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Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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ФРАТТИНИ Паоло, PhD, ассоциированный профессор, Миланский университет Бикокк (Милан, Италия), <https://www.scopus.com/authid/detail.uri?authorId=56538922400>

НУРПЕИСОВА Маржан Байсановна, доктор технических наук, профессор Казахского национального исследовательского технического университета им. К.И. Сатпаева (Алматы, Казахстан), <https://www.scopus.com/authid/detail.uri?authorId=57202218883>; <https://www.webofscience.com/wos/author/record/AAD-1173-2019>

РАТОВ Боранбай Товбасарович, доктор технических наук, профессор, заведующий кафедрой «Геофизика и сейсмология», Казахский национальный исследовательский технический университет им. К.И. Сатпаева (Алматы, Казахстан), <https://www.scopus.com/authid/detail.uri?authorId=55927684100>; <https://www.webofscience.com/wos/author/record/1993614>

РОННИ Берндтссон, профессор, Директор Центра современных ближневосточных исследований, Лундский университет (Лунд, Швеция), <https://www.scopus.com/authid/detail.uri?authorId=7005388716>; <https://www.webofscience.com/wos/author/record/1324908>

МИРЛАС Владимир, PhD, профессор, Восточный научно-исследовательский центр, Университет Ариэля (Ариэль, Израиль), <https://www.scopus.com/authid/detail.uri?authorId=8610969300>; <https://www.webofscience.com/wos/author/record/53680261>

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©**Guvalov A.A.¹, Aghazade M.E.¹, Ibraimbayeva G.B.^{2,3*}, Stanevich V.T.⁴,
Vyshar O.V.⁴, 2026.**

¹Azerbaijan University of Architecture and Construction, Baku, Azerbaijan;

²International Educational Corporation, Almaty, Kazakhstan;

³Kazakh Leading Academy of Architecture and Civil Engineering,
Almaty, Kazakhstan;

⁴Toraigyrov University, Pavlodar, Kazakhstan.

*E-mail: gulnazik1971@mail.ru

STUDY OF ASH OBTAINED FROM HOUSEHOLD WASTE INCINERATION AS A MINERAL ADDITIVE

Guvalov Abbas — Doctor of Technical Sciences, Professor, Azerbaijan University of Architecture and Construction, Baku, Azerbaijan,

E-mail: abbas-guvalov@mail.ru, <https://orcid.org/0000-0003-0189-1848>;

Aghazade Mahira — PhD student, Azerbaijan University of Architecture and Construction, Baku, Azerbaijan,

E-mail: aghazada.m@mail.ru, <https://orcid.org/0000-0001-9957-4116>;

Ibraimbayeva Gulnaz — Candidate of Technical Sciences, Professor, International Educational Corporation (Kazakh Leading Academy of Architecture and Civil Engineering), Almaty, Kazakhstan,

E-mail: gulnazik1971@mail.ru, <https://orcid.org/0000-0002-4778-5664>;

Stanevich Viktor — Candidate of Technical Sciences, Professor, Toraigyrov University, Pavlodar, Kazakhstan,

E-mail: svt_18@mail.ru, <https://orcid.org/0000-0002-7581-2658>;

Vyshar Olga — PhD, Associate Professor, Toraigyrov University, Pavlodar, Kazakhstan,

E-mail: lelya.stn@mail.ru, <https://orsid.org/0000-0002-7726-8393>.

Abstract. Relevance. Ash generated at municipal solid waste incineration plants is a technogenic resource widely used in building materials. Its utilization reduces environmental burden, improves material properties, and conserves natural raw materials. **Objective.** To evaluate the possibility of using fly ash from municipal solid waste incineration as a mineral additive in Portland cement to reduce environmental load. **Methods.** The effect of fly ash on CEM I 52.5N Portland cement was studied. Chemical composition was determined using an X-Max spectrometer; mineralogical composition was studied using a Rigaku MiniFlex 600 X-ray diffractometer. The effect of ash was assessed according to AZS EN

196. Compressive strength was tested on a UTEST hydraulic press. *Results.* Fly ash has elevated contents of CaO, Na₂O, K₂O, P₂O₅, SO₃ and Cl⁻. According to XRD, it contains calcite, portlandite, lime, anhydrite, dicalcium silicate, quartz, halite, sylvite, ferrian sanidine, and an X-ray amorphous aluminosilicate phase. The addition of 1–5% ash does not change normal density, but 28-day strength decreases by 20.1–32.4%. At 10–20% ash, strength decreases by more than one third; at 30%, twofold. Combined use of ash with zeolite rock from the Aydag deposit promotes neutralization of undesirable impurities and heavy metals. The optimal total content of the complex additive is 10–15% (5–7.5% ash and 5–7.5% zeolite), at which strength reduction is moderate and does not exceed 23–24% relative to the unified control. *Conclusions.* Fly ash can be used as a mineral additive in Portland cement mainly in low doses or combined with zeolite rock. The addition of ash changes hydration and hydrolysis processes, promotes formation of a denser modified cement stone structure, ensures immobilization of heavy metals, and reduces consumption of natural raw materials. High doses of ash (20–30%) are not recommended because of significant strength loss. Fly ash, not bottom ash, was studied. Future research should focus on long-term durability and optimization of the ash-to-zeolite ratio for industrial applications.

Key words: fly ash, Portland cement, pozzolanic activity, mineral additives, zeolite rock, cement hydration

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©Гувалов А.А.¹, Агазаде М.Е.¹, Ибраимбаева Г.Б.^{2,3*}, Станевич В.Т.⁴,
Вышарь О.В.⁴, 2026.

¹Әзербайжан сәулет және құрылыс университеті, Баку, Әзербайжан;

²Халықаралық білім беру корпорациясы, Алматы, Қазақстан;

³Қазақ бас сәулет-құрылыс академиясы, Алматы, Қазақстан;

⁴Торайғыров университеті, Павлодар, Қазақстан.

*E-mail: gulnazik1971@mail.ru

ТҰРМЫСТЫҚ ҚАЛДЫҚТАРДЫ ЖАҒУ НӘТИЖЕСІНДЕ АЛЫНҒАН КҮЛДІ МИНЕРАЛДЫҚ ҚОСПА РЕТІНДЕ ЗЕРТТЕУ

Гувалов Аббас — техника ғылымдарының докторы, профессор, Әзербайжан сәулет және құрылыс университеті, Баку, Әзербайжан,

E-mail: abbas-guvalov@mail.ru, <https://orcid.org/0000-0003-0189-1848>;

Агазаде Махира — PhD докторант, Әзербайжан сәулет және құрылыс университеті, Баку, Әзербайжан,

E-mail: aghazada.m@mail.ru, <https://orcid.org/0000-0001-9957-4116>;

Ибраимбаева Гульназ — техника ғылымдарының кандидаты, профессор, Халықаралық білім беру корпорациясы (Қазақ бас сәулет-құрылыс академиясы), Алматы, Қазақстан, E-mail: gulnazik1971@mail.ru, <https://orcid.org/0000-0002-4778-5664>;

Станевич Виктор — техника ғылымдарының кандидаты, профессор, Торайғыров университеті, Павлодар, Қазақстан, E-mail: svt_18@mail.ru, <https://orcid.org/0000-0002-7581-2658>;

Вышарь Ольга — PhD, қауымдастырылған профессор, Торайғыров университеті, Павлодар, Қазақстан, E-mail: lelya.stn@mail.ru, <https://orsid.org/0000-0002-7726-8393>.

Аннотация. *Өзектілігі.* Тұрмыстық қалдықтарды жағу кәсіпорындарында алынған күл – құрылыс материалдарында кеңінен қолданылатын техногендік ресурс. Оны кәдеге жарату экологиялық жүктемені азайтады, материалдардың қасиеттерін жақсартады және табиғи шикізатты үнемдейді. *Мақсат.* Экологиялық жүктемені азайту үшін тұрмыстық қалдықтарды жағудан шыққан ұшпа күлді портландцементке минералдық қоспа ретінде пайдалану мүмкіндіктерін бағалау. *Әдістері.* Ұшпа күлдің СЕМ I 52.5N портландцементінің қасиеттеріне әсері зерттелді. Химиялық құрамы X-Мах спектрометрімен, минералогиялық құрамы Rigaku MiniFlex 600 рентгендік дифрактометрімен анықталды. Күлдің әсері AZS EN 196 стандартының талаптарына сәйкес бағаланды. Үлгілердің беріктігі UTEST гидравликалық прессінде сыналды. *Нәтижелер.* Ұшпа күлдің құрамында CaO, Na₂O, K₂O, P₂O₅, SO₃ және Cl⁻ мөлшері жоғары. РФА деректері бойынша күлде кальцит, портландит, известь, ангидрит, екікальцийлі силикат, кварц, галит, сильвит, ферриан санидин және рентгеноаморфты алюмосиликатты фаза бар. 1–5% күл қосқанда қалыпты тығыздық өзгермейді, бірақ 28 тәуліктік беріктік 20,1–32,4%-ға төмендейді. 10–20% күл қосқанда беріктік үштен бір бөліктен астам, ал 30% кезінде шамамен екі есе төмендейді. Күлді Айдаг кен орнының цеолиттік жынысымен бірге қолдану қажетсіз қоспалар мен ауыр металдарды бейтараптандыруға ықпал етеді. Кешенді қоспаның оңтайлы жалпы мөлшері 10–15% (5–7,5% күл және 5–7,5% цеолит), бұл кезде беріктіктің төмендеуі қалыпты деңгейде және біртұтас бақылауға қатысты 23–24%-дан аспайды. *Қорытындылар.* Ұшпа күлді портландцементке минералдық қоспа ретінде негізінен аз мөлшерде немесе цеолиттік жыныспен бірге қолдануға болады. Күл қосу гидратация және гидролиз процестерін өзгертіп, цемент тасының тығыз модификацияланған құрылымының қалыптасуына ықпал етеді, ауыр металдарды иммобилизациялауды қамтамасыз етеді және табиғи шикізат шығынын азайтады. Күлдің жоғары дозалары (20–30%) беріктіктің айтарлықтай төмендеуіне байланысты ұсынылмайды. Зерттеу нысаны – ұшпа күл, төменгі күл емес.

Түйін сөздер: ұшпа күл, портландцемент, пуццоландық белсенділік, минералды қоспалар, цеолиттік жыныс, цемент гидратациясы

©Гувалов А.А.¹, Агазаде М.Е.¹, Ибраимбаева Г.Б.^{2,3*}, Станевич В.Т.⁴,
Вышарь О.В.⁴, 2026.

¹Азербайджанский архитектурно-строительный университет,
Баку, Азербайджан;

²Международная образовательная корпорация, Алматы, Казахстан;

³Казахская головная архитектурно-строительная академия,
Алматы, Казахстан;

⁴Торайгыров университет, Павлодар, Казахстан.

*E-mail: gulnazik1971@mail.ru

ИССЛЕДОВАНИЕ ЗОЛЫ, ПОЛУЧЕННОЙ ПРИ СЖИГАНИИ БЫТОВЫХ ОТХОДОВ, В КАЧЕСТВЕ МИНЕРАЛЬНОЙ ДОБАВКИ

Гувалов Аббас — доктор технических наук, профессор, Азербайджанский архитектурно-строительный университет, Баку, Азербайджан,

E-mail: abbas-guvalov@mail.ru, <https://orcid.org/0000-0003-0189-1848>;

Агазаде Махира — докторант PhD, Азербайджанский архитектурно-строительный университет, Баку, Азербайджан,

E-mail: aghazada.m@mail.ru, <https://orcid.org/0000-0001-9957-4116>;

Ибраимбаева Гульназ — кандидат технических наук, профессор, Международная образовательная корпорация (Казахская головная архитектурно-строительная академия), Алматы, Казахстан,

E-mail: gulnazik1971@mail.ru, <https://orcid.org/0000-0002-4778-5664>;

Станевич Виктор — кандидат технических наук, профессор, Торайгыров университет, Павлодар, Казахстан,

E-mail: svt_18@mail.ru, <https://orcid.org/0000-0002-7581-2658>;

Вышарь Ольга — PhD, ассоциированный профессор, Торайгыров университет, Павлодар, Казахстан,

E-mail: lelya.stn@mail.ru, <https://orsid.org/0000-0002-7726-8393>.

Аннотация. *Актуальность.* Зола, образующаяся при сжигании твердых бытовых отходов, представляет собой потенциальный техногенный ресурс для производства строительных материалов. Ее использование в качестве минеральной добавки может способствовать снижению экологической нагрузки, рациональному использованию отходов и сокращению потребления природного сырья. Вместе с тем эффективность применения такой золы определяется ее химическим и минералогическим составом, содержанием нежелательных примесей и влиянием на физико-механические свойства цементных материалов. *Цель.* Оценить возможность использования золы-уноса, образующейся при сжигании твердых бытовых отходов, в качестве минеральной добавки к портландцементу для снижения экологической нагрузки и рационального использования вторичных ресурсов. *Методы.* Исследовано влияние золы-уноса на свойства портландцемента класса прочности СЕМ I 52,5 N. Химический состав золы определяли с использованием спектрометра X-Max, а минералогический состав - методом рентгенофазового анализа на дифрактометре Rigaku MiniFlex

600. Оценку влияния добавки на физико-механические характеристики цементных материалов проводили с применением методов испытаний, предусмотренных серией стандартов AZS EN 196. Прочность при сжатии определяли с использованием гидравлического пресса UTEST. *Результаты.* Установлено, что исследуемая зола-унос характеризуется повышенным содержанием CaO, Na₂O, K₂O, P₂O₅, SO₃ и хлоридов. По результатам рентгенофазового анализа в ее составе выявлены кальцит, портландит, известь, ангидрит, двухкальциевый силикат, кварц, галит, силлит, ферриансанидин и рентгеноаморфная алюмосиликатная фаза. Введение 1–5 % золы практически не влияет на нормальную плотность цементного теста, однако приводит к снижению прочности при сжатии в возрасте 28 суток на 20,1–32,4 %. При увеличении содержания золы до 10–20 % снижение прочности превышает одну треть относительно контрольного состава, а при дозировке 30 % прочность уменьшается приблизительно вдвое. Совместное использование золы-уноса с цеолитовой породой Айдагского месторождения способствует снижению негативного влияния нежелательных примесей и потенциальной иммобилизации тяжелых металлов. Оптимальное суммарное содержание комплексной минеральной добавки составляет 10–15 %, при этом доля каждого компонента - золы-уноса и цеолитовой породы - находится в пределах 5–7,5 %. При указанных соотношениях снижение прочности по сравнению с контрольным составом не превышает 23–24 %. *Выводы.* Результаты исследования свидетельствуют о возможности использования золы-уноса от сжигания твердых бытовых отходов в качестве минеральной добавки к портландцементу преимущественно в небольших количествах либо в сочетании с природной цеолитовой породой. Введение золы влияет на процессы гидратации цемента и формирование структуры цементного камня. Применение комплексной добавки может способствовать снижению негативного воздействия отдельных примесей и сокращению потребления природного сырья. При этом высокие дозировки золы-уноса (20–30 %) не рекомендуются вследствие существенного снижения прочности цементных материалов. Полученные результаты относятся к золе-уносу и не могут быть непосредственно распространены на донную золу, образующуюся при сжигании бытовых отходов.

Ключевые слова: зола-унос, портландцемент, пуццолановая активность, минеральные добавки, цеолитовая порода, гидратация цемента

Introduction. In conditions of intensive growth of household waste volumes, one of the most urgent environmental and technological tasks is their efficient processing and disposal. A significant part of solid household waste is subjected to heat treatment at incinerators, which significantly reduces the volume of waste and reduces the load on landfills. However, a large amount of ash is generated during incineration, requiring further processing or safe storage. The accumulation of

ash is a potential environmental hazard due to the content of various mineral and chemical compounds in it.

One of the promising ways to solve this problem is the use of ash in the construction industry as a mineral additive. The use of man-made waste in the production of building materials contributes to the rational use of natural resources, reducing the cost of production and reducing the negative impact on the environment. Of particular interest is the possibility of using ash in the production of cement compositions, since the active mineral components contained in it can affect the hydration processes and the formation of the cement stone structure.

Modern research shows that the ash formed during the incineration of household waste may have pozzolan and mineralizing properties that enhance the performance of building materials. However, the presence of soluble salts and other undesirable impurities in its composition requires a detailed study of the chemical and mineralogical composition, as well as an assessment of the effect of ash on the physico-mechanical properties of cement systems.

In this regard, it is relevant to study the possibility of using ash from the incineration of household waste as an independent or complex mineral additive in the composition of Portland cement. The use of such waste will simultaneously solve the tasks of resource conservation, increasing the efficiency of waste disposal and improving the properties of building materials.

Currently, energy saving in the field of building materials, efficient use of natural rocks using technogenic waste, development of efficient composition of composite adhesives based on natural and artificial mineral components, use of energy of technogenic processes and achieving application of wastes obtained as a result of it in production are considered to be relevant research (Shishakina, 2019; Razakova et al., 2020; Guvalov, 2018.; Kazybayeva et al., 2014; Klinkov, 2010; Larionov, 2009; Klinkov, 2015).

Since the ecologically clean raw material base in the building materials industry is limited, at the same time, in order to prevent environmental pollution, it is advisable to attract less ecologically clean, i.e. naturally polluted raw material sources, on the one hand, and raw material resources for recycling – production and consumption wastes – to this field in order to prevent environmental pollution (Sarmiento, 2019).

The organization of efficient utilization of technogenic wastes, depending on the degree of harmfulness of their composition, is one of the most important issues in both ecological and economic terms, as a partial solution to the problems of eliminating some threats to human life and the environment. Considering that the reserves of sufficiently pure natural raw materials are limited and constantly decreasing, the production of environmentally safe construction materials from naturally polluted sources and technogenic waste is a promising direction in the construction materials industry in terms of expanding the raw material base, reducing the cost of construction products, and preventing the increase in the

volume of newly generated and existing waste (Dzhabbarova, 2020; Aryngazin, 2018; Tekenov et al., 2017; Spanov et al., 2019; Samuseva, 2009; Guvalov, 2018).

The solution to the problem of obtaining environmentally safe construction materials through the use of natural and technogenic raw materials is possible with the implementation of complex measures and a systematic approach, including the stabilization of heavy metals in the presence of high concentrations, their chemical bonding with poorly soluble compounds, or their blocking in the structure of construction materials. Taking into account the above, the direction of the current research work is to find an effective field of application of ashes obtained at the Baku municipal waste plant.

Materials and Methods. CEM I-52.5N Portland cement imported from the Holcim cement plant located in Garadagh district was used for the research. The chemical and mineralogical compositions, setting time and normal density of the cement are given in Table 1-3.

Table 1. Chemical composition of CEM I - 52.5N cement, %.

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	R ₂ O	loss in incandescent light
22.9	4.8	4.4	65.22	1.4	3.2	0.62	0.2

Table 2. Mineralogical composition of of CEM I - 52.5N cement, %.

C ₃ S	C ₂ S	C ₃ A	C ₄ AF
70.7	9.4	5.5	11.5

A large amount of ash is generated every year at the municipal waste incineration plant in Baku. In accordance with the topic of the research work, the composition of the ash was determined using physicochemical analysis methods. The composition of the samples was carried out at the Analytical Center of the Institute of Geology and Geophysics of the Azerbaijan National Academy of Sciences using modern physicochemical methods. Chemical analyses were checked using a Spectrometer (X-Max). Mineralogical composition was checked using an X-ray diffractometer (Rigaku MiniFlex 600). The chemical composition of the ashes is given in Table 3.

Table 3. Chemical analysis of ash from the municipal waste incineration.

Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	SO ₃	K ₂ O	CaO	Fe ₂ O ₃	Cl-	loss in incandescent light (LIL)
6.47	1.32	1.50	5.64	7.01	1.49	6.40	34.25	0.65	0.60	13.99

Note: LIL indicates the amount of volatile components at a temperature of 950°C.

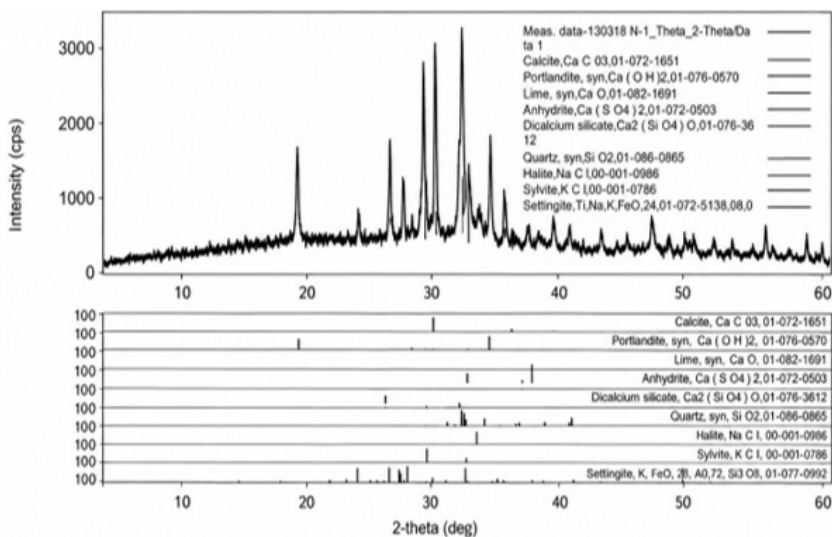


Figure 1. X-ray diffraction pattern of the initial fly ash (sample 130318 N-1). Designations: C – calcite (CaCO_3), P – portlandite ($\text{Ca}(\text{OH})_2$), L – lime (CaO), A – anhydrite (CaSO_4), D – dicalcium silicate (Ca_2SiO_4), Q – quartz (SiO_2), H – halite (NaCl), S – sylvite (KCl), F – ferrian sanidine ($\text{KFe}_{0.28}\text{Al}_{0.72}\text{Si}_3\text{O}_8$). The abscissa is 2θ (deg), the ordinate is intensity (cps).

The mineralogical composition of the initial fly ash was determined by X-ray diffraction using a Rigaku MiniFlex 600 diffractometer. The diffraction pattern of the initial fly ash is presented in Figure 1. According to XRD data, the main crystalline phases identified in the ash are: calcite (CaCO_3), portlandite ($\text{Ca}(\text{OH})_2$), lime (CaO), anhydrite (CaSO_4), dicalcium silicate (Ca_2SiO_4), quartz (SiO_2), halite (NaCl), sylvite (KCl), and ferrian sanidine ($\text{KFe}_{0.28}\text{Al}_{0.72}\text{Si}_3\text{O}_8$). In the range of $20\text{--}35^\circ 2\theta$, a broad halo is observed, which indicates the presence of an X-ray amorphous aluminosilicate (glassy) phase. The presence of soluble chlorides (halite, sylvite), sulfates (anhydrite) and free lime determines the mineralizing and accelerating effect of the ash on cement systems, while the amorphous aluminosilicate phase provides pozzolanic activity.

Imishli river sand was used as a filler for the preparation of solutions.

Ashes brought from the Baku municipal waste incineration plant were dried in a drying cabinet to 1%. Dried ashes were ground to cement fineness in a 3-liter ball mill. The grinding fineness of the ashes was determined by the residue remaining on the 008 N° sieve.

The effect of ash on Portland cement was carried out in accordance with the requirements of the AZS EN 196 standard.

Cement paste was prepared from the composition obtained on the basis of the cement ash mixture, first its normal density and then the setting time were determined.

Samples of $20 \times 20 \times 20 \text{ mm}$ in size were prepared on the basis of the normal

density cement paste and their compressive strengths were tested at 3, 7, and 28 days. The test was carried out on a hydraulic press belonging to the UTEST company.

Phase analyses of the samples were carried out in an X-ray apparatus at the Analytical Center of the Institute of Geology and Geophysics of the Azerbaijan National Academy of Sciences. The mineralogical composition was checked using an X-ray diffractometer (Rigaku MiniFlex 600).

Results and Discussions. The activity of minerals was carried out according to GOST No. 21-9-81. In accordance with the requirements of the standard, the setting time, water resistance and the degree of saturation of the liquid phase with calcium oxide of samples prepared from zeolite rock brought from the Aydag deposit and ash obtained from the incineration of household waste were determined. In this work, fly ash (FA) captured in the gas-cleaning system of the Baku municipal waste incineration plant was studied.

For this, one part of the samples obtained from mixing air-hardening lime and ash was used to determine the setting time, and the other part was used to check the water resistance. The results of the experiment are shown in Table 4.

Table 4. Zeolite rock and ash activities.

N°	Test name	Unit of measure	Standard requirement	Zeolite rock	Ash
				Test results	
1	End of setting of the dough sample	day	7 should be too many	4	3.5
2	Water resistance of dough samples	gün	Must be less than 3	17	12
3	The amount of lime absorbed from the solution after 30 days	mq/q		80	50

As can be seen from the table, both samples fully meet the requirements for mineral active additives, but zeolite rock gives better results than ash. The results of the study show that both additives can be used as mineral additives in the production of Portland cement. It is worth noting that both additives can be used in the production of clinker-free adhesives and, accordingly, in the production of low-grade lime-slaked compositions.

Comparative tests were conducted with natural mineral additives to study the feasibility of using ash obtained as a result of household waste incineration in the production of Portland cement, which is one of the main directions of utilization.

In order to determine the role of ash from the Baku household waste incineration plant as a mineral active additive in Portland cement, zeolite rock was used in parallel as a mineral additive, and Garadagh limestone was used as a mineral additive. The chemical composition of the zeolite rock brought from the Aydag deposit of the Tovuz region is given in Table 5.

Table 5. Chemical composition of zeolite rock

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	R_2O
69.42	13.6	1.55	3.18	0.89	0.14	7.9

Limestone powder brought from the Gulbakh quarry in the Garadagh region was also used in the studies as a mineral additive, the chemical composition of which is given in Table 6.

Table 6. Chemical composition of limestone.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	R_2O
8.42	0.36	0.21	49.25	0.61	0.24	-

To study the effect of zeolite rock on cement, both separately and in combination with limestone, CEM I-52.5 cement from the HOCIM plant was used. The results of the experiment are given in Table 7.

Table 7. The effect of zeolite rock on Portland cement.

N°	Composition, %		Normal density, %	Compressive strength limit, (day), MPa			
	CEM I -52,5	Zeolite rock		1	2	7	28
1	100	0	28	26.0	37.2	49.1	62.5
2	93	7	29.7	16.3	28.2	39.8	50.6
3	80	20	31.4	12.3	27.5	33.0	42.8
4	75	25	32	11.4	19.5	30.1	40.8
5	70	30	32.1	11.3	18.7	29.0	39.9
6	65	35	32.8	6.3	13.8	25.1	35.2

As can be seen from Table 7, as the amount of zeolite rock increases from 7% to 35%, the normal density of Portland cement increases from 28% to 32.8%. While the normal density of Portland cement obtained when adding 20% of zeolite rock increases by 12%, when adding 35% of zeolite rock, the cement grade decreases by 17%. When the amount of zeolite rock increases to 30%, the one-day strength of cement decreases from 26 MPa to 16.3-11.3 MPa, when the amount of zeolite rock increases to 35%, the strength changes sharply and is only 6.3 MPa. When the amount of zeolite rock is 7%, the brand of Portland cement obtained is 50.6 MPa. When the amount of zeolite rock is 20%, the cement grade strength is 42.8 MPa, i.e. it decreases by 31.5%. When the amount of zeolite rock is increased to 35%, the cement's brand strength decreases to 43.7%.

Garadagh limestone powder was used as a mineral additive to replace a certain amount of zeolite rock. 4-17% of the zeolite rock content was replaced with limestone powder. The test results of the cement obtained as a result of the complex addition of zeolite rock and limestone are given in table 8.

Table 8. Effect of zeolite rock and limestone complex additive on cement properties.

N°	Composition, %			Normal density, %	Compressive strength limit, (day), MPa			
	CEM I -52,5	Zeolite rock	Limestone		1	2	7	28
1	83	13	4	27.6	11.9	23.2	34.6	46.3
2	77	15	8	26.4	9.1	20.1	31.6	43.4
3	70	17	13	27.0	6.9	15.4	24.9	34.1
4	65	18	17	27.4	5.9	14.3	22.7	30.5

When adding limestone, the normal density of cement decreases slightly. When adding zeolite rock and limestone in an amount of 20-23%, the decrease in strength is 30.6%. This shows a good result compared to zeolite alone. However, when adding 30-35% of complex additives, the brand strength of cement decreases significantly and is 30.5 MPa.

The effect of ash obtained from the incineration of household waste on the properties of Portland cement is given in table 9.

Table 9. Effect of ash from municipal waste incineration on cement properties.

№	Composition,%		Normal density, %	Strength limit, (day), MPa				Relative compressive strength at 28 days to the unified control, %
	CEM I -52,5	Ash, %		bending		compression		
				1	28	1	28	
1	100	0	28.5	4.00	14.55	44.28	67.27	88.8
2	99	1	28.5	3.96	10.27	49.56	60.52	79.9
3	98	2	28.5	3.54	6.27	46.36	58.00	76.6
4	97	3	28.5	3.44	6.27	36.22	53.61	70.8
5	95	5	29.0	3.12	6.01	30.15	51.21	67.6
6	90	10	29.0	3.74	5.37	24.08	46.34	61.2
7	85	15	29.0	3.87	5.76	22.22	45.29	59.8
8	80	20	29.0	3.23	5.39	17.72	41.58	54.9
9	70	30	29.0	2.94	4.03	13.01	35.71	47.1

As can be seen from Table 9, when ash is added to cement as a mineral additive in an amount of up to 3%, the normal density does not change. However, when the ash content increases above 5%, the normal density increases slightly. When adding 1–5%, the 28-day strength relative to the unified control decreases to 89.96–76.13% (a decrease of 10.04–23.87%). When increasing the ash content to 20%, the relative strength decreases to 61.81–68.89% (a decrease of 31.11–38.19%). However, when increasing the ash content to 30%, the strength decreases to 53.08% (approximately by a factor of two). When adding 1–2% ash, the 1-day strength of cement increases by 5–10% relative to the unified control. This is due to the presence of electrolytes in the ash that accelerate setting.

Comparison of ash with zeolite rock showed that at low doses, both components act as mineral additives, and their effects on the strength of cement are close to each other. When the amount of ash is increased, the various admixtures in it

negatively affect the strength of the cement, so the results are lower than in the case of zeolite rock.

In order to neutralize the heavy metals contained in the ash and mitigate its effect on strength, the effect of both components on Portland cement in composite form was studied using the zeolite-containing component, which is the rock of the Aydag deposit. The results of the effect of ash obtained from the incineration of household waste on the properties of Portland cement in a complex form are given in Table 10.

Table 10. Effect of ash and zeolite complex additive on cement properties.

No	Composition, %			Normal density, %	Strength limit, (day), MPa				Relative compressive strength at 28 days to the unified control, %
	CEM I -52,5	Ash	ending		bending		compression		
					1	28	1	28	
1	100	0	0	28.5	4.16	15.73	42.68	67.27	100
2	95	2.5	2.5	28.5	4.64	9.49	36.02	56.18	83.5
3	90	5	5	28.5	4.39	11.60	36.78	54.72	81.3
4	85	7.5	7.5	29.0	3.55	11.06	35.54	51.61	76.7
5	80	10	10	29.5	4.00	8.12	47.43	51.13	76.0
6	70	15	15	30.5	3.67	5.99	25.39	51.73	76.9

The control compositions in Tables 9 and 10 belong to different experimental series. Their absolute 28-day compressive strengths (67.27 MPa and 75.76 MPa, respectively) are therefore not compared directly. For correct comparison, relative strength values should be used.

As can be seen from Table 10, when the components are added in a complex form up to 15%, the brand strength of Portland cement decreases to 83.5–76.9% relative to the unified control (a decrease of 16.5–23.1%). When the components are added by 20–30%, the 28-day strength limit of Portland cement decreases by 31.52–36.16% relative to the control of this series. Comparison of Tables 9 and 10 showed that the decrease in the strength of Portland cement is somewhat smaller when the ash is added together with zeolite rock. This is explained by the formation of additional cementing compounds as a result of the activating effect of the electrolytes included in the ash on the zeolite.

During the research, samples hardened for 28 days were taken and the changes in the microstructure of the cement stone were determined using modern testing methods in the central testing laboratory of the Azerbaijan National Academy of Sciences.

In order to determine the changes in the structure and phase composition of the cement stone as a result of the addition of ash, research was conducted using X-ray phase analysis and electron microscopy methods. During the research, X-ray phase (Figure 2-5) and microscopic (Figure 6) analyses of cement stones prepared without additives, with 10%, 20%, 30% ash addition were conducted.

The results of X-ray phase analysis showed that when ash is added to cement,

the intensity of the peaks of the portlandite mineral (4.93, 2.63, 1.93 Å) formed as a result of hydrolysis decreases. The decrease in the intensity of the peaks of alite, the main mineral of cement (3.04, 2.74 Å), indicates an increase in the intensity of the hydration process due to the influence of ash.

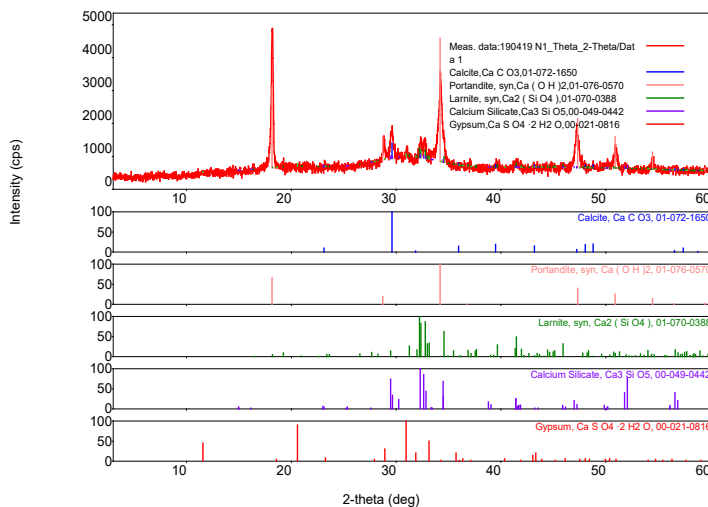


Figure 2. X-ray phase analysis of cement stone without additives.

Designations: C – calcite (CaCO₃), P – portlandite (Ca(OH)₂), L – larnite (Ca₂SiO₄), CS – calcium silicate (Ca₃SiO₅), G – gypsum (CaSO₄·2H₂O). The abscissa is 2θ (deg), the ordinate is intensity (cps).

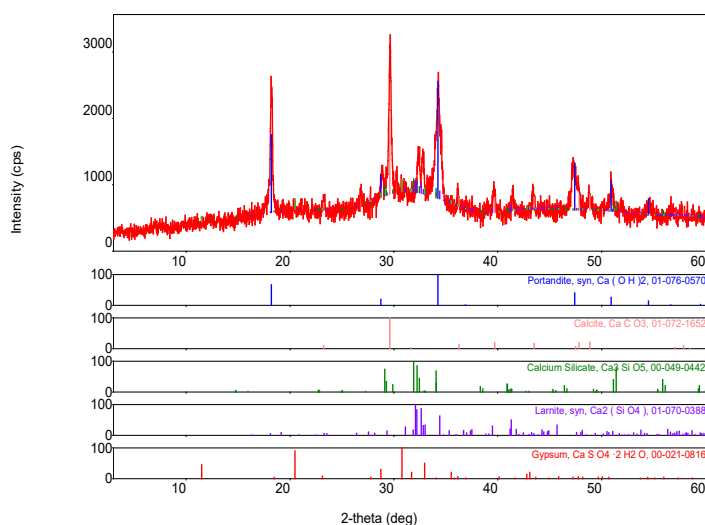


Figure 3. X-ray phase analysis of cement stone with 10% ash addition
Designations as in Figure 2.

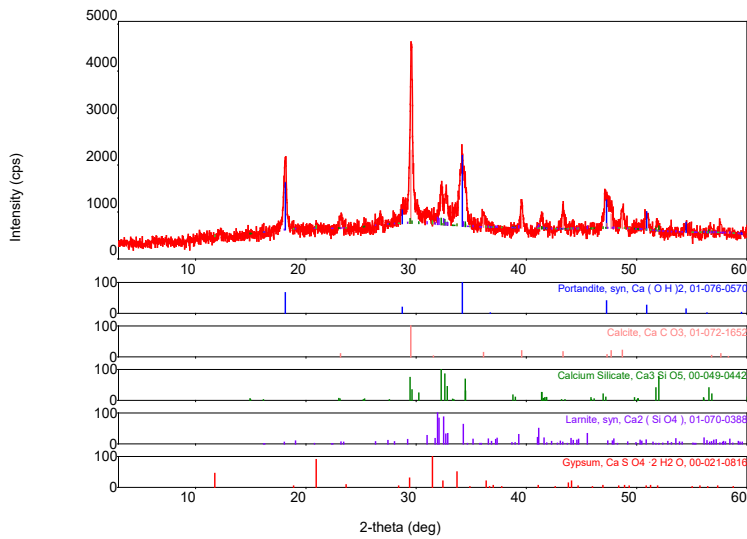


Figure 4. X-ray phase analysis of cement stone with 20% ash addition
Designations as in Figure 2.

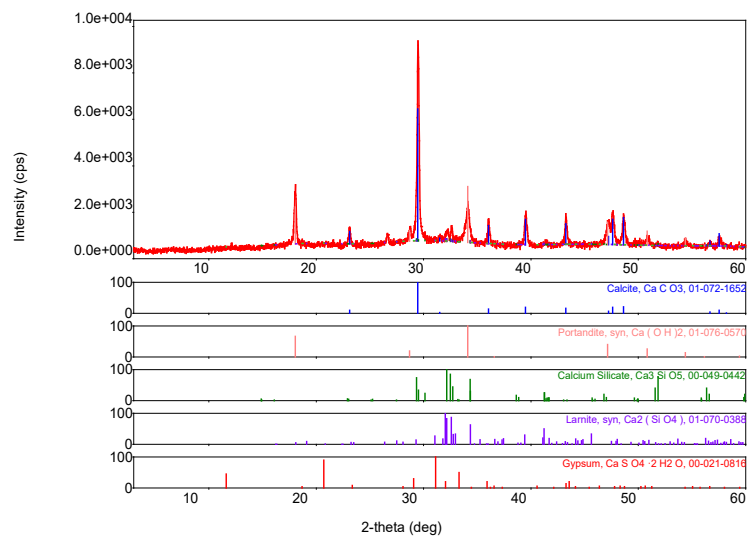


Figure 5. X-ray phase analysis of cement stone with 30% ash addition
Designations as in Figure 2.

The results of studies conducted with the addition of ash showed that the structural formation of cement changes significantly. Microstructural analysis of the samples showed that the nature of the newly formed hydrate compounds is different. Portlandite crystals are clearly visible in cement stone without additives.

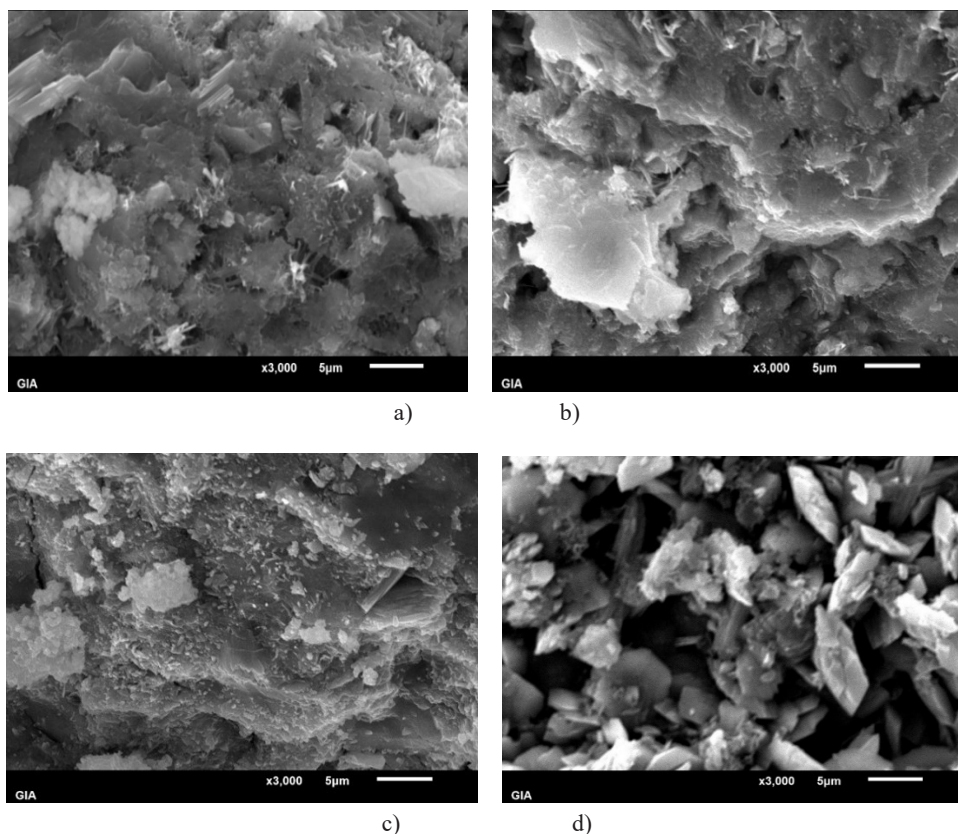


Figure 6. Microstructure of cement stone: a) microstructure of cement stone without additives; b) microstructure of cement stone with 10% ash; c) microstructure of cement stone with 20% ash; d) microstructure of cement stone with 30% ash.

Conclusion. Comprehensive studies on the use of municipal solid waste incineration ash as a mineral additive in Portland cement formulations have yielded significant results. The research focused on the structural changes and mechanical properties of cement systems modified with ash additives. Furthermore, to address environmental concerns related to the presence of heavy metals in the ash and mitigate their negative impact on strength development, the effect of using a zeolite-containing component from the Aydag deposit as a complex additive along with the ash was investigated.

According to X-ray diffraction data, the initial fly ash contains calcite, portlandite, lime, anhydrite, dicalcium silicate, quartz, halite, sylvite, ferrian sanidine, and an X-ray amorphous aluminosilicate phase. The presence of soluble chlorides and sulfates determines the accelerating and mineralizing effect of the ash, while the amorphous aluminosilicate phase provides its pozzolanic activity. This combination explains both the acceleration of setting at low ash doses and the decrease in strength at high ash doses.

With the addition of 10% ash to the cement formulation, significant

microstructural changes are observed. The amount of portlandite crystals significantly decreases, while the amount of softwood calcium silicate hydroxides (C-S-H phases) increases, creating a more interconnected microstructure. With an ash content increasing to 20%, portlandite crystals almost completely disappear, indicating their consumption in pozzolanic reactions, resulting in the formation of a dense, well-packed cement paste. However, with an increase in ash content to 30%, unreacted ash particles are observed, which act as microfillers in the systems.

Experimental results showed that adding ash along with zeolite rock results in a slightly smaller reduction in strength compared to using ash alone. This phenomenon is explained by the formation of additional cementitious compounds due to the activating effect of electrolytes present in the ash on the zeolite.

The neutralizing effect of zeolite on heavy metals contained in ash is particularly important. Zeolite minerals adsorb and immobilize heavy metal ions through ion exchange and physical entrapment within their channel structures, preventing their release into the environment and ensuring the environmental safety of building materials. Furthermore, the alkaline environment created by cement hydration, combined with soluble salts present in the ash, can partially activate the surface of zeolite particles, releasing additional silica and alumina, which participate in pozzolanic reactions.

The optimal total additive content for achieving balanced properties is in the range of 10-15% (5-7.5% ash and zeolite each), where the strength reduction is moderate while maintaining the environmental benefits of heavy metal immobilization. At these levels, the complex additive promotes a more uniform and dense microstructure with improved durability. The normal consistency of cement pastes increased slightly with increasing additive content, from 28.5% for the reference sample to 30.5% for the composition with 30% total additive.

It should be emphasized that high doses of ash (20–30%) are not recommended for use as a mineral additive in Portland cement, since the 28-day compressive strength decreases by more than one third and at 30% ash — by approximately a factor of two relative to the unified control. Thus, fly ash should be used either in low doses (1–5%) or as part of a complex additive with zeolite rock (total content 10–15%).

Thus, the conducted studies convincingly demonstrated that ash obtained from municipal waste incineration can be effectively used as a mineral additive in Portland cement, especially when combined with zeolite-containing rock from the Aydag deposit. The complex additive offers a number of advantages: sustainable waste management, reduced need for primary raw materials, effective neutralization and immobilization of heavy metals by the zeolite, and the formation of additional cementitious compounds due to the activating effect. An optimal substitution level of 10-15% provides the best balance between mechanical properties, environmental safety, and economic benefits. Future research should focus on long-term durability and optimization of the ash-to-zeolite ratio for industrial applications.

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