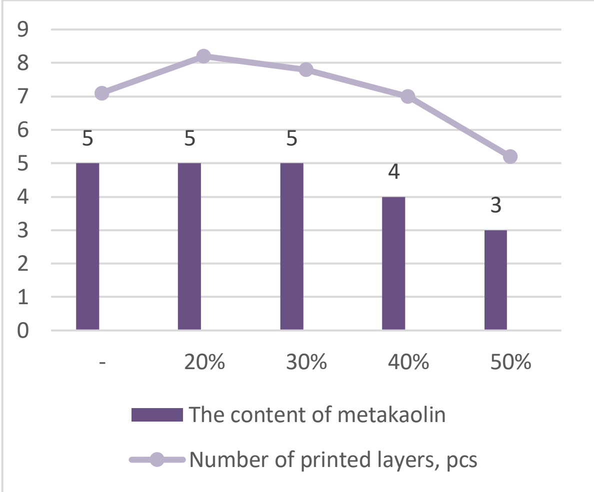

Figure 6 – The effect of the metacaolin content on the shape stability of a fine-grained concrete mixture based on cement CEM I 42.5N and sand with FM 2.3

Figure 7 – Photofixation of the fracture process (loss of shape stability with displacement of the printed layers) of a sample printed on a 3D printer

Finally, the studied mineral additives led to an increase in water absorption (except for the following cases): Microsilicon; Biosilicon (at 10% by weight of Portland cement); Metakaolin (at 30–40% by weight of Portland cement). For all other additives, water absorption increased by 6.0–96.4% compared with the control composition.

4. RESULTS AND DISCUSSION

The most notable improvement in shape stability—by 40% and 60% (i.e., 2 and 3 additional layers)—was observed for mixtures containing: 20% biosilicon: 10–20% diatomite. For all studied mineral additives, the highest number of printed layers without interruption was observed at an optimal additive content of 10–20%. This phenomenon is attributed to the interparticle forces within the mixture. With the introduction of mineral additives (particle sizes 0.5–3 μm) at 10–20% by weight of Portland cement, the dominance of flocculation and colloidal interactions increases. This leads to: greater cohesion of the mixture; Better formability; Higher shape stability.

However, when the mineral additive content exceeds 20%, the water demand increases due to the high specific surface area of the solid particles required to maintain the given mobility. This results in: decreased mixture density (**Table 3,4**); increased thickness of the solvate shell of colloidal particles; reduced flocculation (i.e., less attraction between positively and negatively charged particles, forming fewer floccules); increased free water in the system. Consequently, the excessive increase in sliding between solid particles due to repulsive forces reduces the dimensional stability of the mixture.

It is important to note that failure in freshly formed samples with mineral additives was characterized by incomplete overturning—similar to compositions containing plasticizing additives. Upon reaching a critical force, loss of mold stability was observed, leading to displacement of printed layers (**Figure 7**).

When determining the shape stability of the mixture, the maximum number of printed layers was compared to the total height of these layers without technological interruption. It was found that different total heights could correspond to the same number of printed layers (**Figures 1–6**). Therefore, this phenomenon should be considered when assessing the shape stability of a concrete mix.

5 CONCLUSIONS

The conducted studies have shown that the examined mineral additives generally have a positive effect on the formability of the extruded mixture. They improve cohesion and uniformity while reducing the occurrence of tears and other defects during 3D printing. Special attention should be paid to the ability of mineral additives to enhance the shape stability of printed layers, which is crucial for 3D printing technology. In this regard, the most effective types and contents of mineral additives were determined not only from the standpoint of ensuring high physico-mechanical properties of concrete but also in terms of enhancing the form stability of the mixture with a given mobility, considering the technological parameters and features of the 3D printer. Among the studied mineral additives, biosilicon and diatomite were found to be the most effective in improving the form stability of the mixture. At the same time, any reduction in the physico-mechanical properties of fine-grained concretes containing mineral additives in 3D-printed structures can be compensated by using Portland cement and complex additive formulations.

The analysis of the influence patterns of the studied mineral additives on the properties of cement dough and fine-grained concrete in additive manufacturing technology allowed us to determine the following:

1. All studied mineral additives lead to an increase in the normal density of cement dough by 3.2–85.4% compared to the additive-free composition, with the largest increase observed for diatomite. The setting time of cement dough containing mineral additives in amounts of 10–40% by weight of Portland cement generally increases (by 6–67 minutes for the initial setting and 71–79 minutes for the final setting).
2. Ensuring equal mobility (Dc 3) results in a reduction of the limiting shear stress by 6.7–49.3% compared to the additive-free composition. However, within the 10–20% range of mineral additive content, an increase in mixture cohesiveness, improved formability, and enhanced shape stability (up to 82.3%) during 3D printing is observed. This is likely due to the intensification of flocculation and the colloidal nature of interactions between solid particles in the system.
3. Mixtures modified with biosilicon (20%) and diatomite (10–20%) are the most effective in enhancing shape stability, achieving increases of 40% and 60%, respectively.
4. For further research, metakaolin, kaolin, and biosilicon will be studied at a concentration of 10% by weight of Portland cement.

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