WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2023.146072

ARCHIVES OF CIVIL ENGINEERING

Vol. LXIX ISSUE 3 2023

 pp. 147 – 156

Research paper

The effect of air-entraining agent on the properties of mortars

Zinoviy Blikharskyy[1], Taras Markiv[2], Khrystyna Sobol[3], Yurii Turba[4], Jacek Selejdak[5]

Abstract: The effect of the air-entraining agent on properties of mortar mixtures as well as on the compressive strength of hardened mortars was the objective of this study. Such mortars contain a certain amount of evenly spread closed air-voids pores with dimensions of 0.02-0.05 mm. On the one hand, the presence of a large volume of such air bubbles results in the reduction of mechanical properties of mortar. On the other hand, the use of this technological approach improves rheological properties of mortar mixture. The effect of the air entrainment on the flow, density, volume of entrained air of mortar mixture and compressive strength of hardened mortar was established. Obtained results show substantial increasing in the mortar flow at cement to sand ratio 1:2 by 1.8 times. The further decrease of C:S ratio results in a slight increase of the flow and even negligible its decrease at C:S = 1:4 compared to the reference mortar. The increase of the volume of entrained air results in the decrease of the density and compressive strength of mortar, but improve the resistance to freezing/thawing cycles. The results of this study can be a guide for mortar mix design to choose the most appropriate mix proportion to produce economically efficient mortars.

Keywords: air-entraining agent, compressive strength, durability, frost resistance, mortar

[1]Prof., Faculty of Civil Engineering, Czestochowa University of Technology, 69 St. Dabrowskiego, 42-201 Czestochowa, Poland, e-mail: zinoviy.blikharskyy@pcz.pl, ORCID: 0000-0002-4823-6405
[2]PhD., Department of Building Production, Institute of Civil Engineering and Building Systems, Lviv Polytechnic National University, S. Bandery Street 12, 79013 Lviv, Ukraine, e-mail: taras.y.markiv@lpnu.ua, ORCID: 0000-0002-0865-3984
[3]Prof., Department of Highways and Bridges, Institute of Civil Engineering and Building Systems, Lviv Polytechnic National University, S. Bandery Street 12, 79013 Lviv, Ukraine, e-mail: khrystyna.s.sobol@lpnu.ua, ORCID: 0000-0003-0798-413X
[4]PhD., Department of Highways and Bridges, Institute of Civil Engineering and Building Systems, Lviv Polytechnic National University, S. Bandery Street 12, 79013 Lviv, Ukraine, e-mail: yurii.v.turba@lpnu.ua, ORCID: 0000-0003-3692-8890
[5]Associate Prof., Faculty of Civil Engineering, Czestochowa University of Technology, 69 St. Dabrowskiego, 42-201 Czestochowa, Poland, e-mail: jacek.selejdak@pcz.pl, ORCID: 0000-0001-9854-5962

1. Introduction

The cement mortar is used widely in various construction phase and it is very important civil engineering material. A lot of scientists study the effect of different factors on the properties of mortars [1–7]. The frost resistance is one of the most important. Winter is a period of year which can define the durability of structures because of the some amount of freezing and thawing cycles which concrete and mortar can be subjected to and is always a challenge for a construction manager [8]. The behavior of the water in the cement paste (the microstructure‘s level of mortar) at negative temperature was studied by Koniorczyk et al. [9]. The water in a concrete or in a mortar exposed to the alternate freezing and thawing freezes and expands by about 9% [8, 10, 11]. Lack of enough space to accommodate this extra volume cases internal stresses exceeding the tensile strength of a mortar. They can provoke its cracking and scaling [11–13]. Usage of air-entraining admixtures (AEAs) became one of the important invention made in the concrete technology. Such surface active agents (surfactants) are amphiphilic molecules. They can be anionic, cationic, amphoteric and non-ionic. It should be noted that anionic surfactants (head group charged negatively) dominate the AEA market, because of their recognized reliability and low cost [10]. The nature of such surfactants can be also different. The synthetic surface active agent of anionic type on the basis of sodium laureth sulfate was used in this study. It should be noted that air-entraining admixtures consist mainly of various surfactants [14].

The structure of concrete and mortars incorporating AEA has the air void system with uniformly distributed dispersed, particle-armored bubbles shell at the air/paste interface. It differs both chemistry and morphology from the bulk paste [10, 15]. The volume of entrapped air in concrete without AEA ranges from 1 to 3%. The diameter of voids in such mortars and concretes is usually higher than 0.5 mm [10].

It is known that the appropriate amount of AEA improves the workability of a fresh mortar and concrete as well as the resistance to alternate freezing and thawing cycles [10–12, 16–18]. That is why the study of the influence of an air entraining agent on mortar rheological properties, density and compressive strength has a practical and theoretical significance [16, 19]. The literature analysis [18] shows that AEA can improve fluidity, slump retention ability and freeze-thaw durability without strength reduction. Some researchers [14, 18] confirm that the air-entraining agents facilitate the placement of fresh concrete and resistance to alternate freezing and thawing. Frost durability of mortar is very important, because it has a porous structure in which water is in various forms. The appropriate amount of entrained air that meets specifications is required to protect the concrete against damage due to the water freezing [18]. It was established that the absence of AEA in concrete exposed to freezing and thawing cycles causes a rather significant decrease in compressive strength [18]. Some researchers [17,20] state that the yield stress increases and the plastic viscosity decreases if a concrete contains the entrained air. The air entrainment is rather a complex process. It can be affected by many factors, such as the mixing process, mixture proportioning, aggregates‘ characteristics, properties of Portland cement, amount and quality of water, dosage and properties of AEA, and some other parameters [14]. However, there are not so much researches devoted to the effect of the sodium laureth sulfate based air-entraining admixtures on the volume of entrained air depending on the mix proportion of mortar and its properties including frost resistance.

That is why, the aim of this paper is to study the effect of air-entraining agent and the mix proportion of cement mortar on the volume of the entrained air, flow, density, compressive strength and resistance to freezing and thawing cycles.

2. Materials and methodology

2.1. Raw materials

Portland cement CEM I 42.5 was used in this study. Physical and mechanical properties of Portland cement are presented in Table 1.

Table 1. Physical and mechanical properties of Portland cement

Properties		Results
Specific surface [m^2/kg]		325
Residue on sieve 008 [%]		3.1
Water demand [%]		29.0
Setting time [min]	initial	155
	final	205
Compressive strength [MPa], age [days]	2	31.2
	7	41.3
	28	52.1

The results of sand tests are shown in Table 2.

Table 2. Properties of aggregate

Aggregate type	Density [g/cm^3]	Bulk density [kg/m^3]	Voidage [%]	Dust and clay particles [%]	Fineness modulus
Quartz sand	2.63	1360	48.3	1.4	1.0

Anionic type air-entraining agent with a specific gravity of 1.02, pH = 8 and solid content of 0.34% was used in the research.

2.2. Test method

The properties of Portland cement and fine aggregate were determined according to Ukrainian standards [21–23]. The air permeability method (Tovarov device) is used to measure the specific surface area of Portland cement (Fig. 1a). The fineness of cement is also measured by sieving it on the standard 0.08 mm sieve.

The setting time is determined using Vicat apparatus (Fig. 1b). Firstly, the determination of standard consistency of cement paste takes place. The appropriate amount of water is determined to produce a distance between plunger and base-plate of (6 ± 1) mm. Then the initial and final setting time is determined. The time between 'zero time' and the time at which the distance between the needle and the base-plate is 2–4 mm is the initial setting time and the time at which the needle first penetrates only 1–2 mm into the specimen is the final setting time of a cement.

The proportions by mass of constituents to determine the compressive strength of Portland cement are one part of the cement, three parts of standard sand, and the appropriate amount of water to get water/cement ratio 0.39. The mortar is prepared mechanically using the mixer (Fig. 1c). The flow table was used to determine the mortar consistency (Fig. 1d). The spread of the mortar must be higher than 106 mm. The test specimens are 40 × 40 × 160 mm prisms (Fig. 1e). After demoulding marked specimens are submerged in water at (20.0 ± 1.0)°C in the containers and are tested at the appropriate time.

The properties of a fine aggregate were determined according to Ukrainian standard [24]. The Fineness Modulus (FM) of sand is determined by adding the total percentage of the sample of a fine aggregate retained on each of specified series of sieves, dividing the sum by 100. Sieves sizes (Fig. 1f) are: 160 µm (№ 016), 315 µm (№ 0315), 630 µm (№ 063), 1.25 mm (№ 1.25), 2.5 mm (№ 2.5).

Four mixture proportions of cement mortars have been prepared (C:S = 1:2, R and C:S = 1:2, C:S = 1:3, C:S = 1:4, with 0.75% by mass of AEA) at W/C ratio 0.5. Consistency of mortar was tested by using the flow table. The mortars with appropriate cement : sand ratio and W/C = 0.5 were prepared and moulded according to [22] to determine their compressive strength. The test specimens were 40 × 40 × 160 mm prisms. Nine specimens for each series C:S = 1:2, R and C:S = 1:2, C:S = 1:3, C:S = 1:4, with 0.75% by mass of AEA were moulded and three of them from each series were tested at 7, 14 and 28 days of hardening. The properties of mortars at constant fresh mortar flow (125–135 mm) were also studied [26]. The pressure method was used to determine the air content in the mixtures (Fig. 1g).

The freeze–thaw resistance of mortars was determined according to [25]. Six specimens (3 basic and 3 control for the appropriate amount of cycles) of mixture proportion (C:S = 1:4, the depth of penetration of the standard cone was 100 mm (Fig. 1h)) with AEA and the same quantity without one were moulded and cured 28 days according to Ukrainian standard [25] to determine the freeze–thaw resistance of mortars. The volume of entrained air of the mortar incorporating AEA was 6%. Both control and basic specimens cured 28 days were saturated by water before test. Then all specimens were removed from the water and compressive strength of the control specimens was determined before freeze-thaw test. The basic specimens were placed in a freezing chamber and were frozen gradually up to –20°C. The basic specimens were subjected to freeze-thaw cycles. After the appropriate freeze-thaw cycles the compressive strength of the basic specimens was determined. Then the compressive strength reduction was calculated.

Fig. 1. Tovarov device (a), Vicat apparatus (b), mixer (c), flow table (d), 40×40×160 mm prism filled in with reference mortar (e), standard sieves (f), air content meter (g) and standard cone apparatus (h) were used to determine the properties of mortar and its constituents

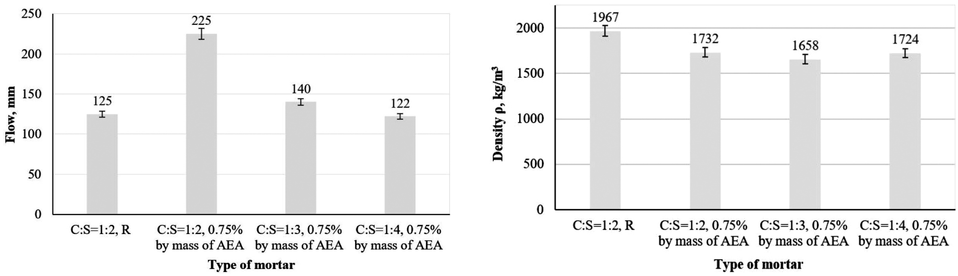
3. Results and discussion

Air-entraining admixtures allow obtaining stable air-void systems in mortar and concrete resulting in reducing segregation and bleeding, improving workability, increasing resistance to freezing and thawing cycles and as a result the durability.

The workability is very important quality characteristic of fresh mortars and defines the ease of their casting. According to the obtained results (Fig. 2a), the incorporation of AEA results in the enhancement of fresh mortar flow due to "ball bearing" effect [10] by 80 and 12% if the ratio of cement to sand is 1:2 and 1:3, respectively. If the content of a sand increases (C:S = 1:4), the slight decrease of flow is observed in comparison with reference mortar (C:S = 1:2) without AEA. The positive effect of AEA on the flow of fresh mortars is also confirmed by some researchers [8, 19].

The density of mortars depending on the proportion of cement to sand and the presence of AEA is shown in Fig. 2b. As can be seen from the obtained results, the density of fresh mortar (C:S = 1:2) incorporating AEA reduces from 1967 to 1732 kg/m^3. If the proportion of cement to sand is 1:3, the density reaches 1658 kg/m^3. The increase of the sand in fresh mortar (C:S = 1:4) causes the growth of density by almost 4% compared with fresh mortar with proportion of cement to sand 1:3.

The volume of entrained air of fresh mortars with the different proportions of cement to sand at W/C ratio of 0.5 is presented in Fig. 3. The results show that the volume of



(a) (b)

Fig. 2. Flow (a) and density (b) of fresh mortars with the different proportions of cement to sand (W/C = 0.5)

entrained air does not only depend on the flow, but also on the mixture proportion. Thus, the highest amount of entrained air (14.5%) was obtained at cement to sand ratio 1:2. It was increased by almost 3 times compared with reference mortar. The growth of sand content in mortars with cement to sand ratio 1:3 and 1:4 results in the increase of the air content in comparison with reference mortar by only 59 and 51%, respectively. This may be attributed to the lower viscosity of the mix.

The volume of entrained air of fresh mortars with the different proportions of cement to sand at W/C ratio of 0.5 is presented in Fig. 3. The results show that the volume of entrained air does not only depend on the flow, but also on the mixture proportion. Thus, the highest amount of entrained air (14.5%) was obtained at cement to sand ratio 1:2. It was increased by almost 3 times compared with reference mortar. The growth of sand content in mortars with cement to sand ratio 1:3 and 1:4 results in the increase of the air content in comparison with reference mortar by only 59 and 51%, respectively. This may be attributed to the lower viscosity of the mix.

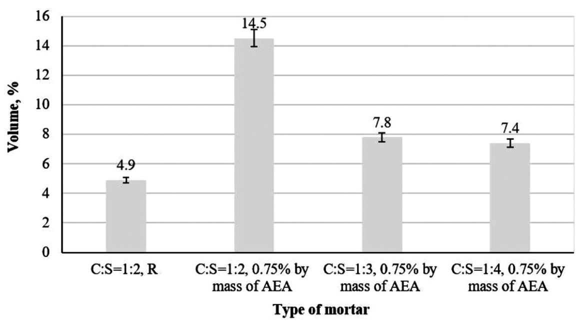


Fig. 3. The volume of the entrained air of fresh mortars with the different proportions of cement to sand (W/C = 0.5)

As shown in Fig. 4, the same tendency is observed when the influence of AEA on compressive strength of hardened mortars was studied.

The higher volume of the entrained air the lower compressive strength of the cement mortar is observed at the same cement to sand ratio. As seen from the Fig. 4, the compressive strength of mortar containing 0.75% by mass of AEA (C:S = 1:2) reduces compared with the reference mortar (C:S = 1:2, R) by 58.3, 59.8 and 65.9% after 7, 14 and 28 days, respectively. If cement to sand ratio decreases the volume of entrained air reduces. The compressive strength reduces slightly after 7 days of hardening (C:S = 1:3) and increases by 18.2 and 20.9% after 14 and 28 days in comparison with the mortar incorporating AEA (C:S = 1:2). The further reduction of C/S ratio (C:S = 1:4) results in the reduction of the compressive strength by 11.4, 12.8 and 3.2% after 7, 14 and 28 days of hardening.

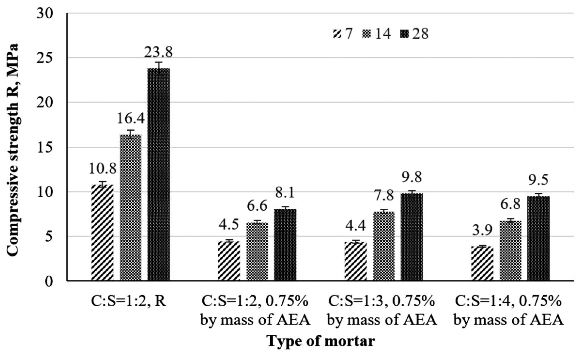


Fig. 4. Compressive strength of mortars with the different proportions of cement to sand (W/C = 0.5)

The durability of mortars is of great interest to the construction industry. It directly depends on the frost resistance. Many factors can have the influence on the resistance of mortars to freezing and thawing cycles, namely the value of the water-to-cement and cement to sand ratios, content of the entrained air, type and mineralogical composition of Portland cement. The destruction of mortars takes place under the influence of negative temperatures, which cause the water freezing in pores and further increase of the ice in volume. The walls of the pores break down resulting in the appearance of internal stresses and, as a result, cracks. Alternating freezing and thawing of mortars in water-saturated state can cause their complete destruction. The mechanism of the reduction of the compressive strength with further destruction of concrete according to a theory, called the "glue-spall" model, after the appropriate amount of freeze thaw cycles was described in detail by Tunstall et al. [10].

The properties of mortars after 35, 50 and 100 freezing/thawing cycles were studied. The reduction of compressive strength is shown in Table 3.

According to obtained results after 50 freezing/thawing cycles the lowest compressive strength reduction (18.9%) was observed for reference mortar. At the same time, the reduction of compressive strength for mortar containing AEA was only 8.1%. The further increase the quantity of freeze/thaw cycles up to 100 for mortar incorporating AEA results in 23.5% reduction of compressive strength. It confirms the positive effect of AEA on the frost resistance of mortars. The benefit of AEAs use for the improvement of the concrete resistance to the alternate freezing and thawing cycles was also confirmed by many researchers [10, 12, 18].

Table 3. Compressive strength of mortars after freeze-thaw cycles

Mixture identification	Number of freeze-thaw cycles	Compressive strength of mortars, MPa		Strength decrease of mortars comparing to control ones without freeze-thaw cycles, %
		Before freeze-thaw cycles	After freeze-thaw cycles	
C:S = 1:4	35	15.9	14.7	–7.5
	50		12.9	–18.9
C:S = 1:4, 0.75% by mass of AEA	50	13.6	12.5	–8.1
	100		10.4	–23.5

The properties of mortar and concrete incorporating both superplasticisers and air-entraining admixtures at different mixture proportions will be studied in the further research.

4. Conclusions

This article is dedicated to the study of properties of mortars incorporating air-entraining agent. The main conclusions are as follows:

1. The fresh mortar flow improves (by 12–80%) and density decreases (by 11–16%) for C:S = 1:2 and 1:3 compared to the reference mortars and even increase by 4% for C:S = 1:4 compared with the fresh mortar with proportion of cement to sand 1:3. Thus, obtained values depend on the proportion of mortar mixture.
2. The volume of entrained air of fresh mortars does not only depend on the flow, but also on the mixture proportion. It increases by 1.5–3 times if the cement to sand ratio changes from 1:4 to 1:2. The highest volume of entrained air (14.5%) is observed in fresh mortar with the highest content of cement paste (the cement to sand ratio is 1:2).
3. The compressive strength reduces if AEA is added to mortars. The rate of reduction depends both on the content of entrained air and mixture proportion. The most significant compressive strength reduction (by 65.9%) of mortar incorporating 0.75% by mass of AEA (C:S = 1:2) is observed compared with the reference mortar after 28 days of hardening.
4. The addition of AEA improves the resistance of mortars to freezing and thawing cycles and their durability that follows the principles of sustainable development, adopted in the construction industry.

References

[1] E. Mehmetoğulları, H. Güneyli, and S. Karahan, "The effect of gradation and grain-size properties of fine aggregate on the building mortars", *Production Engineering Archives*, vol. 26, no. 3, pp. 121–126, 2020, doi: 10.30657/pea.2020.26.23.

[2] B. Dębska, J. Krasoń, and L. Lichołai, "The evaluation of the possible utilization of waste glass in sustainable mortars", *Construction of Optimized Energy Potential (CoOEP)*, vol. 9, no. 2, pp. 7–15, 2020, doi: 10.17512/bozpe.2020.2.01.

[3] J. Jura, "Influence of type of biomass burned on the properties of cement mortar containing fly ash", *Construction of Optimized Energy Potential (CoOEP)*, vol. 9, no. 1, pp. 77–82, 2020, doi: 10.17512/bozpe.2020.1.09.

[4] E.A. Ohemeng, S.O. Ekolu, H. Quainoo, and A. Naghizadeh, "Economical and eco-friendly masonry mortar containing waste concrete powder as a supplementary cementitious material", *Case Studies in Construction Materials*, vol. 17, art. no. e01527, 2022, doi: 10.1016/j.cscm.2022.e01527.

[5] A.A. Azmi, et al., "Crumb rubber geopolymer mortar at elevated temperature exposure", *Archives of Civil Engineering*, vol. 68, no. 3, pp. 87–105, 2022, doi: 10.24425/ace.2022.141875.

[6] J. Gołaszewski and M. Gołaszewska, "The effect of shrinkage reducing admixture and expansive admixture on properties of mortars with Portland and slag cement", *Archives of Civil Engineering*, vol. 68, no. 2, pp. 337–353, 2022, doi: 10.24425/ace.2022.140646.

[7] J. Gołaszewski and M. Gołaszewska, "Properties of mortars with calcium sulfoaluminate cements with the addition of Portland cement and limestone", *Archives of Civil Engineering*, vol. 67, no. 2, pp. 425–435, 2021, doi: 10.24425/ace.2021.137177.

[8] M. Babiak, M. Ratajczak, P. Kulczewski, and J. Kosno, "Effect of modern air entraining admixtures on physical properties of construction mortars", *Materials Science Forum*, vol. 923, pp. 115–119, 2018, doi: 10.4028/www.scientific.net/MSF.923.115.

[9] M. Koniorczyk, D. Bednarska, A. Wieczorek, and P. Konca, "Freezing of fully and partly saturated cement paste", *Archives of Civil Engineering*, vol. 67, no. 2, pp. 383–396, 2021, doi: 10.24425/ace.2021.137174.

[10] L.E. Tunstall, M.T. Ley, and G.W. Scherer, "Air entraining admixtures: Mechanisms, evaluations, and interactions", *Cement and Concrete Research*, vol. 150, art. no. 106557, 2021, doi: 10.1016/j.cemconres.2021.106557.

[11] Z. Blikharskyy, K. Sobol, T. Markiv, and J. Selejdak, "Properties of concretes incorporating recycling waste and corrosion susceptibility of reinforcing steel bars", *Materials*, vol. 14, no. 10, pp. 1–15, 2021, doi: 10.3390/ma14102638.

[12] Z. Sun and G.W. Scherer, "Effect of air voids on salt scaling and internal freezing", *Cement and Concrete Research*, vol. 40, no. 2, pp. 260–270, 2010, doi: 10.1016/j.cemconres.2009.09.027.

[13] O. Coussy and P.J.M. Monteiro, "Poroelastic model for concrete exposed to freezing temperatures", *Cement and Concrete Research*, vol. 38, no. 1, pp. 40–48, 2008, doi: 10.1016/j.cemconres.2007.06.006.

[14] L. Du and K.J. Folliard, "Mechanisms of air entrainment in concrete", *Cement and Concrete Research*, vol. 35, no. 8, pp. 1463–1471, 2005, doi: 10.1016/j.cemconres.2004.07.026.

[15] M.T. Ley, R. Chancey, M.C.G. Juenger, and K.J. Folliard, "The physical and chemical characteristics of the shell of air-entrained bubbles in cement paste", *Cement and Concrete Research*, vol. 39, no. 5, pp. 417–425, 2009, doi: 10.1016/J.CEMCONRES.2009.01.018.

[16] X. Deng, Y. Liu, and R. Wang, "Investigating freeze-proof durability of air-entrained C30 recycled coarse aggregate concrete", *Archives of Civil Engineering*, vol. 67, no. 2, pp. 507–524, 2021, doi: 10.24425/ace.2021.137182.

[17] L.J. Struble and Q. Jiang, "Effects of air entrainment on rheology", *ACI Materials Journal*, vol. 101, no. 6, pp. 448–456, 2004, doi: 10.14359/13483.

[18] T. Markiv, K. Sobol, M. Franus, and W. Franus, "Mechanical and durability properties of concretes incorporating natural zeolite", *Archives of Civil and Mechanical Engineering*, vol. 16, no. 4, pp. 554–562, 2016, doi: 10.1016/j.acme.2016.03.013.

[19] N. Tebbal, Z. El Abidine Rahmouni, and L.R. Chadi, "Study of the influence of an air-entraining agent on the rheology of motars", *MATEC Web of Conferences*, vol. 149, 2018, doi: 10.1051/matecconf/201714901054.

[20] Q. Gu, A. Kang, B. Li, P. Xiao, and H. Ding, "Effect of fiber characteristic parameters on the high and low temperature rheological properties of basalt fiber modified asphalt mortar", *Case Studies in Construction Materials*, vol. 17, 2022, doi: 10.1016/j.cscm.2022.e01247.

[21] DSTU B V 2.7-185:2009 Building materials. Cements. Methods of determination of normal thickness, setting time and soundness. Kyiv, Ukraine: Ukrarkhbudinform, 2009.

[22] DSTU B V 2.7-187:2009 Building materials. Cements. Methods of determination of bending and compression strength. Kyiv, Ukraine: Ukrarkhbudinform, 2009.

[23] DSTU B V 2.7-188:2009 Building materials. Cements. Methods of determination of fineness. Kyiv, Ukraine: Ukrarkhbudinform, 2009.

[24] DSTU B V 2.7-232:2010 Building materials. Sand for construction work testing methods. Kyiv, Ukraine: Ukrarkhbudinform, 2010.

[25] DSTU B V 2.7-239:2010 Building materials. Building mortars. Methods of test. Kyiv, Ukraine: Ukrarkhbudinform, 2010.

[26] T. Markiv, "Properties of fresh and hardened mortars with air-entraining agent", *Theory and Building Practice*, vol. 2022, no. 2, pp. 105–110, 2022, doi: 10.23939/JTBP2022.02.105.

Wpływ domieszki napowietrzającej na właściwości zapraw

Słowa kluczowe: domieszka napowietrzająca, mrozoodporność, trwałość, wytrzymałość na ściskanie, zaprawa

Streszczenie:

Celem badań był wpływ domieszki napowietrzającej na właściwości mieszanek zaprawowych oraz wytrzymałość na ściskanie zapraw. Zaprawy takie zawierają pewną ilość równomierne rozprowadzonych, zamkniętych porów powietrznych o wymiarach 0,02–0,05 mm. Z jednej strony, obecność dużej ilości takich pęcherzyków powietrza powoduje obniżenie właściwości mechanicznych zaprawy. Z drugiej strony, zastosowanie tego podejścia technologicznego poprawia właściwości reologiczne mieszanki zaprawy. Określono wpływ domieszki napowietrzającej na urabialność, gęstość, objętość wprowadzonego powietrza oraz wytrzymałość na ściskanie zaprawy. Uzyskane wyniki wskazują na znaczny, 1,8-krotny wzrost rozpływu zaprawy przy stosunku cementu do piasku 1:2. Dalsze zmniejszanie stosunku C:S powoduje niewielki wzrost urabialności, a nawet znikomy jego spadek przy C:S = 1:4 w porównaniu do zaprawy wzorcowej. Wzrost objętości wprowadzonego powietrza powoduje zmniejszenie gęstości i wytrzymałości na ściskanie zaprawy, ale poprawia mrozoodporność. Wyniki badań mogą być wskazówką przy projektowaniu zapraw, aby wybrać najbardziej odpowiednie proporcje mieszanki w celu wytworzenia ekonomicznie efektywnych zapraw.

Received: 2023-04-29, Revised: 2023-05-04