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RESEARCH ARTICLE

EFFECT OF CHEMICAL ADMIXTURES ON HYDRATION AND STRENGTH OF FINE-GRAINED CONCRETE

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Abstract. *The performance of fine-grained concrete strongly depends on chemical admixtures, yet the combined effect of superplasticizers and air-entraining agents on early hydration and strength remains insufficiently understood. This study evaluates the influence of a polycarboxylate-ether superplasticizer (PS) and an air-entraining admixture (AER), applied separately and in combination, on the hydration kinetics, compressive strength, and microstructure of fine-grained concrete. PS (0.5–1.5 % by mass of cement) and AER (0.10–0.30 %) and their combinations were tested against a control paste at W/C = 0.28. Early-age hydration was assessed by temperature-evolution monitoring, determining the maximum hydration temperature (T_{max}) and the time to peak (t_{max}); compressive strength was measured at 7 and 28 days, and the microstructure was examined by SEM. AER progressively reduced T_{max} (by up to 17.8 %) and delayed hydration (t_{max} up to +52.7 %). PS at an optimal dosage of 1.0 % produced the highest T_{max} (87.5 °C), while combined PS–AER systems showed the strongest retardation (t_{max} up to 18.89 h). PS increased compressive strength by up to 33.2 % at 7 days, whereas AER alone markedly reduced it. The optimal combination SA0.1 (1.0 % PS + 0.10 % AER) reached 27.3 MPa at 7 days and 34.0 MPa at 28 days. SEM revealed a denser C–S–H network for PS-modified samples and characteristic spherical air voids in AER-modified ones. Overall, a superplasticizer at 1.0 % combined with a low AER dosage (0.10 %) optimally balances hydration, strength, and microstructure.*

Keywords: *fine-grained concrete; polycarboxylate ether superplasticizer; air-entraining admixture; hydration kinetics; temperature evolution; compressive strength; microstructure.*

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ҒЫЛЫМИ МАҚАЛА

ХИМИЯЛЫҚ ҚОСПАЛАРДЫҢ ҰСАҚ ТҮЙІРШІКТІ БЕТОННЫҢ ГИДРАТАЦИЯСЫ МЕН БЕРІКТІГІНЕ ЫҚПАЛЫ

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Аңдатпа. *Ұсақ түйіршікті бетонның қасиеттері химиялық қоспаларға айтарлықтай тәуелді, алайда суперпластификаторлар мен ауа тартқыш қоспалардың ерте гидратация мен беріктікке біріккен әсері әлі жеткілікті зерттелмеген. Бұл жұмыста поликарбоксилат эфирі негізіндегі суперпластификатордың (PS) және ауа тартқыш қоспаның (AER) жеке және бірлескен түрде ұсақ түйіршікті бетонның гидратация кинетикасына, сығылу беріктігіне және микроқұрылымына әсері бағаланды. PS (цемент массасынан 0,5–1,5 %) және AER (0,10–0,30 %), сондай-ақ олардың комбинациялары W/C = 0,28 болатын бақылау цемент қамырымен салыстырылды. Ерте гидратация температураның өзгеруін бақылау арқылы бағаланып, максималды гидратация температурасы (T_{max}) және шыңға жету уақыты (t_{max}) анықталды; сығылу беріктігі 7 және 28 тәулікте өлшеніп, микроқұрылым сканерлеуші электронды микроскопия (SEM) әдісімен зерттелді. AER мөлшері артқан сайын T_{max} мәнін төмендетіп (17,8 %-ға дейін) және гидратацияны кешеуілдетті (t_{max} 52,7 %-ға дейін артты). Оңтайлы мөлшері 1,0 % болатын PS ең жоғары T_{max} мәнін (87,5 °C) көрсетті, ал біріктірілген PS–AER жүйелері ең қатты кешеуілдеуді байқатты (t_{max} 18,89 сағатқа дейін). PS сығылу беріктігін 7 тәулікте 33,2 %-ға дейін арттырды, ал AER жеке қолданылғанда оны айтарлықтай төмендетті. Оңтайлы SA0.1 (1,0 % PS + 0,10 % AER) комбинациясы 7 тәулікте 27,3 МПа және 28 тәулікте 34,0 МПа беріктікке жетті. SEM PS-пен түрлендірілген үлгілерде тығызырақ C–S–H желісін, ал AER-мен түрлендірілген үлгілерде сфералық ауа қуыстарын көрсетті. Жалпы, 1,0 % суперпластификаторды төмен AER мөлшерімен (0,10 %) біріктіру ұсақ түйіршікті бетонның гидратациясын, беріктігін және микроқұрылымын оңтайлы теңгереді.*

Түйінді сөздер: *ұсақ түйіршікті бетон; поликарбоксилат эфирі негізіндегі суперпластификатор; ауа тартқыш қоспа; гидратация кинетикасы; температуралық эволюция; қысымға беріктік; микроқұрылым.*

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НАУЧНАЯ СТАТЬЯ

ВЛИЯНИЕ ХИМИЧЕСКИХ ДОБАВОК НА ГИДРАТАЦИЮ И ПРОЧНОСТЬ МЕЛКОЗЕРНИСТОГО БЕТОНА

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Аннотация. *Свойства мелкозернистого бетона существенно зависят от химических добавок, однако совместное влияние суперпластификаторов и воздухововлекающих добавок на раннюю гидратацию и прочность изучено недостаточно. В настоящей работе оценивается влияние суперпластификатора на основе поликарбоксилатных эфиров (PS) и воздухововлекающей добавки (AER), применяемых по отдельности и в комбинации, на кинетику гидратации, прочность при сжатии и микроструктуру мелкозернистого бетона. Добавки PS (0,5–1,5 % от массы цемента) и AER (0,10–0,30 %), а также их комбинации сравнивали с контрольным цементным тестом при W/C = 0,28. Раннюю гидратацию оценивали по изменению температуры, определяя максимальную температуру гидратации (T_{max}) и время достижения пика (t_{max}); прочность при сжатии измеряли в возрасте 7 и 28 суток, а микроструктуру исследовали методом СЭМ. С увеличением дозировки AER снижал T_{max} (до 17,8 %) и замедлял гидратацию (t_{max} возрастал до 52,7 %). Суперпластификатор PS при оптимальной дозировке 1,0 % обеспечил наибольшую T_{max} (87,5 °C), тогда как комбинированные системы PS–AER показали наиболее выраженное замедление (t_{max} до 18,89 ч). PS повышал прочность при сжатии до 33,2 % в возрасте 7 суток, тогда как AER при самостоятельном применении заметно её снижал. Оптимальная комбинация SA0.1 (1,0 % PS + 0,10 % AER) достигла прочности 27,3 МПа в возрасте 7 суток и 34,0 МПа — 28 суток. СЭМ выявила более плотную сетку C–S–H у образцов с PS и характерные сферические воздушные поры у образцов с AER. В целом, суперпластификатор при 1,0 % в сочетании с низкой дозировкой AER (0,10 %) оптимально уравновешивает гидратацию, прочность и микроструктуру.*

Ключевые слова: *мелкозернистый бетон; суперпластификатор на основе поликарбоксилатного эфира; воздухователь; кинетика гидратации; температурная эволюция; прочность на сжатие; микроструктура.*

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1 INTRODUCTION

Fine-grained concrete remains one of the most widely used construction materials in modern building practice due to its high workability, structural homogeneity, and broad range of applications. Improving the performance characteristics of such systems is primarily achieved through chemical admixtures, among which polycarboxylate ether-based superplasticizers and air-entraining admixtures hold a special place [1–3].

Polycarboxylate ether-based superplasticizers provide effective dispersion of cement particles through an adsorption-steric mechanism, reduce the water demand of the mixture, and contribute to the formation of a dense and homogeneous cement matrix [4–6]. Studies have established that the molecular structure and dosage of superplasticizer have a decisive influence on the rheological properties of cement paste, the adsorption behavior of polymer molecules on the surface of clinker phases, and the kinetics of early hydration [7; 8]. At optimal dosages, the superplasticizer intensifies hydration processes by improving particle wetting and creating favorable conditions for nucleation of hydrate phases, whereas exceeding the optimal concentration may lead to retardation of hydration due to excessive adsorption onto the surface of C_3S and C_3A [9; 10]. The use of complex mineral and chemical modifiers is an effective way of controlling the structure formation of the cement matrix and improving concrete performance [11; 12].

Air-entraining admixtures reduce the surface tension of mixing water and ensure the formation of a stable system of uniformly distributed microscopic air voids within the cement matrix [13]. The introduction of air-entraining admixture significantly alters the pore structure of hardened cement paste, which is directly reflected in the mechanical characteristics of the hardened material [14; 15]. At the same time, the influence of air-entraining admixture on the kinetics of exothermic hydration reaction of cement, in particular on the time to reach maximum temperature and the intensity of heat release, is considerably less covered in literature comparing to studies of its effect on fresh mixtures and hardened concrete [16; 17].

The combined use of a superplasticizer and an air-entraining admixture in cementitious systems is of particular scientific and practical interest, since these admixtures exert opposing effects on the formation of cement stone structure. On the one hand, the superplasticizer densifies the matrix and increases strength; on the other hand, the air-entraining admixture forms a pore system that reduces the material's mechanical properties [18; 19]. The interaction of superplasticizer molecules with surface-active substances in air-entraining admixtures can affect the stability of entrained pores and the intensity of hydration processes; systematic studies in this area remain limited to date [20; 21].

Microstructural investigations by scanning electron microscopy confirm that the type and dosage of chemical admixtures have a decisive influence on the morphology of hydration products, the packing density of C–S–H gel, and the character of pore space in hardened cement paste [6; 7]. At the same time, the relationship between the exothermic hydration profile, microstructural development of the system, and the resulting compressive strength of concrete, depending on the dosage of superplasticizer and air-entraining admixture, remains insufficiently studied, indicating the existence of a significant scientific gap [22-24].

Similar approaches, in which the properties of cement-based materials are governed by chemical admixtures and the water–cement ratio, have been reported for various cementitious systems, including the microstructural analysis of modified cement [25] and the study of surface-active agents together with the water–cement ratio in concrete [26].

The present work aims to fill this gap through a systematic two-stage experimental program. In the first stage, the influence of a superplasticizer and an air-entraining admixture on the kinetics of early cement paste hydration was investigated using the exothermic analysis method. In the second stage, the influence of the same admixture combinations on the compressive strength of fine-grained concrete at 7 and 28 days was evaluated. Microstructural observations using scanning electron microscopy were conducted to confirm and interpret the results obtained.

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2 MATERIALS AND METHODS

2.1 Materials

CEM I 42.5 N Portland cement, meeting the requirements of EN 197-1:2011, was selected as the main binding component. The phase composition was characterized by a predominance of alite (C_3S — 58.54%), with belite (C_2S — 15.29%), aluminate (C_3A — 10.4%), and ferrite (C_4AF — 10.17%) phases present in smaller proportions. Setting characteristics were assessed in accordance with standard procedures: the initial and final setting times were recorded at 139 and 185 min, respectively. Particle size analysis revealed a distribution spanning from 0.1 to 70 µm, with percentile values of d_{10} = 0.69 µm, d_{50} = 8.31 µm, and d_{90} = 31.89 µm. The corresponding particle size distribution curve is shown in Figure 1.

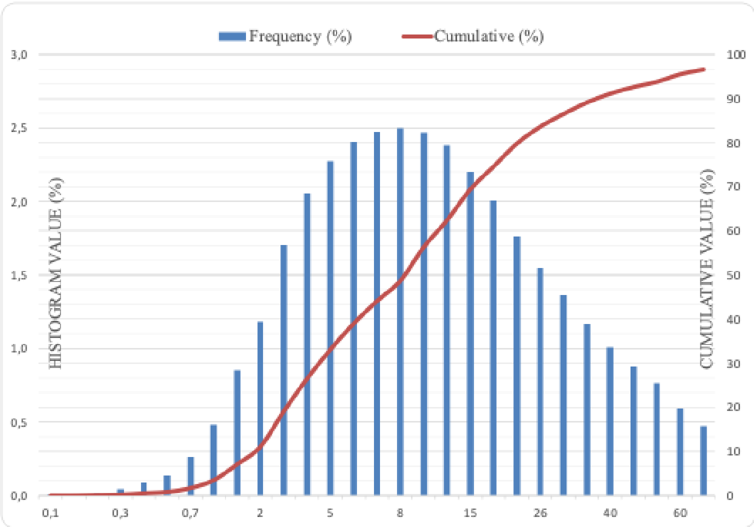

Figure 1 – Particle size distribution of CEM I 42.5 N Portland cement.

A polycarboxylate ether-based superplasticizer (PS), Sika ViscoCrete 20HE KZ, was used to reduce water demand and enhance workability of the fine-grained concrete mixtures. The admixture is a modified polycarboxylate ether composition with a density of 1.07 ± 0.02 g/cm³ and a pH of 4–6. It provides up to 40% water reduction and does not contain chlorides or other corrosion-inducing substances.An air-entraining admixture (AER), Sika Aer Solid, was incorporated to improve freeze–thaw resistance by forming a stable, uniformly distributed air-void system within the cement matrix. The admixture is based on a complex of surface-active substances, with a density of 1.00 ± 0.02 g/cm³ and a pH of 6–9.

Natural quartz sand from the Kapchagay deposit was used as fine aggregate. The sand had a fineness modulus of 2.66, a particle density of 2620 kg/m³, and a bulk density of 1630 kg/m³. The clay and dust content did not exceed 0.9%, and the water demand was 5.4%. The chemical composition of the sand is dominated by SiO_2 (56.67%) and Al_2O_3 (13.24%), confirming its aluminosilicate nature, as shown in Table 1.

Table 1 - Chemical composition of Kapchagay sand (wt.%) [Author's material].

Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3	BaO	LOI
2.87	4.71	13.24	56.67	0.22	2.01	8.73	0.93	0.11	6.70	0.09	2.69

Potable water complying with the requirements for concrete mix preparation was used throughout the study. The temperature of the mixing water was controlled and maintained at 21.9 ± 0.5 °C to ensure consistent hydration conditions across all tested compositions.

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2.2 Mixture design

The experimental program was structured in two consecutive stages.

In the first stage, cement paste systems without fine aggregate were prepared to evaluate the influence of PS and AER on early hydration kinetics. The exothermic behavior of the investigated pastes was assessed using the ALCOA methodology by recording temperature evolution during the first 24 h of hardening. Specimens of 1.5 kg were placed in insulated 100 × 100 × 100 mm textolite molds at 20 °C. A type T thermocouple embedded in each specimen was connected to a data acquisition system to continuously record temperature over time. The mixed proportions of the cement paste compositions are presented in Table 2.

Table 2 - Mix design of cement paste systems used for exothermy analysis [Author's material].

Mix ID	Cement, %	PS, %	AER, %	W/C
CO	100	—	—	0.28
SP0.5	100	0.5	—	0.28
SP1	100	1.0	—	0.28
SP1.5	100	1.5	—	0.28
AER0.1	100	—	0.1	0.28
AER0.2	100	—	0.2	0.28
AER0.3	100	—	0.3	0.28
SA0.1	100	1.0	0.1	0.28
SA0.2	100	1.0	0.2	0.28
SA0.3	100	1.0	0.3	0.28

In the second stage, fine-grained concrete mixtures based on the same admixture combinations were prepared to assess compressive strength development. Compressive strength was determined at 7 and 28 days of standard water curing on 100 × 100 × 100 mm cube specimens in accordance with EN 12390-3. The mixed proportions of the fine-grained concrete compositions are presented in Table 3.

All raw materials were weighed and mixed under controlled laboratory conditions following a standardized preparation procedure. The sequence of component addition and mixing parameters was kept constant across all compositions to ensure reproducibility and comparability of results.

Table 3 - Mix proportions of fine-grained concrete compositions [Author's material].

Mix ID	Cement, g	Sand, g	Water, ml	PS, %	AER, %	W/C
CO	490	1460	220	—	—	0.45
SP0.5	490	1460	209	0.5	—	0.43
SP1	490	1460	207	1.0	—	0.42
SP1.5	490	1460	203	1.5	—	0.41
AER0.1	490	1460	218	—	0.10	0.44
AER0.2	490	1460	218	—	0.20	0.44
AER0.3	490	1460	218	—	0.30	0.44
SA0.1	490	1460	207	1.0	0.10	0.42
SA0.2	490	1460	207	1.0	0.20	0.42
SA0.3	490	1460	207	1.0	0.30	0.42

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2.3 Scanning electron microscopy (SEM)

The microstructural characterization of the hardened paste specimens was performed using a JEOL JSM-7000F scanning electron microscope operated in secondary-electron (SED) mode at an accelerating voltage of 10 kV under high vacuum. Fragments of approximately 10 mm in size were extracted from the specimens after compressive strength testing. Prior to analysis, each fragment was air-cleaned to remove surface debris and mounted on a 25 mm metallic stub; the specimens were examined without a conductive coating. The prepared samples were then introduced into the SEM chamber and observed at magnifications ranging from ×100 to ×500 to assess the morphology of the hydration products and the overall microstructural development of the investigated compositions.

3 RESULTS AND DISCUSSION

3.1 Temperature evolution curves

The exothermic temperature profiles of the investigated cement paste compositions recorded during the first 24 h of hardening are presented in Figures 2–4. The key hydration parameters — the maximum hydration temperature (T_{max}) and and the time to reach it (t_{max}) — are summarised for each series.

Effect of AER

The incorporation of the air-entraining admixture progressively delayed the hydration peak and reduced the maximum temperature compared with the reference composition shown in Figure 2. The control paste (CO) reached its maximum temperature of 73.5 °C after 7.81 h. With increasing AER dosage, t_{max} increased to 9.39 h (AER0.1), 9.60 h (AER0.2), and 12.00 h (AER0.3), while T_{max} decreased to 69.5 °C, 66.2 °C, and 60.3 °C, respectively. The reduction in peak temperature by up to 17.8% at the highest AER dosage indicates that the air-entraining admixture consistently slowed the early hydration process. This behavior can be attributed to the formation of a discontinuous liquid–solid contact environment due to entrained air voids, which reduce the effective contact area between cement particles and water, thereby decreasing the rate of early hydration reactions.

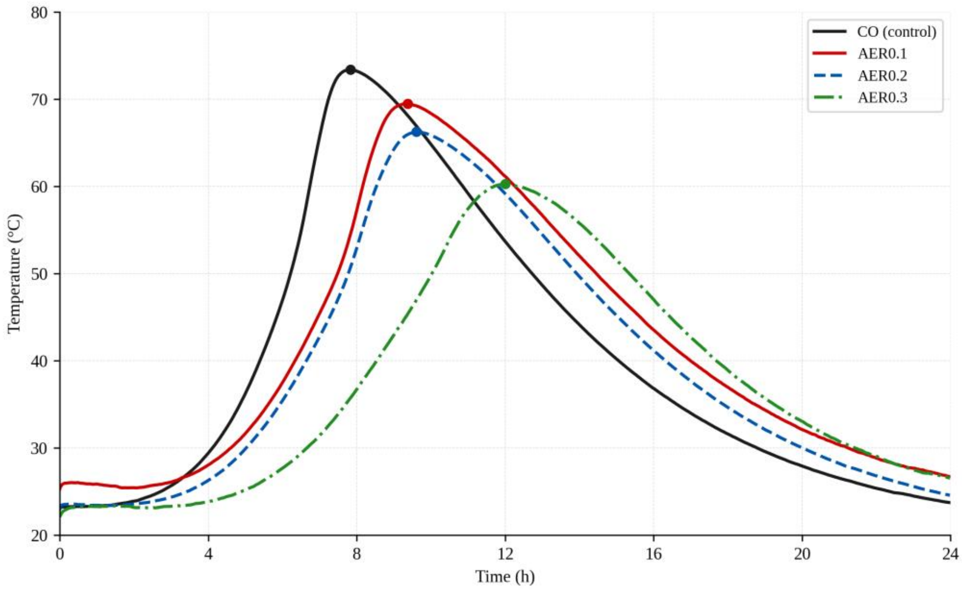

Figure 2 – Exothermic temperature profiles of cement pastes containing different AER dosages [Author's material].

Effect of PS

The polycarboxylate ether superplasticizer produced a different hydration pattern (Figure 3). All PS-modified pastes exhibited a delayed hydration peak relative to the control, with t_{max} increasing from 7.81 h (CO) to 9.83 h (SP0.5), 11.24 h (SP1), and 14.29 h (SP1.5). Notably, the composition

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SP1 reached the highest maximum temperature of 87.5 °C among all tested compositions, exceeding the control by 19.6%. This result indicates that a moderate PS dosage of 1.0 wt.% delayed the hydration peak but did not suppress the overall hydration intensity; instead, improved particle dispersion and more efficient wetting of cement grains led to a more intense heat release once hydration was initiated. At the highest dosage of 1.5 wt.%, however, T_{max} decreased to 78.5 °C, suggesting that excessive adsorption of PS molecules on cement particle surfaces led to stronger retardation and partial limitation of early hydration intensity. These findings confirm that an optimal PS dosage exists, beyond which the retarding effect outweighs the dispersion benefit.

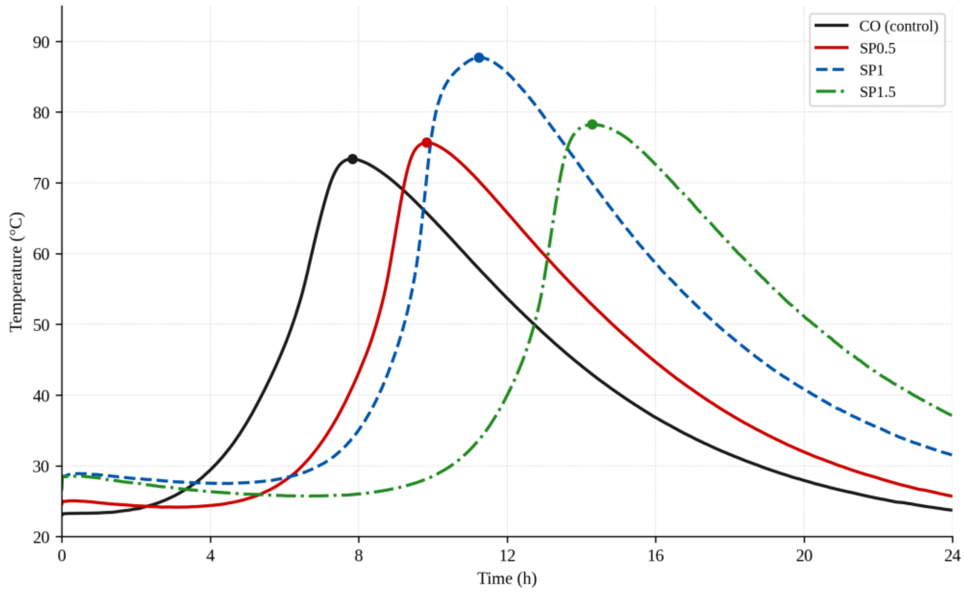

Figure 3 – Exothermic temperature profiles of cement pastes containing different PS dosages [Author's material].

Effect of combined PS–AER

The combined use of PS (1.0 wt.%) and AER produced the most pronounced retardation of the hydration process among all investigated systems (Figure 4). Compared to the control, t_{max} increased substantially to 14.38 h (SA0.1), 17.28 h (SA0.2), and 18.89 h (SA0.3). Simultaneously, T_{max} decreased progressively to 69.0 °C, 63.0 °C, and 60.9 °C.

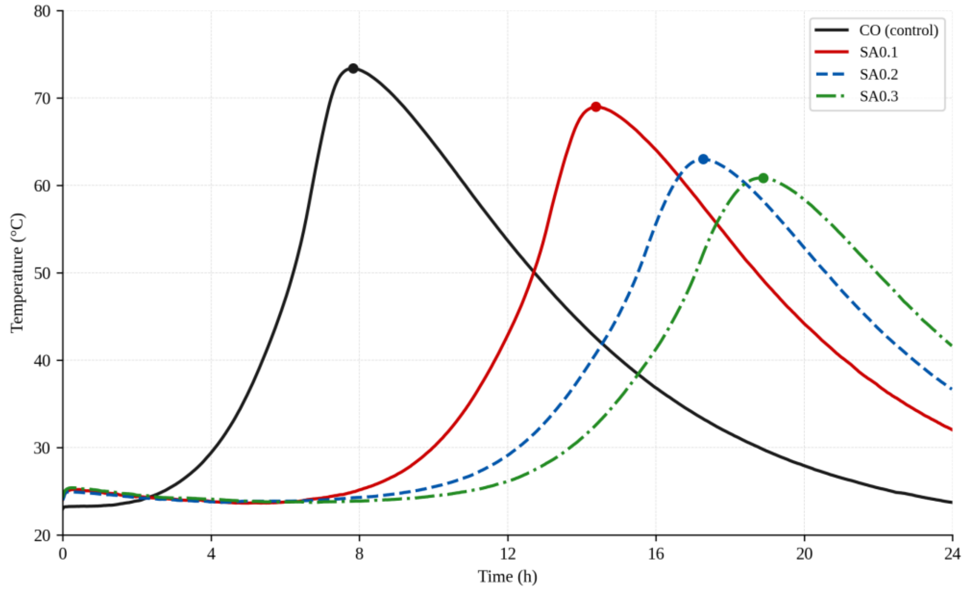

Figure 4 – Exothermic temperature profiles of cement pastes containing combined PS–AER systems [Author's material].

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The combined retarding effect of PS and AER was significantly more pronounced than that of either admixture used individually, indicating a synergistic interaction between the two components. The adsorption of PS molecules on cement particle surfaces, combined with the disruption of the liquid–solid contact environment caused by entrained air, collectively prolonged the induction period and suppressed the thermal peak of hydration. These results are consistent with the setting time data and confirm that the hydration kinetics of cement pastes can be effectively controlled through the targeted combination of PS and AER dosages.

The retarding effect of the polycarboxylate superplasticizer observed in this study is consistent with previously reported mechanisms. Zhu et al. [9] showed that PCE superplasticizers delay the initial dissolution and early hydration of Portland cement through adsorption onto clinker phases, while Lei et al. [8] demonstrated that the adsorption behaviour of polycarboxylate molecules governs the induction period of cement hydration. The retardation at the highest PS dosage (1.5 wt.%) recorded here agrees with these findings, confirming that excessive PS adsorption on C_3S and C_3A surfaces suppresses early hydration. Similarly, the delaying effect of the air-entraining admixture corresponds to the results of Tunstall et al. [13], who attributed the reduced rate of early reactions to the discontinuous liquid–solid contact created by entrained air voids. The pronounced synergistic retardation of the combined PS–AER system is in line with Pundienė and Pranckevičienė [16] and Tolegenova et al. [17], who reported that the simultaneous presence of superplasticizing and air-entraining admixtures markedly alters the rheological behaviour and stability of the air-void system in cement pastes.

3.2 Compressive strength

The compressive strength results of the investigated fine-grained concrete compositions at 7 and 28 days of curing are presented in Figure 5. The reference composition (CO) achieved compressive strengths of 19.75 MPa at 7 days and 29.0 MPa at 28 days, serving as the baseline for comparative assessment. The incorporation of the polycarboxylate ether superplasticizer consistently improved compressive strength at both testing ages. At 7 days, the strength increased progressively from 24.6 MPa (SP0.5) to 25.5 MPa (SP1) and 26.3 MPa (SP1.5), representing gains of 24.6%, 29.1%, and 33.2%, respectively, relative to the control. At 28 days, a similar trend was observed, with strength values of 33.39, 34.28, and 36.0 MPa for SP0.5, SP1, and SP1.5. This strength enhancement is attributed to the water-reducing effect of PS, which lowered the W/C ratio from 0.45 to 0.41–0.43, resulting in a denser and less permeable cement matrix with reduced capillary porosity.

The introduction of the air-entraining admixture adversely affected compressive strength at all tested dosages. At 7 days, strength decreased from 20.3 MPa (AER0.1) to 18.6 MPa (AER0.2) and 12.5 MPa (AER0.3), corresponding to reductions of 2.8%, 5.8%, and 36.7% relative to the control, respectively. The same tendency was observed at 28 days, with strength values of 27.0, 24.0, and 16.7 MPa for AER0.1, AER0.2, and AER0.3, respectively. The pronounced strength reduction at the highest AER dosage is consistent with the well-established relationship between entrained air content and compressive strength, whereby each 1% increase in air content results in an approximate 4–6% reduction in strength.

The combined PS–AER compositions demonstrated that the strength-reducing effect of AER can be partially compensated by the water-reducing action of PS. At 7 days, SA0.1 achieved the highest strength among all tested compositions at 27.3 MPa, exceeding the control by 38.2%. With increasing AER content, strength decreased to 26.5 MPa (SA0.2) and 24.0 MPa (SA0.3). At 28 days, the same trend was observed, with values of 34.0, 31.0, and 29.0 MPa for SA0.1, SA0.2, and SA0.3, respectively. Notably, the composition SA0.3 at 28 days achieved a strength level comparable to the reference, indicating that the combined admixture system maintained adequate mechanical performance even at the highest AER dosage. Overall, the results confirm that the rational combination of PS and AER achieves an effective balance between strength development and the benefits of air entrainment, with SA0.1 identified as the most favorable composition for mechanical performance.

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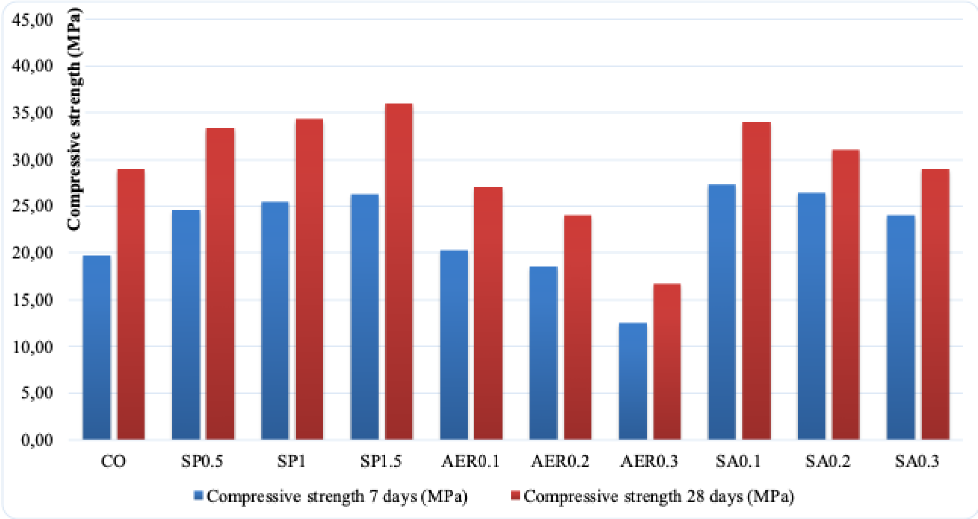

Figure 5 – Compressive strength of fine-grained concrete compositions at 7 and 28 days [Author's material].

The strength reduction caused by air entrainment observed in this study is in good agreement with the well-established inverse relationship between air content and compressive strength. Chen et al. [14] and Choi et al. [15], using mercury intrusion porosimetry and air-void analysis, reported that increasing entrained-air content enlarges the pore volume of hardened concrete and consistently lowers its mechanical performance, which supports the pronounced strength loss recorded here at the highest AER dosage. Conversely, the strength gain achieved with the superplasticizer is consistent with Huang et al. [4] and Chen et al. [6], who linked the improved mechanical properties of PCE-modified cementitious systems to a reduced water-to-cement ratio and a denser, less permeable matrix. The compensating behavior of the combined PS–AER compositions, in which the water-reducing action of PS partially offsets the strength loss induced by AER, corroborates the findings of Tolegenova [19], who reported that the combined introduction of plasticizing and air-entraining admixtures improves both the workability and strength of concrete while reducing the water–cement ratio.

3.3 Scanning electron microscopy (SEM)

The microstructural analysis of the hardened cement paste compositions is presented in Figure 6. The reference composition (Figure 6a) exhibited a relatively loose and heterogeneous matrix with visible macropores and regions of incomplete hydration.

The air-entraining admixture composition (Figure 6b) showed clearly distinguishable spherical air voids within the cement matrix, confirming effective air entrainment and explaining the observed reduction in compressive strength in the AER series. The superplasticizer-modified composition (Figure 6c) exhibited a denser, more homogeneous microstructure, attributed to improved particle dispersion and a reduced water-to-cement ratio, consistent with the higher compressive strength values observed for the SP series. Overall, the SEM observations are in good agreement with the mechanical performance data and confirm the distinct influence of each admixture type on the pore structure and matrix densification of the investigated compositions.

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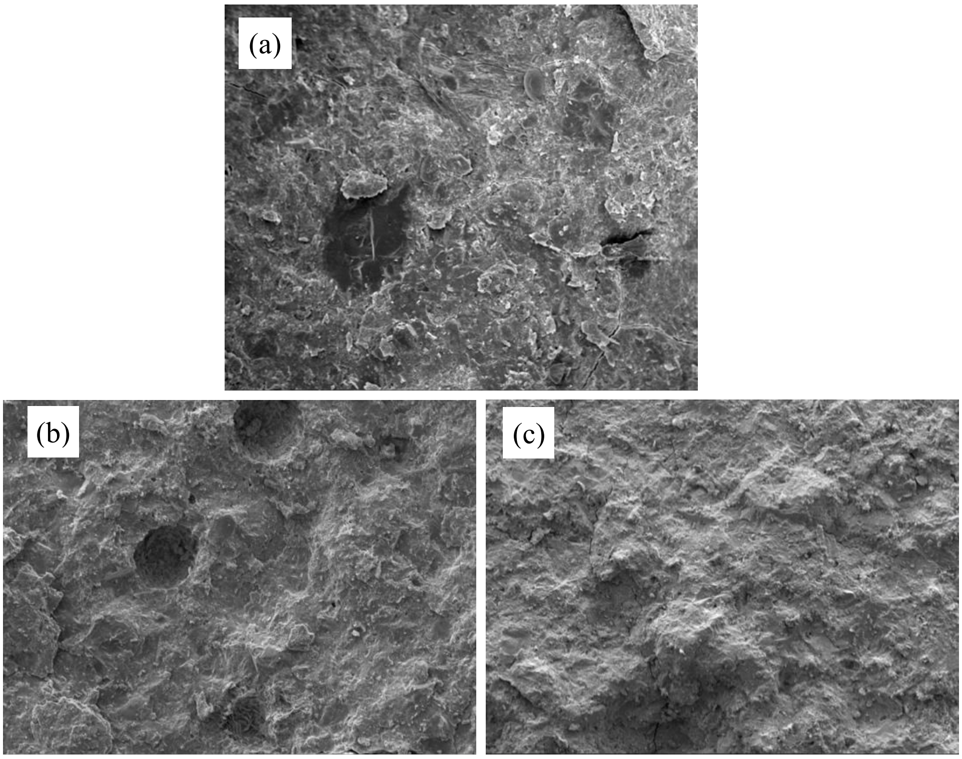

Figure 6 – SEM micrographs of hydrated cement paste modified: (a) C0 control; (b) AER; (c) SP×250. [Author's material].

These microstructural observations are consistent with previously published data. The spherical air voids identified in the AER-modified paste are characteristic of air-entrained systems and correspond to the pore morphology reported by Chen et al. [14] and Chatterji [20]. The denser and more homogeneous C–S–H network observed in the PS-modified paste agrees with Moeinian et al. [7] and Huang et al. [4], who associated polycarboxylate modification with an improved packing density of hydration products and matrix densification. Thus, the SEM results provide direct microstructural evidence that the opposing effects of PS and AER on compressive strength originate from their contrasting influence on the pore structure and the density of the C–S–H matrix.

4 CONCLUSIONS

This study experimentally evaluated the influence of a polycarboxylate ether superplasticizer (PS) and an air-entraining admixture (AER) on the hydration kinetics, compressive strength, and microstructural development of cement paste and fine-grained concrete. The results demonstrate that PS and AER exert distinct and complementary effects on the properties investigated. Key findings include:

1. Systematic reduction in hydration intensity by AER. The maximum hydration temperature decreased progressively with increasing AER dosage, reaching a reduction of 17.8% at 0.30 wt.%, while the time to peak temperature increased by up to 52.7% relative to the control. The incorporation of AER was accompanied by a significant reduction in compressive strength of up to 36.7% at 7 days and 42.4% at 28 days.
2. Intensification of hydration by PS at optimal dosage. The superplasticizer at 1.0 wt.% increased the maximum hydration temperature by 19.6% relative to the control, attributed to improved particle dispersion and more efficient cement hydration. Compressive strength increased by 24.6–33.2% at 7 days and 15.1–24.1% at 28 days across the PS series.

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3. Compensation effect of combined PS–AER systems. The combined use of PS and AER partially offset the strength reduction caused by air entrainment. Composition SA0.1 achieved the highest compressive strength among all tested compositions, exceeding the control by 38.2% at 7 days, while SA0.3 maintained strength comparable to the reference at 28 days.

4. Microstructural confirmation. SEM analysis confirms the observed mechanical trends. The PS-modified composition exhibited a dense and homogeneous C–S–H gel network, whereas the AER-modified composition showed characteristic spherical air voids within the cement matrix. The reference composition exhibited a relatively loose, heterogeneous microstructure.

5. The obtained results indicate the potential for further investigation of the developed compositions in terms of freeze–thaw resistance. The presence of a uniformly distributed air-void system, combined with a compacted cement matrix, provides favorable conditions for improved durability under cyclic freezing and thawing, warranting comprehensive frost resistance testing as the next stage of research.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ARTIFICIAL INTELLIGENCE STATEMENT

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

AUTHOR CONTRIBUTIONS

Berdikul Nazerke – Conceptualization, Methodology, Investigation, Writing – Original Draft.
Akmalaiuly Kenzhebek - Supervision, Project Administration, Writing – Review & Editing.
Tolegenova Aigerim - Formal Analysis, Data Curation, Visualization.
Kanarbay Assel – Investigation, Resources, Writing – Original Draft.
Pundiene Ina - Review and Editing.

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