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METHODS OF HARDENING THE LAYING ARRAY AND ACOUSTIC CONTROL OF ITS STABILITY DURING UNDERGROUND MINING

Abstract. Underground excavation produces voids that must be backfilled to provide ground support. Backfilling is widely used in the underground mining industry; however, in many mines, backfill strength design is not properly considered, and detailed laboratory studies are lacking. This paper investigates backfill strength mobilization over time using acoustic emission (AE) monitoring. Cylindrical samples with binder contents of 5%, 10%, 15%, and 20% were cured for 1, 3, 7, 14, and 28 days, then tested under unconfined compression with AE monitoring. Uniaxial compressive strength (UCS) increased with curing time for all binder contents, e.g., from 0.06081 MPa (1 day) to 0.3814 MPa (28 days), about 6.5 times higher. UCS growth rates were similar (~45%) regardless of cement content.
Key words: *mining seismicity, crack propagation, microseismic monitoring system, underground mining, acoustic emission, uniaxial compression test.*

Жерасты кен орындарын игеру кезінде толтырма сілемін нығайту әдістері және оның тұрақтылығын акустикалық бақылау

Аңдатпа. Жер асты қазбаларында бос жерлер пайда болады, олар жерге қолдау көрсету үшін қайта толтырылуы керек. Толтыру жерасты тау-кен өнеркәсібінде кеңінен қолданылады; дегенмен, көптеген шахталарда толтыру беріктігінің конструкциясы дұрыс қарастырылмаған және егжей-тегжейлі зертханалық зерттеулер жетіспейді. Бұл мақалада акустикалық эмиссия (АЕ) мониторингін қолдана отырып, уақыт өте келе толтырғыштардың беріктігін жұмылдыру зерттеледі. Құрамында 5%, 10%, 15% және 20% байланыстырғыштары бар цилиндрлік үлгілер 1, 3, 7, 14 және 28 күн бойы өңделді, содан кейін АЕ бақылауымен шексіз қысу жағдайында сыналды. Бір осьті қысу беріктігі (UCS) байланыстырғыштың барлық мазмұнын өңдеу уақытымен бірге өсті, мысалы, 0,06081 Мпа-дан (1 күн) 0,3814 Мпа-ға (28 күн) дейін, бұл шамамен 6,5 есе жоғары. UCS өсу қарқыны цемент құрамына қарамастан ұқсас болды (~45%).
Түйінді сөздер: *тау-кен сейсмикасы, жарықшақтардың таралуы, микросейсмикалық бақылау жүйесі, жерасты тау-кен жұмыстары, акустикалық эмиссия, бір осьті қысу сынағы.*

Методы упрочнения закладочного массива и акустический контроль его устойчивости при подземной разработке месторождений

Аннотация. При проведении подземных выработок образуются пустоты, которые необходимо засыпать для обеспечения опоры грунта. Засыпка широко используется в горнодобывающей промышленности подземным способом; однако на многих шахтах расчет прочности засыпки не проводится должным образом, а подробные лабораторные исследования отсутствуют. В данной статье исследуется повышение прочности засыпки с течением времени с помощью мониторинга акустической эмиссии (АЭ). Цилиндрические образцы с содержанием связующего 5%, 10%, 15% и 20% отверждали в течение 1, 3, 7, 14 и 28 дней, затем испытывали при неограниченном сжатии с контролем АЭ. Прочность на одноосное сжатие (UCS) увеличивается со временем отверждения для всех компонентов связующего, например, с 0,06081 МПа (1 день) до 0,3814 МПа (28 дней), что примерно в 6,5 раз выше. Темпы роста ПСК были одинаковыми (~45%) независимо от содержания цемента.
Ключевые слова: *сейсмичность горных работ, распространение трещин, система микросейсмического мониторинга, подземные горные работы, акустическая эмиссия, испытание на одноосное сжатие.*

Introduction

Study on backfill strength mobilization enhance the safety conditions of workplace, since instability of mine will lead to adverse consequences. Therefore, it is important to evaluate the backfill strength properly. Outcomes of this thesis work will give suggestions for the mix-design of backfill in underground mines, which can be realized and used by mine engineers. The improvement of mine productivity will be obtained, since the results provide optimal backfill strength, which will reduce possible breakdowns. Backfill cost can be reduced by using pertinent backfill mix-design and therefore mine profits will be improved. In addition, the results of this thesis will demonstrate the importance of curing, because most mines that use backfill do not pay full attention on curing. Consequently, this research topic is relevant for the underground mining industry [1].

Methodology

A clear laboratory research plan was established to study the backfill strength mobilization. Two different experimental tests were performed, which are uniaxial compression tests and acoustic emission tests. In order to perform the above-mentioned tests several operations were carried out, such as material preparation, sample production, equipment set-up and testing process [2].

The main objective of the uniaxial compression tests was to examine the strength and deformation behaviour of pre-prepared cylindrical backfill specimens. In addition, for the strength mobilization, the effects of binder content and cure time on the strength of backfill were examined. Total 20 cylindrical backfill samples were generated with different binder content and cure time. Sand, Portland cement and water were used for preparing cylindrical backfill specimens. Four different mix-design were employed with various cement contents, which are 5%, 10%, 15% and 20%. Moreover, molded cylindrical backfill samples were cured with at different times, such as 1 day, 3 days, 7 days, 14 days and 28 days.

First of all, the necessary materials were prepared for making cylindrical backfill samples, as it was mentioned before, Portland cement CEM II / A-K (SH – I) 32.5H provided by Zhambyl Cement Plant, silty sand provided by local dealer and tap water were used.

Type II cement with mineral additives, such as slag and limestone, was chosen as binder for producing the cylindrical backfill specimens. According to GOST 10178-85, the mineralogical composition of Portland cement CEM II / A-K (SH – I) 32.5H used in this study is shown in Table 1. The required amount of cement for the production of cylindrical backfill specimens was poured into the box using a scoop.

Silty sand was dried before use in order to clean the sand from unnecessary additives, as well as provide the required moisture for sieve analysis. The sand was sprinkled on a polypropylene bag and dried naturally at room temperature conditions in two days.

Table 1
Mineralogical composition of Portland cement
Кесте 1
Портландцементтің минералогиялық құрамы
Таблица 1
Минералогический состав портландцемента

Mineral	Content, %
Tricalcium silicate or alite (C3S)	62
Dicalcium silicate or belite (C2S)	20
Tricalcium aluminate (C3A)	5
Tetracalcium aluminoferrite (C4AF)	13

Sieve analysis was applied to determine the grain size distribution of the silty sand, especially to remove the particles larger than 250 µm. Sieve analysis was carried out by vibratory sieve shaker AS 200 basic. The measuring range of the vibratory sieve shaker AS 200 basic is between 20 µm and 25 mm and the maximum mass of sieve stack is 4 kg. 1.305 kg of sand was sieved for 5 minutes in the vibratory sieve shaker.

The six sieve stacks were used to remove the oversize fragments leaving sand, silt, clay and gravel was removed by sieving.

The necessary amount of fine and medium sand for the production of cylindrical backfill samples was poured into the pan using a scoop. The calculation of particles passing can be seen in Table 2. In addition, the particle size distribution curve on the silty sand was produced and can be seen in Figure 1.

Table 2
Sieve analysis on silty sand
Кесте 2
Лайлы құмдағы електерді талдау
Таблица 2
Ситовой анализ илистого песка

Sieve		Soil Retained (g)	Accumulative Retaining (g)	% Mass Retaining	% Passing
Number	Size (mm)				
#4	4	6	6	0,459911084	99,54008892
#10	2	12	18	1,379733252	98,62026675
#20	1	6	24	1,839644335	98,16035566
#40	0,5	7,6	31,6	2,422198375	97,57780163
#60	0,25	772	803,6	61,5974245	38,4025755
#200	0,125	402	1205,6	92,41146712	7,588532884
Pan		99	1304,6		

After material preparation, the next stage of the laboratory resarch is sample production. The preparation of the cylindrical backfill specimens were carried out by mixing sand, cement and tap water. A total 25 cylindrical backfill samples were required to conduct uniaxial compression test with different cement content and different curing time. The required amount of sand, cement and tap water was calculated by ASTM C-109C standard. According to ASTM C-109C, water to cement ratio is 0.485, while sand to cement ratio is 2.75.

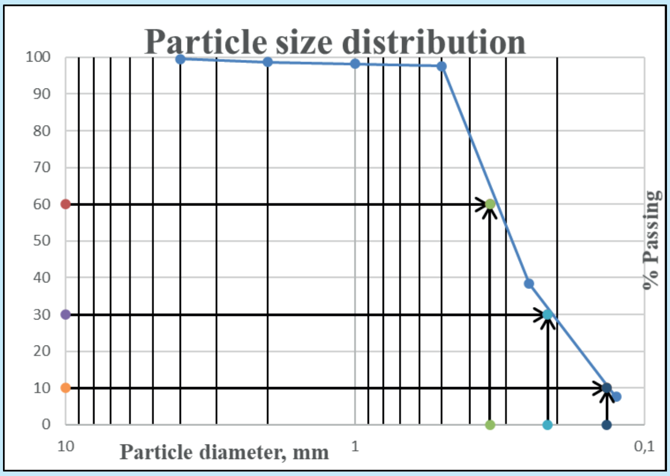

Figure 1. Particle size distribution of the silty sand.
Сурет 1. Лайлы құмның бөлшектер мөлшерінің таралуы.
Рис. 1. Гранулометрический состав илистого песка.

The materials were mixed by Benchtop Laboratory Mixer. The capacity of Benchtop Laboratory Mixer is 4.7L and it has 1/6 hp motor for mixing, which is enough for our study [3].

Preparation of slurry consisted of two stages, such as dry mixing and wet mixing. Dry mixing was performed by blending sand and cement in specified ratio for 3 minutes. After that, the specified amount of tap water was poured into the mixer to perform the wet mixing for 3 minutes. Before pouring the slurry into the cylindrical mold, they were cleaned and greased with lubricating oil on the internal parts to alleviate samples demolding. Ultimately, the slurry was poured into the cylindrical mold, which is demonstrated in Figure 2. Compaction was not applied during the preparation of backfill specimens to be close to real strength of in-situ backfill [4].

Figure 2. Casting of backfill UCS samples.
Сурет 2. UCS толтыру үлгілерін құю.
Рис. 2. Отливка образцов UCS обратной засыпки.

The cylindrical backfill samples were extruded after 8 hours and were put in the box for curing. The curing boxes were marked with cement content and day of pouring the samples. The curing of cylindrical backfill samples was held in normal conditions, such as at room temperature 200–250 °C and relative humidity 85±5%.

The dimensions of the backfill specimens were as follows: diameter 37 mm and height 76 mm. The geometry of backfill samples is appropriate to conduct the uniaxial compression test referred to ISRM standard. The standard requires height-to-diameter ratio equals between 2 and 2.5. All backfill samples were polished and ground by the GCTS RSG-200 Specimen Grinder. Sample polishing was performed to obtain smooth faces in order to diminish planetary error, which should be less 1 mm in accordance with ISRM standard. After sample grinding and polishing, the smoothness of surface was checked by absolute digimatic indicator. Finally, all backfill samples are ready to be examined by uniaxial compression test and acoustic emission monitoring [5].

For determination of uniaxial compressive strength of backfill specimens, GCTS PLT-2W Point Load Testing Device was utilized. The PLT test frame is modified to perform UCS test by replacing the point Load Pointed platens with the regular UCS test platens in accordance with the ISRM suggested methods for UCS tests. The maximum load capacity of this equipment is 100 kN. The data is collected automatically and is revealed the average strength by software connected to this equipment. This device can gauge specimen size automatically, which is convenient for experiments.

For this study, platens with diameter 43 mm and thickness 18 mm were used. The platens were fixed the of PLT equipment. The specimen was placed between the top and bottom platens. After all calibration processes, the load was applied by the hydraulic pump until the sample failed. The data was generated by embedded software to iPod and the results sent by e-mail to the tester.

SAEU3H 8-channel Integrated Acoustic Emission System was used for backfill strength monitoring study. SAEU3H 8-channel Integrated Acoustic Emission System is an acoustic emission monitoring system that is developed to evaluate and treat acoustic emission data in laboratory conditions. It is able to give measurement of acoustic emission parameters, such as threshold arrival time, ring counts, amplitude, rise counts, rise time and relative energy. Operating bandwidth of this AE system is between 30 Hz to 200 kHz and the maximum signal range is 100 dB.

Therefore, the signals coming to the sensor with or near magnitude to the resonance frequency would have a higher AE amplitude than the signals coming with large magnitude difference of the resonant frequency. The broad band of this sensor is 60 kHz-400 kHz, which permits to embrace most pertinent frequencies, which makes it the prevalent sensor. Electromagnetic isolation of shell and object under experiment happens due to ceramic material of the contact surface. The interference efficiently is mitigated by rustproof steel shell with integral protective structure. The 150 kHz resonance frequency was chosen in order to make a reduction of low frequency background obstacles. However, the high frequencies induce high levels of attenuation [6].

AE sensors transmit the voltage signals which are very weak. Inevitable reduction of strength takes place due to low voltage signals, as transferred through long distance. Therefore, the use of a preamplifier was necessary in order to make an amplification of weak waves from the sensor by 40 dB, then preamplifier will transmit signals to acquisition equipment through cable. For this research preamplifier model SAEPA2 was chosen, which is embedded with filter. Band pass filter was applied not to comprise too low and high frequency signals in the output signal. Frequency filter range was established to 20–120 kHz. Several wave modes could be covered within this frequency bandwith. Simplification of the eventual output and alleviation of the recognization of wave modes are achieved by this filtering.

Backfill strength monitoring with time was performed by acoustic emission system and Cyber-plus compression equipment, since the calibration of GCTS PLT-2W Point Load Testing Device was broken. Contingency plan was applied [7], therefore Cyber-plus evolution compression equipment was borrowed from Civil Engineering school in order to obtain data properly.

Firstly, platens with diameter 120 mm were established in pressure cell to meet the height of sample. Since all backfill samples were grinded and polished, next stage was mounting sensors on the backfill sample surface. For this study, SR150M AE sensors were used. They were mounted by hot-glue gun. Backfill sample with mounted sensors was placed in a pressure cell.

After backfill sample placement in a pressure cell, acoustic emission monitoring system was establihsed. Sensors were connected to SAEPA2 preamplifiers, while preamplifiers were connected to acoustic emission system via coaxial cables. Finally, the acoustic emission system was attached to data acquisition equipment via USB port.

After equipment and backfill sample set-up, both equipment were calibrated and sample settings were established in both equipment. The load was applied at 0.05 kN/s rate automatically by the compression equipment until the sample failed, at the same time acoustic emission system started to monitor AE parameters. Starting load of 0.05 kN was established and load was stopped manually. The data were generated by SAE AE software and Cyber-plus evolution compression equipment.

Results

Total 20 cylindrical backfill samples were examined under uniaxial compression in this laboratory tests. The cylindrical backfill samples were designated by the cement content and curing time for convenient data processing. The study shows that the uniaxial compressive strength increases with increasing curing time. For example, uniaxial compressive strength of backfill sample cured 1 day is 0.06081 MPa, while uniaxial compressive strength of backfill sample cured 28 day is 0.3814 MPa, which is almost 6.5 times higher.

Overall results reveal low UCS strength for backfill samples in comparison with other studies. There are several reasons for low UCS strength of backfill samples, such as lack of compaction during sample preparation, lack of tailing materials and curing method.

According to the laboratory experiment results, the relation curves between the uniaxial compressive strength and curing time were generated for cylindrical backfill samples with different cement content. It can be seen from Figure 3, cylindrical backfill samples with 15% cement content show larger uniaxial compressive strength than backfill samples with 15% less cement content. The uniaxial compressive strength growth rate was almost the same for all backfill samples despite cement content. The uniaxial compressive strength growth rate for backfill samples were nearly 45%.

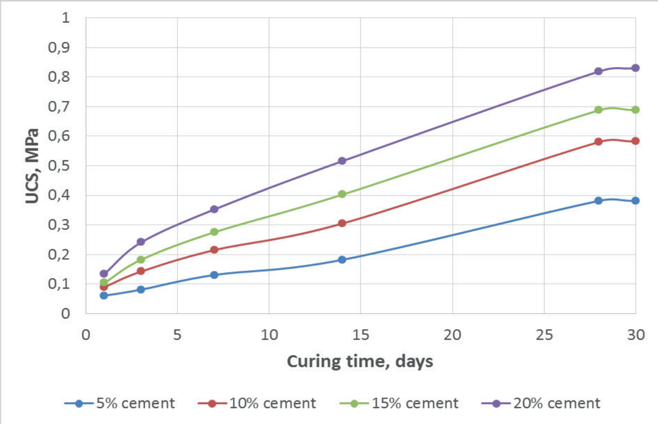

Figure 3. Backfill strength and curing time relationship.
Сурет 3. Толтырудың беріктігі мен емделу уақытының арақатынасы.
Рис. 3. Соотношение прочности засыпки и времени отверждения.

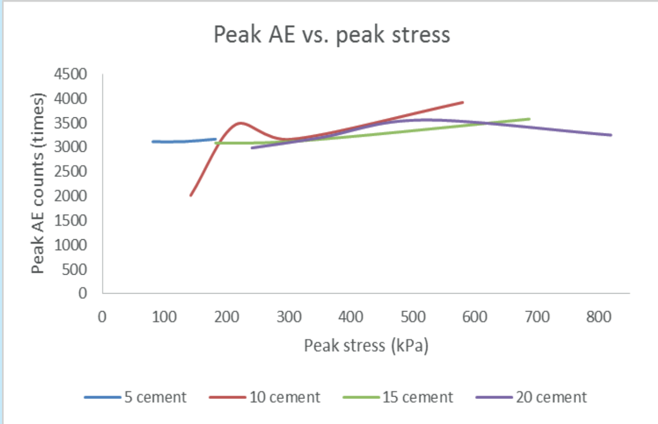

Figure 4. Peak AE counts vs. peak stress.
Сурет 4. АЕ шыңы стресстің шыңына қарсы есептеледі.
Рис. 4. Количество пиковых АЭ в зависимости от пикового напряжения.

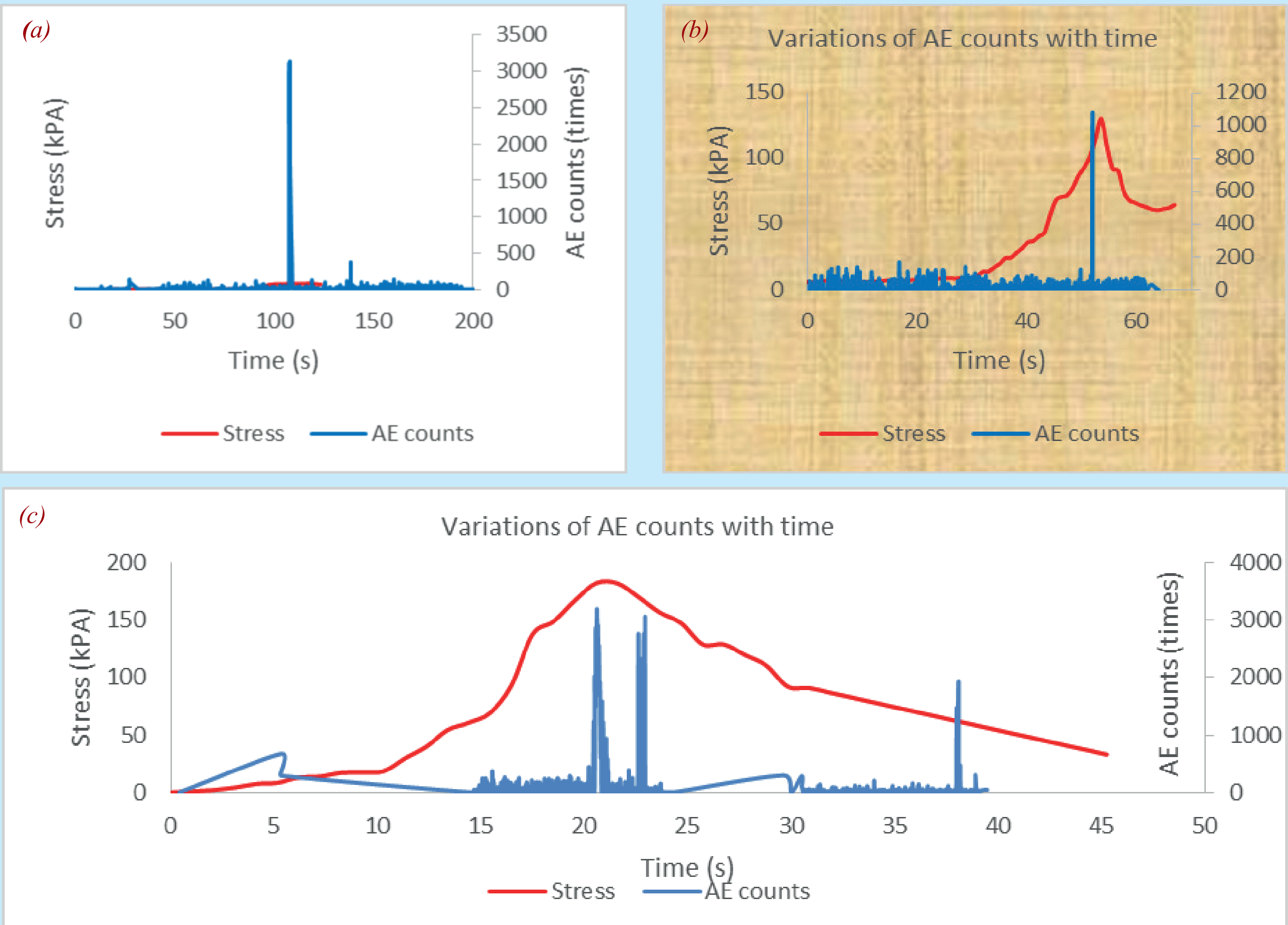

Figure 5. Variations of AE counts with time of 5% cemented backfill samples: (a) – 3 day curing; (b) – 7 days curing; (c) – 14 days curing.
Сурет 5. 5% цементтелген толтыру үлгілерінің уақытымен АЕ көрсеткіштерінің өзгеруі: (a) – 3 күндік өңдеу; (b) – 7 күндік өңдеу; (c) –14 күндік өңдеу.
Рис. 5. Изменение количества АЭ в зависимости от времени отверждения образцов с 5%-ой цементированной засыпкой: (a) – отверждение в течение 3 дней; (b) – отверждение в течение 7 дней; (c) – отверждение в течение 14 дней.

Discussion of the results

Total 15 cylindrical backfill samples with different cement content were tested under acoustic emission monitoring with the uniaxial compression in this laboratory tests. 1 day curing backfill samples were not examined since the sensors could not be mounted due to the wet surface of backfill samples. In addition, 5% backfill sample was not examined because curing time was missed according to unseen circumstances.

The maximum magnitude of AE counts is a peak count, which was registered during uniaxial compression test. The average peak counts were calculated for 5%, 10%, 15% and 20% backfill samples were calculated, and they are 2454, 3141, 3147 and 3249 respectively. Also, peak AE counts versus peak stress graph was produced, which can be seen in Figure 4.

According to [8], the acoustic signals are followed by microfractures formation and distribution, therefore indirect reflection of the fracture condition can be seen by AE counts. The small value of the AE counts show, the fewer number of brittle fractures. Therefore, backfill samples with 5% and 10% cement content have less crack number than backfill samples with 15% and 20% cement content. The most crack number was registered for backfill samples 20% cement content, since the average value of AE peak counts is 3249.

The variations of AE counts with time for various cemented backfill samples with different curing time are revealed in Figures 5–6. It can be seen from the Figures 5–6 that the peak AE count coincides with the peak stress point almost for all backfill samples.

Overall, acoustic emission monitoring test results show reliable accurate values. However, different systematic

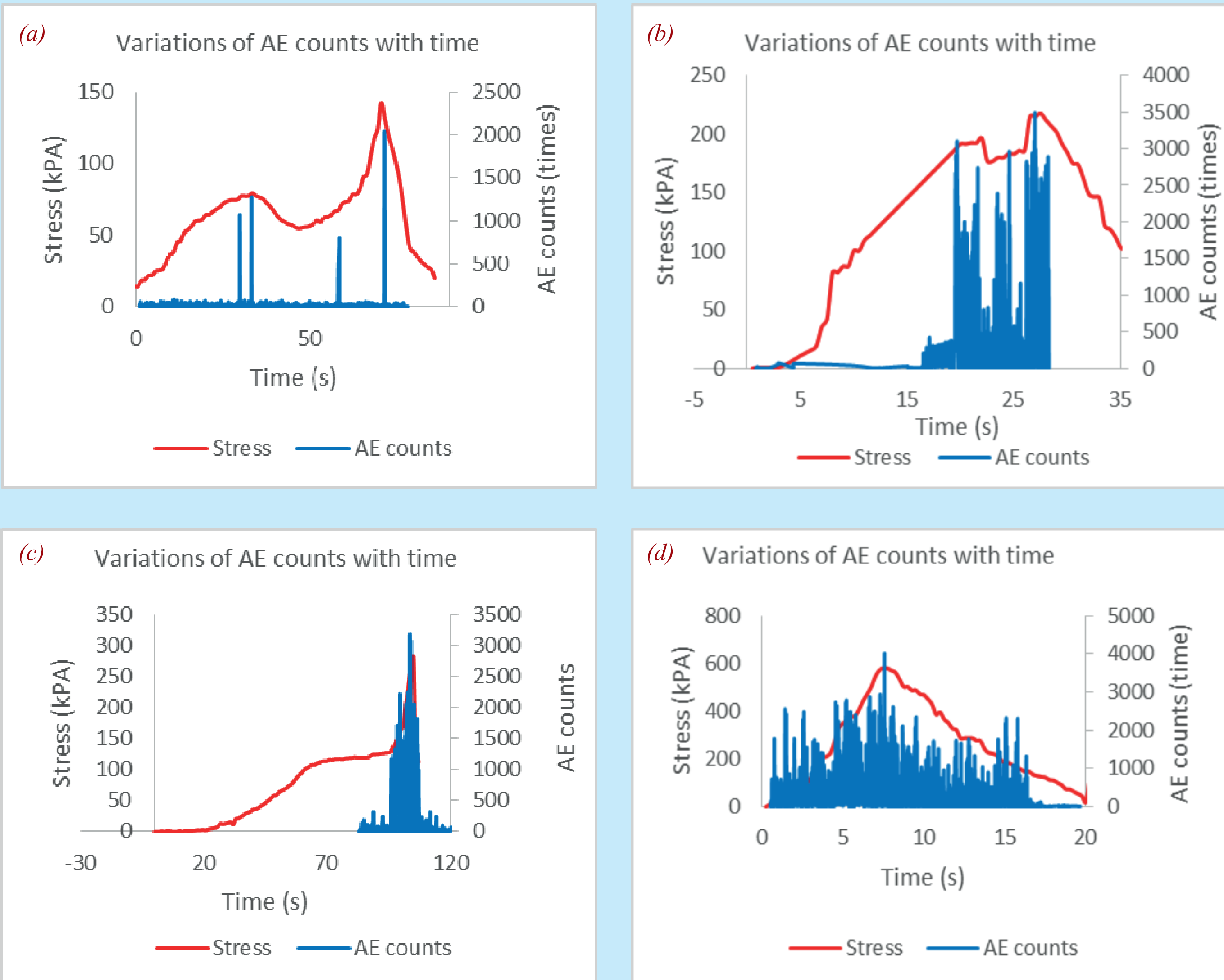

Figure 6. Variations of AE counts with time of 10% cemented backfill samples: (a) – 3 day curing; (b) – 7 days curing; (c) – 14 days curing; (d) – 28 days curing.

Сурет 6. 10% цементтелген қайта толтыру үлгілерінің уақытымен АЕ көрсеткіштерінің өзгеруі: (a) – 3 күндік өңдеу; (b) – 7 күндік өңдеу; (c) – 14 күндік өңдеу; (d) – 28 күндік өңдеу.

Рис. 6. Изменение количества АЭ в зависимости от времени отверждения образцов с 10%-ой цементированной засыпкой: (a) – отверждение в течение 3 дней; (b) – отверждение в течение 7 дней; (c) – отверждение в течение 14 дней; (d) – отверждение в течение 28 дней.

and random errors occurred while testing backfill samples. Human errors probably occurred during sample preparation. It should be noted the imperfection of acoustic emission equipment [9]. In addition, AE test results were affected by environment noise. Different imperfections can be seen of obtained AE test results from the graphs [10]. For example, the sensor was not worked properly during testing of 5% backfill sample between 0 and 15 s, which can be seen from Figure 5c. During the testing 10% backfill sample, acoustic emission monitoring test and uniaxial compression strength test were not started simultaneously, the UCS test was started earlier, which is shown in Figure 6 *(c)*.

Conclusion

The laboratory study showed that the uniaxial compressive strength of cemented backfill samples increases with curing time, reaching values more than six times higher after 28 days compared to 1 day, though overall UCS remained lower than reported in other studies due to limitations in compaction, curing, and material composition. Acoustic emission monitoring confirmed that peak AE activity coincides with peak stress, reflecting fracture development, with higher cement contents (15–20%) exhibiting greater AE counts and thus more brittle cracking than lower contents. Despite some measurement errors and equipment imperfections, the results highlight the strong influence of curing time and cement content on backfill strength and demonstrate the potential of AE monitoring as a reliable method for assessing fracture processes in cemented backfill.

Acknowledgments

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