

# Acoustic emission monitoring for engineered barriers in nuclear waste disposal

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**Abstract.** To safely dispose of nuclear waste in underground facilities, engineered barrier systems are needed to seal shafts and galleries. The material used in these barriers must be adapted to the host rock parameters. Shrinking and cracking must be avoided to provide a barrier with almost zero permeability. For repositories in salt rock environments, several types of salt concrete (SC) are possible construction materials.

Within the project SealWasteSafe, we compared the behavior of an innovative alkali-activated material (AAM) with standard SC in their hydration and hardening phase. To monitor the microstructural changes within the two materials SC and AAM, acoustic emission (AE) signals have been recorded for up to ~250 days on 340-liter-cubic specimens.

The phenomenon of AE is defined as the emission of elastic waves in materials due to the release of localized internal energy. Such energy release can be caused by the nucleation of micro-fracture, e.g., in concrete while curing or when exposed to load. The occurrence of AE events gives first rough indications of microstructural changes and potentially occurring cracking and thus, provides insights for structural health monitoring (SHM).

The results show, that for the first 28 days after casting, less AE activity was detected in the AAM compared to SC. After 61 days, in the AAM material, the number of AE events exceeded those observed in the SC. However, the majority of the AE detected and located in AAM was related to surface effects, and not to microstructural changes or occurring cracks within the bulk volume. Additionally, the source location analysis indicated, that despite lower activity in SC, we observed some clustering of the events. In contrast, in AAM, the activity inside the specimen is randomly distributed over the whole volume. The monitoring results help to estimate the material's sealing properties which are crucial to assess their applicability as sealing material for engineered barriers.

**Keywords:** nuclear waste repositories, event localization, acoustic emission monitoring



## 1. Introduction

One of the challenges in nuclear waste disposal is the design of underground repositories where radioactive waste can be stored safely for extremely long periods (>100,000 years). To safely dispose of nuclear waste in underground facilities, reliable and carefully engineered barrier systems are needed to seal shafts and galleries. Using salt as a host rock for such underground repositories requires using a sealing construction material that ensures sufficient mechanical strength, and high durability and adapts to the host rock parameters. Additionally, shrinking and cracking must be avoided to provide a barrier with almost zero permeability.

Currently, a standard recipe of the material used for test structures for repositories in salt rock environments is salt concrete (SC). This type of concrete has undergone extensive in-situ testing [1] and has shown overall suitability for sealing structures. However, a high heat reaction, and, consequently, increased deformation and cracking risk, potentially jeopardize the structural integrity of the SC structures.

To overcome these obstacles, an innovative construction material based on alkali-activated materials (AAM) has been proposed as an alternative to the SC. The laboratory experiments on small samples showed significantly lower heat reaction ([2, 3, 4]), however, more studies on larger samples are required to properly evaluate its usability for sealing structures design.

Within the SealWasteSafe project (Bundesanstalt für Materialforschung und –prüfung (BAM), Berlin, 2019-2022 [4, 5, 6, 7] <https://www.bam.de/Content/DE/Projekte/laufend/SealWasteSafe/seal-waste-safe.html>), we compared the performance of the innovative AAM and standard SC in their hydration and hardening phase in two 340-liter-cubic specimens. In the presented paper, we analyze the development of crack formation within the materials based on the acoustic emissions occurring during the monitoring period for up to ~250 days.

## 2. Experiment

### 2.1. Specimen

Two cubic specimens (edge length of 0.7 m, Figure 1a) were manufactured for the need of the experiment:

- SC – a blended Portland cement-based salt concrete (“M2” in [1]), and
- AAM – an innovative material with AAM-mortars (“F1” in [2]).

A special formwork was designed to enable the installation of different sensors for the monitoring phase before casing removal (Figure 1b). Additionally, to simulate the in-situ underground conditions and avoid heat release, both specimens were insulated after pouring.

The pouring of the SC specimen was on 05.05.2021 and, in total, it was monitored for 253 days (until 13.01.2022), with the casing removed on 10.11.2021 after 188 days. The pouring of AAM was around one month later (03.06.2021) and due to technical constraints, it was monitored for a shorter period – 155 days (until 04.11.2021). The casing of the AAM cube was removed on 13.10.2021 after 132 days.

### 2.2. Instrumental setup and acquisition settings

For the monitoring part of the experiment, both specimens we instrumented with temperature, humidity, strain, and acoustic emission sensors (more information in [7]). To detect acoustic emission activity starting from the very beginning of the hydration phase [8, 9], special partly embedded stainless steel adapters were designed (Figure 1c; see also [4, 7]).

The adapters were meant to enable good coupling for constant acoustic emission monitoring without direct contact with the strongly alkaline ( $\text{pH} > 13$  in AAM) and salt corrosive (NaCl) environments of the specimens.

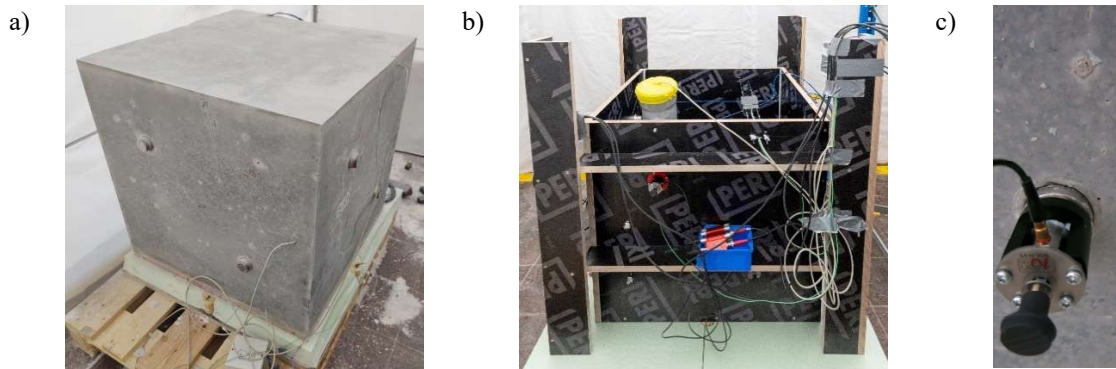


Figure 1 Experimental design of cubic specimen (edge length 0.7 m) equipped with a multisensory monitoring setup. a) SC specimen after removal of the casing b) formwork to arrange sensors before concrete casting, c) acoustic emission adapter with sensor. Figures modified from [7].

Six piezo-electric sensors (VS45H, Vallen) were installed diagonally on three vertical sides of each specimen (Figure 2). The sensors were connected to 34 dB pre-amplifiers (AEP5, Vallen), which were connected to the AMSY6 data acquisition system (Vallen). The acoustic emission events were recorded in a threshold-crossing mode (34 dB threshold) with 10 MHz sampling rate and fixed recording duration set to 16384 samples. The recorded signals were bandpass filtered from 20 kHz to 500 kHz.

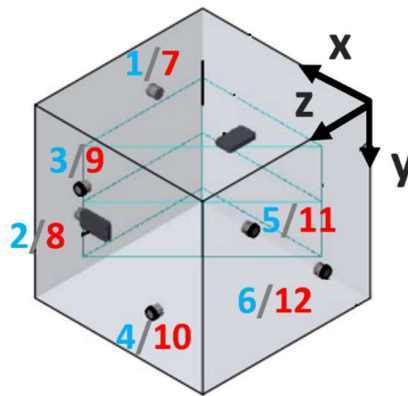


Figure 2 Schematic drawing of the acoustic emission sensor location on the cubic specimens. Numbers in the plot indicate each sensor channel. Blue numbers correspond to the SC specimen sensors, and red colors to the AAM specimen. Figure modified from [7].

### 3. Methods

The analysis presented in this paper is based on classical hit count over the monitoring period and localization of the recorded events. Acoustic emission events which were recorded by at least four out of six sensors, were selected for the source localization analysis using the so-called Geiger's method [10, 11]. This method is based on the calculation and reduction of the differences between the observed and calculated arrival time with each iteration during the inversion process. The source location is estimated in 3D volume using P-wave velocity (calculated from averaging ultrasonic pulse velocity:  $2940 \text{ m/s} \pm 367 \text{ m/s}$  for SC and  $3496 \text{ m/s} \pm 144 \text{ m/s}$  for AAM) and the first arrival time (estimated using Akaike information

criterion (AIC) picker based on [12]). In our iteration process, we used the center of the specimen as the initial source location.

## 4. Results and Discussion

### 4.1. Acoustic Emission in Time

For the first 28 days of monitoring, the cumulative number of acoustic emission events in AAM material (around 7000 recorded hits) is significantly smaller than for the SC (almost 15000 hits). These results are in agreement with the acoustic emission monitoring performed on the cylindrical specimen over the first 28 days after pouring in [4]. However, during the long-term monitoring of the cuboid specimen, we observed that the number of acoustic emissions continuously increased over time in the AAM specimen, whereas the activity in the SC specimen remained at a relatively constant level during the rest of the monitoring period. Around 61 days after pouring, the cumulative number of acoustic emission events in AAM material becomes higher than in the SC.

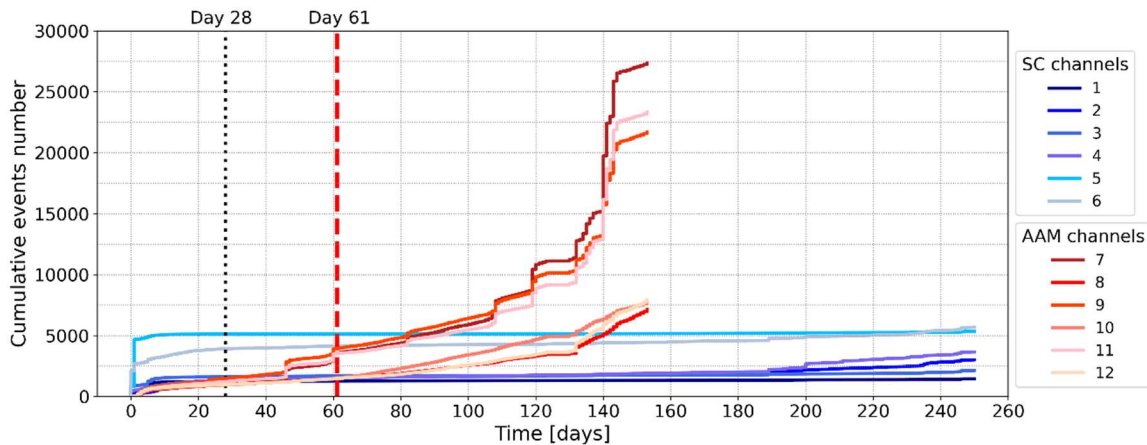


Figure 3 Cumulative acoustic emission hits over the whole monitoring period for the salt concrete (SC) specimen (blue colors) and the alkali-activated material (AAM, red colors). The black vertical dotted line indicates the first 28 days, and the vertical dashed red line – day 61 when the cumulative number of events in AAM material exceeded those in SC. Figure modified from [7]

The most significant increase of the acoustic emission events in AAM material is observed for channels 7, 9, and 11, which were located in the upper part of the specimen (see Figure 2).

### 4.2. Localization of Acoustic Emission Events

Much higher acoustic emission activity recorded by the sensors installed in the upper part of the AAM specimen gives the first order estimation about the location of the event sources. To analyze in detail the increased activity we calculated the 3D coordinates of each event which was recorded by four or more sensors. The localization of the event sources is depicted in Figure 4. Events apparently localized outside the specimen geometry are caused by slightly erroneous localizations as no boundary conditions have been applied.

The distribution of the acoustic emission shows that events are uniformly distributed along the horizontal planes of both specimens (Figures 4a and 4c). In SC, however, events are located in a central area, with a relatively low number of events 10 cm from the specimen sides. In the vertical plane (Figures 4b and 4d), the difference between the two specimens is much more significant. Similar to the horizontal distribution in SC material, located events

are relatively uniformly distributed along the height of the specimen, with some event accumulation between 40 cm and 60 cm (cluster SC1 in Figure 4b). The clear contrast is visible for the events located in AAM material, where the localized events are concentrated in the top layer of the specimen (cluster AAM1 above 60 cm in Figure 4d). Some smaller clusters are visible in both materials but are less significant than the vertical distribution.

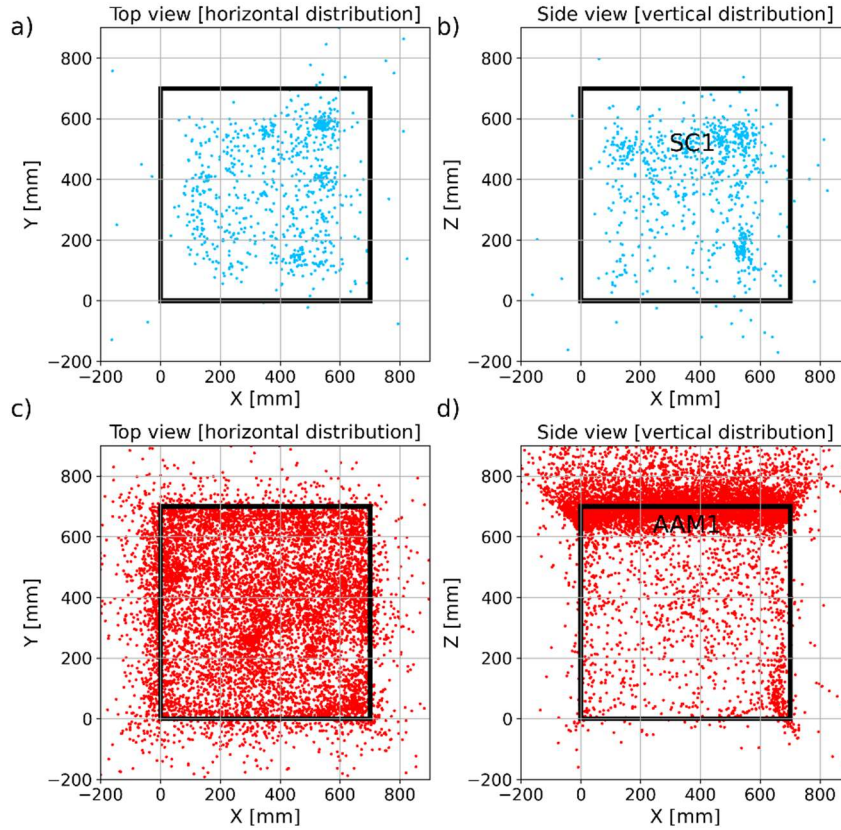


Figure 4 Spatial horizontal and vertical distribution of acoustic emission events within the specimens for a), b) SC and c), d) AAM, respectively. The black line indicates the outline of the specimens.

To understand better the high concentration of the events in the top layer of the AAM specimen, we plotted the temporal evolution of located acoustic emission events, with differentiation for height levels (Figure 5a). Each specimen height was divided in virtual slices of three 20-cm-wide levels (0 – 20 cm, 20 – 40 cm, and 40 – 60 cm), and one 10-cm-wide level in the upper part of the specimen (60 – 70 cm).

As is clearly shown in both Figures 5a and 4d, the majority of acoustic emission events in the AAM specimen are localized in the upper 10 cm part of the cube. Compared to the other levels, the cumulative number of events is so high that the curve is out of the plot scale, to properly visualize the other results. In the case of the SC specimen, most events are localized in the 40 – 60 cm level and, in contrast to the AAM specimen, the least activity is present in the top 10 cm layer.

The reason for such a difference between the two materials could be related to the slower reaction kinetics of the AAM material compared to the SC [2]. As previously observed by [4] for the cylindrical specimens, the slow reaction kinetics relates to the creation of the bubble-like surface effects. This phenomenon is a result of air entrapped inside the material mixture, which did not fully escape during the hardening process. This hypothesis is confirmed with the visual evaluation of the top layer of both specimens, where the bubble-like surface is clearly visible on the top corner AAM specimen photo in Figure 5c. The surface effects are not present in the SC specimen (Figure 5b).

The origin of the events localized in the top layer of the AAM specimen could also be related to the decreased accuracy of the event localization (i.e., events outside the specimen boundary in Figures 4c and 4d). The use of the P-wave velocity in the implemented localization algorithm might be a reason for a strong localization inaccuracy of the events originating from the bubble-like surface formation, which have different source mechanisms than standard acoustic emission from crack nucleation.

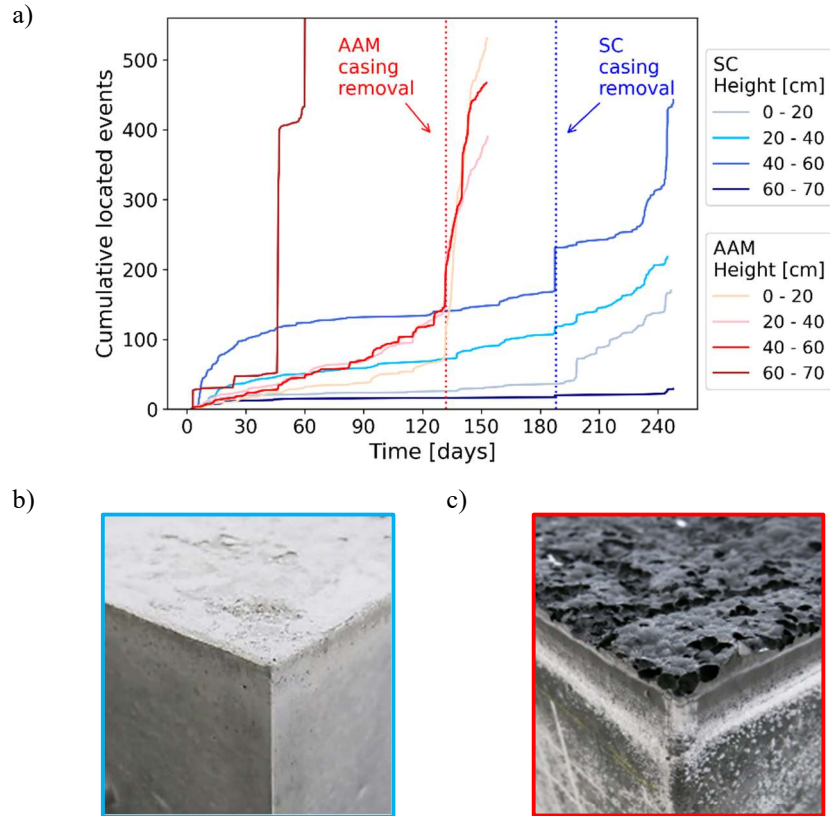


Figure 5 a) Cumulative located acoustic emissions as a function of different virtual height slices, b) top corner of SC specimen after casing removal, c) top corner of AAM specimen after casing removal. Figures modified from [7].

## 5. Conclusions

The presented study focuses on the long-term acoustic emission monitoring of two cubic specimens made of salt concrete and alkali-activated materials. Despite the initially lower acoustic emission activity in AAM material, the importance of the long monitoring period has been highlighted by the significant increase in the cumulative number of events after 61 days of recordings.

The increased acoustic emission activity in the AAM specimen, however, was most likely caused by the formation of bubble-like surface and was not necessarily related to the nucleation of macrocracks within the material. This was confirmed with other non-destructive evaluation methods used for specimens' inspection described in detail in [7].

Even though evaluating which material is better for the construction of engineered barriers for nuclear waste disposal based solely on acoustic emission analysis is not feasible, we have demonstrated that it provides valuable insight into complex material behavior.

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