Oil Shale, 2025, Vol. 42, No. 1, pp. 1–28
doi: https://doi.org/10.3176/oil.2025.1.01

ISSN 0208-189X

Fly ash applications for mine workings backfilling – review of current practices and perspectives for oil shale industry residues

Madis Osjamets(a,b)*, Riho Mõtlep(a)

(a) Institute of Ecology and Earth Sciences, University of Tartu, Ülikooli 18, 50090 Tartu, Estonia

(b) Geological Survey of Estonia, F. R. Kreutzwaldi 5, 44314 Rakvere, Estonia

Received 28 June 2024, accepted 10 January 2025, available online 14 January 2025

Abstract. *Mining subsidence prevention has not been systematically addressed in Estonia. Despite the presence of numerous shallow and hazardous old mines, including some in urban areas, there are only a few practical examples of land stabilization. This article provides an overview of stabilization methods commonly used elsewhere. By considering the specific characteristics of shallow Estonian mines and existing infrastructure, we propose injectable backfilling through treatment boreholes as the most applicable land stabilization method in Estonia. The backfill typically consists of locally available byproducts or waste materials. We evaluate how Estonian oil shale ash, a residue from power and oil production, compares to the properties required for effective backfilling. Some properties, such as self-cementation, make it suitable for use in backfills. However, it also exhibits less desirable features – high water demand and fast setting. Despite extensive research on oil shale ash, certain material properties that critically impact its usability in backfills – such as its pumpability over longer distances – remain to be fully determined.*

Keywords: *mine stabilization, backfill injection, oil shale ash backfill.*

1. Introduction

Over the last century, oil shale (OS) mining in Estonia has generated more than 585 million m^3 of mine workings on an area extending over 210 km^2 [1]. Early mining took place at shallow depths, where mine workings and shaft collapses continue to cause unpredictable land subsidence today and presumably well into the future. Known occurrences of subsidence events in

---

* Corresponding author, Madis.Osjamets@egt.ee

Estonian OS mine areas indicate that the risk of land subsidence is high above mine workings shallower than 20 m [2], specifically in areas where mining was manual, using the longwall mining and shortwall stoping method with partial backfilling, practiced in the early days of OS mining [1, 3]. Longwall mining extracted a single 2.5 m thick, nearly horizontal OS seam from a 120 m long face, with the limestone roof permanently supported only near the roadways. After extracting the seam, temporary supports in the working face were advanced, causing the strata behind to collapse onto partial backfill supports made of limestone slabs. Land above the supported roadways of old OS mines is considered quasi-stable, as support structures were designed to keep mine workings stable only during mining operations. Similarly, land at the edges of subsidence zones from longwall mining and above shallow galleries from shortwall stopings is also regarded as quasi-stable [3–5].

Some abandoned shallow mine areas are now urbanized, with buildings located on quasi-stable land, raising concerns about ground stability in the long term [5]. Similar problems of ensuring land stability beneath existing buildings and future developments on quasi-stable land are acute worldwide [6–8]. Consolidating old mine workings is a common global practice [9, 10], but in Estonia, this method is rarely used, with only a few exceptions [11–13].

While it is possible to mitigate land stability issues on new developments with piling, bulk excavation, and controlled backfilling, these practices are not feasible in the vicinity of existing buildings. Partial or full backfill grouting of mine workings is often the only option to ensure ground stability in developed, populated areas [7]. As old mine workings are rarely accessible, backfill is typically injected underground from the surface through drillholes [10]. Solid rock and aggregate fills are not applicable in such cases, and therefore, injectable backfilling (grouting) is the most commonly applied technique [6]. With no comprehensive practices to mitigate land stability issues in heavily mined northeastern Estonia, this review contributes to the general understanding of various land stabilization methods and their applicability in Estonia. We analyze global practices for stabilizing ground above mine workings and the applicability of solid residues from the Estonian OS industry for backfilling local OS mines.

2. Stabilization methods of mined lands

Land stability issues caused by mining can be tackled by several stabilization methods, each with its benefits and limitations. In this chapter, we give an overview of commonly used land stabilization techniques, while those limited by special conditions are only briefly described. We focus on techniques applicable to stabilizing land above abandoned mine voids, especially in urban areas such as northeastern Estonia. Land support methods are categorized into area-wide stabilization techniques and point support techniques. Area-wide techniques, such as solid bulk filling, earthworks, and backfill injection, are used where mine workings collapse can cause subsidence in large areas (Fig. 1).

Point support techniques, such as piling, geosynthetics, and injection of grout columns, are used to provide support at a single location (Fig. 2). Some of these techniques require safe access to workings that is typically granted in active mining but is lacking in historical mining areas. Furthermore, the

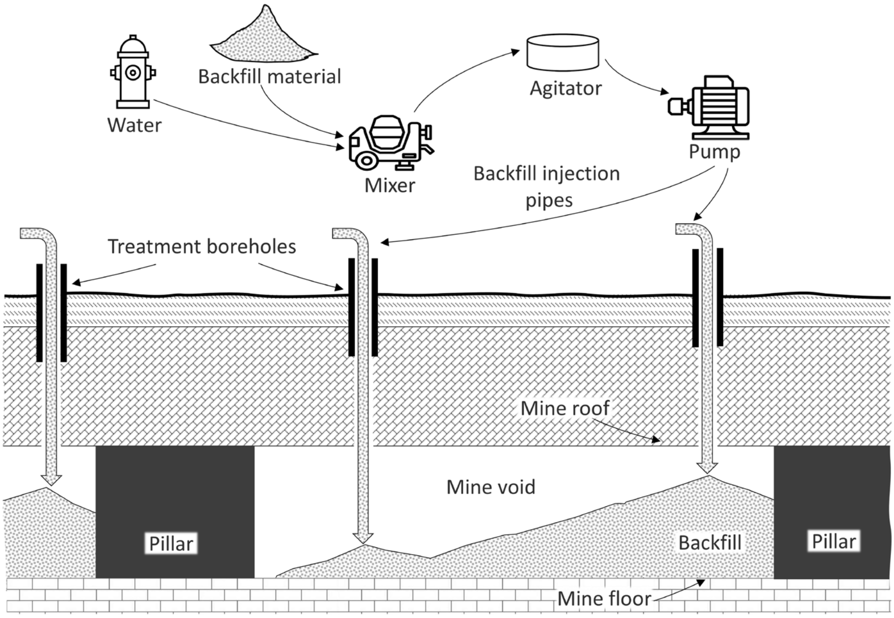

Fig. 1. Hydraulic backfilling as an area-wide stabilization technique. Based on Walker [14].

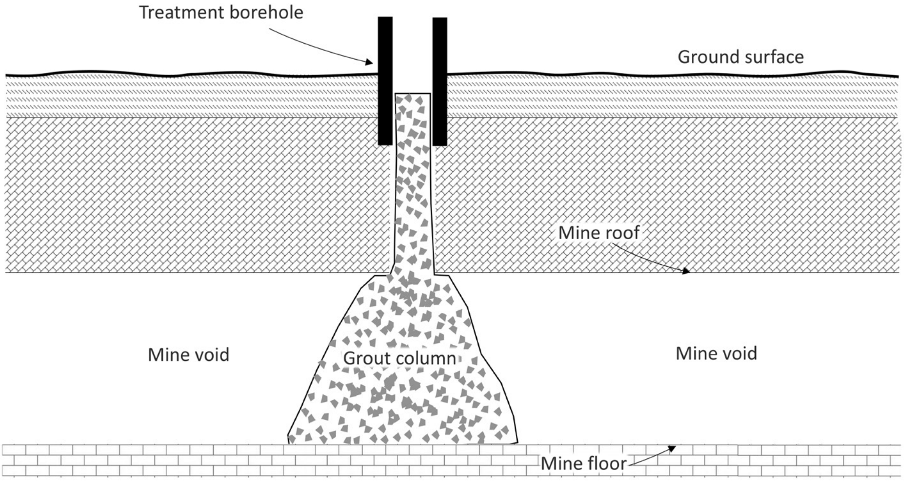

Fig. 2. Grout column as a point support stabilization technique. Based on Watson et al. [10].

stabilization of inaccessible voids located in the vicinity of existing buildings or infrastructure does not allow large excavations, and usually only injection backfilling through treatment boreholes can be used [6, 7, 14].

2.1. Earthworks

Earthworks are an area-wide land stabilization technique. Mine workings are excavated down to the floor level and backfilled uniformly to allow future safe land development (Fig. 3). Shallow workings are preferred, as an increase in the remediation depth makes it more difficult to excavate and compact the backfilled layer. This method allows for the excavation and use of ore originally left underground to support the mine roof [10]. Earthworks may be the most economical method in areas where abandoned workings are near the ground surface [15]. However, it is not applicable to areas with a high number of existing buildings and underground communications. Additionally, dry mine workings are preferred for this method, as it is more difficult to excavate and fill waterlogged workings situated below the groundwater level [9].

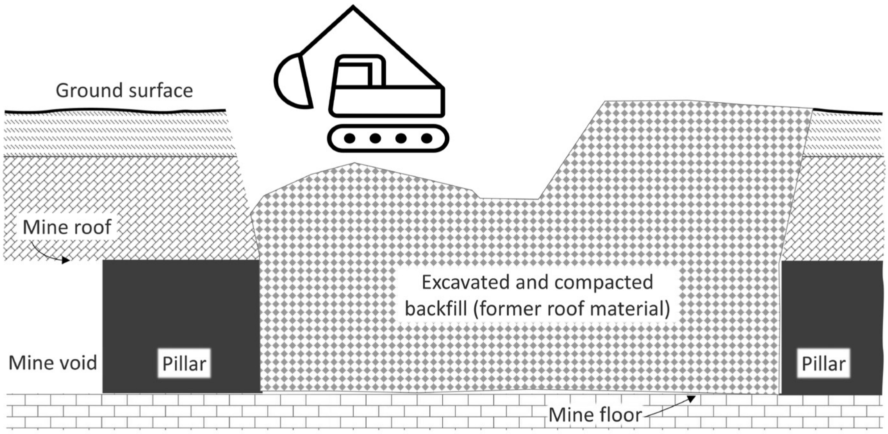

Fig. 3. Stabilization of a shallow mine using the earthworks method.

2.2. Piling, bridging and plugs

Piling is a point support method suitable for building new constructions above existing mine workings. Piles are drilled through the excavated mine level into the firm mine floor (Fig. 4) [14]. Piling is considered a costly method, as piles consisting of metal and cement are more expensive than materials commonly used in backfills.

The bridging technique involves creating a stable structure, most often made of concrete, above a known critical area to prevent surface collapse or subsidence and seal access to workings. This technique requires sufficient dependable ground to support the bridging structure and does not entirely tackle mining void migration. Thus, it is not considered a best possible

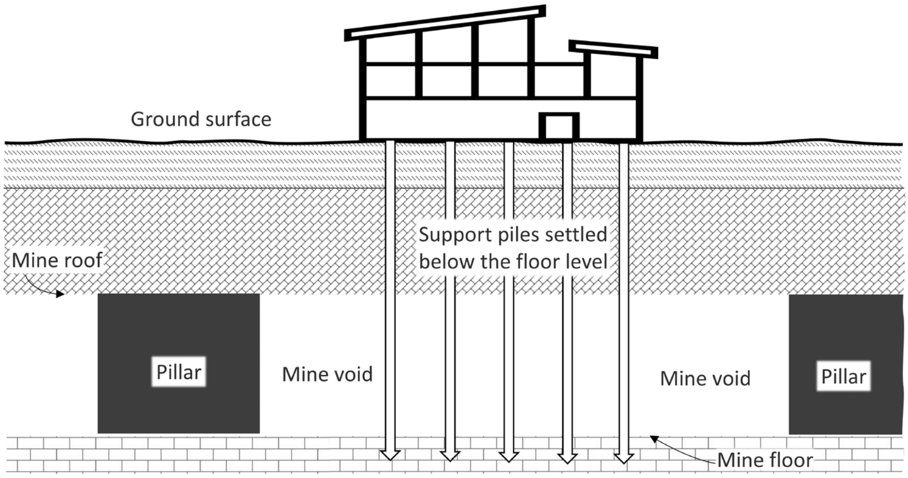

Fig. 4. Piling as land support method above mine workings. Based on Walker [14].

solution. Due to high costs, piling and bridging are unsuitable for stabilizing large areas [10]. Plugs are used to seal smaller diameter objects, such as mine shafts or open workings. The aim is to prevent further surface collapse and seal access to workings. Non-compacted material is removed, and the cavity is filled and compacted with coarse and non-degradable granular material. A concrete cap, similar to the bridging technique, is commonly added on top (Fig. 5) [10].

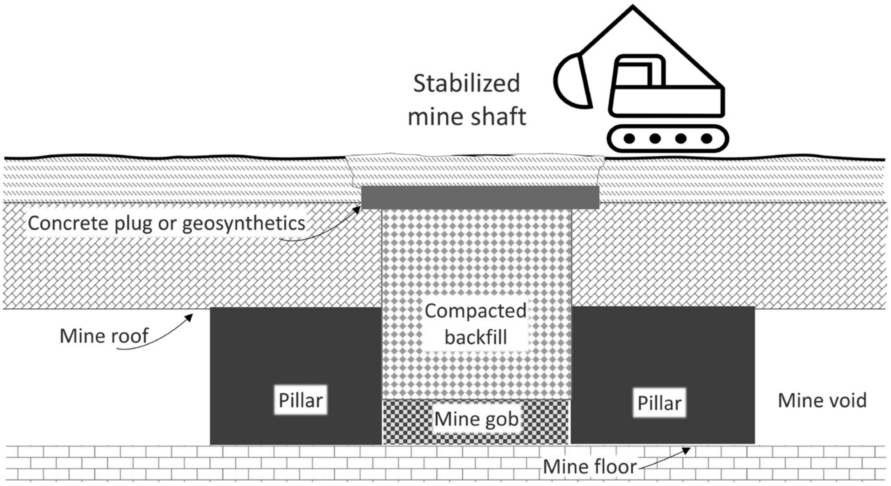

Fig. 5. Mine shaft stabilized with either a concrete plug or geosynthetics, commonly used to seal mine shafts.

2.3. Geosynthetics

Using geosynthetics in construction above mined land is another stabilization technique, primarily used in situations like road construction, where loadings are not very high. Geosynthetics are often combined with other stabilization techniques and may be designed to only minimize and delay sudden underground deformation [8, 10]. Research on using geosynthetics shows that geosynthetic reinforcements significantly reduce deformation in overlying road layers; however, in cases of discontinuous deformations, this technique may not always be the best solution to protect road surface against tearing and cracking [16].

2.4. Blasting

Blasting support pillars or mine roofs above voids is an experimental stabilizing method for mitigating land subsidence [14, 17]. The idea is to convert the blasted rock mass into rubble to fill a larger volume (Fig. 6). Blasting may be best used for filling workings of irregular shape or unknown location, or for reclaiming vertical shafts [17]. This method is thought to work better on deeper mines, as in shallower ones, the rubbled zones of overburden often extend to the surface [14]. A recent literature review by Gray finds that blasting has remained a theoretical stabilization method and recommends conducting a test program prior to its use [9].

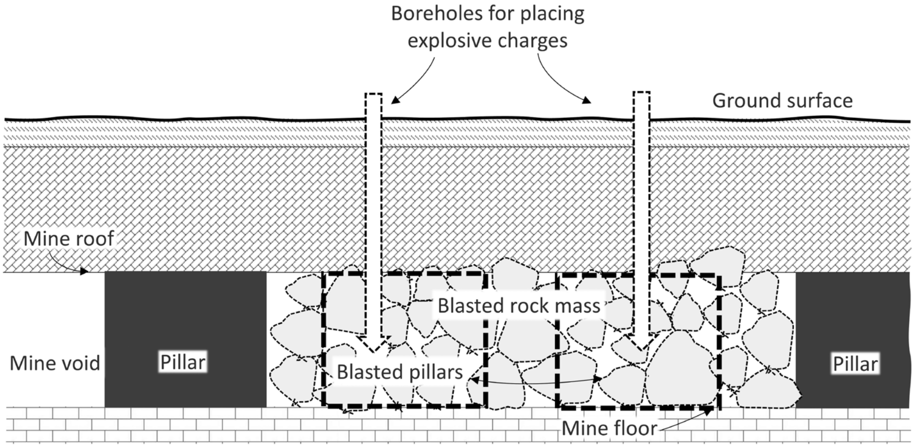

Fig. 6. Land stabilization with blasting: rock mass from blasted pillars and roof generates loose rubble that is capable of filling larger voids.

2.5. Mine backfill

Mine backfilling methods are distinguished by the delivery medium (air, water, stowing), the backfill material, and the use of binders. Common types of backfill methods used to stabilize mining voids are presented in Table 1 [18, 19]. Access to workings influences the transportation of backfill. Solid rock fill requires safe access because the material is transported to the backfill area by machinery or slinger. Hydraulic and cemented hydraulic backfilling often requires access to workings for constructing barricades to contain the backfill and dewatering the backfill body [20]. Safe access is usually granted in working mines but is lacking in abandoned or inactive mines, where the injection treatment of mostly paste backfill or grouts with lower solid content is used [10].

Table 1. Backfill methods, fill materials used and transportation means to voids

Backfill method	**Bulk material**	**Processing method**	**Transportation**	**Binder**	**Fines**	**Access to workings required**	**Drain-ing excess water required**	**Solids content by weight, %**
Rock fill	Waste rock	Crushing	Machine transport (pneumatic, slinger)	Yes/ no	Yes/ no	Yes	No	100
Hydraulic fill	Sand, waste rock, tailings	Flotation, desliming, crushing, screening	Gravity, pumping	No	No	Preferred	Yes	50–75
Cemented hydraulic fill	Waste rock	Flotation, desliming, crushing, screening	Gravity, pumping	Yes	No	Preferred	Yes	50–75
Paste backfill	Tailings, processing waste	Desliming	Gravity, pumping	Yes	Yes	No	No	78–87
Non-structural grout	Tailings, sand, processing waste	Desliming	Gravity, pumping	Yes	Yes	No	No	<50–65

2.6. Injectable backfill

Injectable backfill can be used locally or as an area-wide technique. During the injection treatment, mining voids are filled with a backfill mixture. In active mining, hydraulic backfilling and paste backfilling are the most common technologies to apply injectable backfill [20]. Hydraulic backfill is a low-strength backfill that consists of non-cohesive aggregates, such as sand or crushed waste rock, mixed with a high amount of water. Paste backfill has lower water content, contains fines (particles <20 μm), and possesses cementing properties due to an added binder [20]. Non-structural grouts that are similar to paste backfill but have higher water content are most often used in backfilling abandoned mine workings [21, 22]. These grouts are designed to have low compressive strength, good flow properties, and low bleeding [23]. The stabilization process involves drilling a grid of treatment boreholes that intercept the mining voids. Injectable backfill or grout is then pumped into the voids through pipes placed in the treatment boreholes [6, 10, 24].

In the Estonian context, injectable backfill is the most viable area-wide stabilization method. This is primarily due to the proximity of many old mine workings with potential land stability risk to existing developments, which restricts extensive earthworks or other methods. Moreover, residues from the Estonian OS industry, particularly different ash types from power generation and oil-retorting plants, present a potential material for pumpable backfill suitable for injection into underground voids. Therefore, this review focuses on the application and requirements of injectable backfill methods.

3. Development of injectable backfilling methods

Early backfill methods employed hydraulic backfill that consisted of uncemented aggregates. This method has been used to fill both active and abandoned mines. One of the first reported uses of hydraulic backfilling of mine workings took place in the Anthracite region of Pennsylvania, USA, in the late 1800s, where the workings were backfilled under an existing church to avoid ground subsidence. Prior to the 1970s, hydraulic backfill was placed in voids by gravity, which resulted in only about a third of the space filled. Later, pumping backfill under pressure improved the backfilling rate [6, 25].

Typically, hydraulic backfill mixtures contain 50–75% solids by mass and lack fines to ensure dewatering of the backfill body. The absence of fines is achieved by using natural sand or flotation and desliming of tailings [26]. Once pumped into underground voids, the hydraulic backfill body drains and develops inner particle friction to resist rock mass displacement stresses [18]. While the hydraulic backfill body does not gain high strength through settling, it has a damping effect during mine collapses. A disadvantage of this method is the high amount of bleed water that can cause problems during stabilization works [18]. Hydraulic backfill requires access to workings for constructing barriers and drains on the perimeter of the backfilling area to prevent the slurry from spreading and to drain excess bleed water [20].

Cemented hydraulic backfill slurry was introduced in Canada in 1959, where it shortly became a standard practice in active mining [27]. A small dosage of binder (e.g., 3%) was added to hydraulic fills to increase the strength of the backfill body [20, 28]. Although hydraulic fills were cheap when suitable mill tailings were available, the downside of the method was still the high quantity of drain water and added cost of cement. The use of tailings dewatering equipment and pumps allowed cemented hydraulic fills to develop into paste backfill, first used in South Africa and Canada during the late 1970s and in Germany in the early 1980s [18, 26]. Paste fills became a widespread mine backfilling method in the mid-1990s [20]. Cemented hydraulic and paste backfill methods use mixtures containing binder phases that harden the backfill body after placement, providing additional support to the mine workings' roof, along with a damping effect. Portland cement and coal fly ash are most often used as binder materials in paste backfills [22, 28]. Whereas hydraulic backfills are clay-free to ensure drainage of free water, paste backfill contains fines (particles <20 μm) and has a higher solids content of 78–87% by mass [18]. Paste backfill is usually non-draining, retaining most of the water in the paste mixture for cement hydration. Pastes are designed to bleed below 5% excess water during backfilling [18, 29]. The fines fraction in paste enables the backfill to gain adequate flow properties and avoid settlement and segregation of particles. During transportation in filling pipes, paste fills exhibit laminar flow, while hydraulic fills, acting as Newtonian fluids, require turbulent flow with a critical velocity to avoid segregation [18, 20, 29].

In Britain, hundreds of thousands of cubic meters of voids have been filled with coal fly ash-based backfills (non-structural grout) since the 1980s, when interest in stabilizing abandoned mines increased [15]. These grouts typically have a lower solids content (50–70%) compared to paste backfill [21, 22] and thus possess higher consistency, which is beneficial for backfilling old, inaccessible voids.

4. Properties of paste backfill materials

Finding the right components that ensure the desired technical outcome, low cost, and environmentally acceptable impact is vital for stabilizing underground voids with injectable backfill [30]. For economic reasons, local mining waste products are usually considered for backfill materials [31]. Based on literature, mill tailings from mineral processing dominate as aggregate material in backfills [28]. To ensure sufficient workability and hardening properties of backfills, a small portion of fine-grained binders is usually added to aggregates. In UK guidance materials, it is considered sufficient for most construction sites that the backfill body achieves a compressive strength of only 1–2 MPa in 28 days [10]. Typically, in active cut and fill mines, the binder proportion in paste backfill is around 2–10%, whereas cement is most commonly used as a binder in backfills. Due to the high cost of cement, its replacement with alternative binders is often considered [20, 32]. Based on a literature review, fly ash and slag of different origin are the most researched Portland cement replacements in backfills (Fig. 7) [28].

Coal fly ash-dominated backfills (grouts) have a long history of stabilizing abandoned mine workings in the UK [33]. The advantages of using coal fly ash include excellent pumpability and flow characteristics, reduced permeability, bleeding, and water content, as well as increased compressive strength of grouts [21]. Physical properties, such as particle size and water demand, are important characteristics of coal fly ash that control its usability and performance in backfilling. The proportion of fine particles affects the performance of backfill mostly through its water demand, bleeding properties, and flowability. Backfill materials with a fines proportion of 35–60% (particles <20 μm) are categorized as medium, while a proportion over 60% is regarded as fine [28]. For example, in the UK, coal fly ash used for backfilling abandoned mines typically has a fines proportion between 45–75% [21], and coal fly ashes from various sources have a median particle size between 8 to 75 μm, being commonly classified as material with a medium fines fraction (Table 2).

The flow properties of paste backfills that are non-Newtonian slurries depend on their viscosity and yield stress [26]. For adequate flowability, pastes are required to have a sufficient fines proportion that in most pastes exceeds 15% by weight [28, 34]. Adding a coarse fraction is described to reduce paste friction in distribution pipes, thus reducing the required pumping pressures [26]. The maximum grain size of pumpable backfill should be less than 1/5 of the infilling pipe's diameter [18], commonly between 50–250 mm [35]. Water content in backfill needs careful dosage, as more water in backfill constitutes

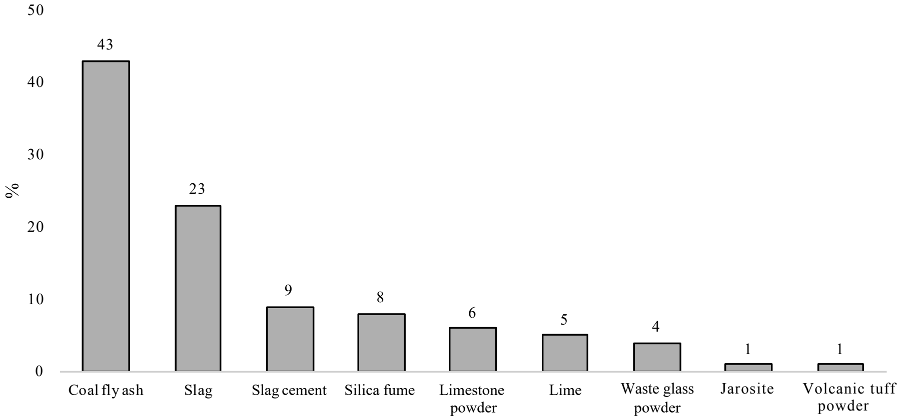

Fig. 7. Binders used to replace ordinary Portland cement in paste backfill, based on literature review [28].

Table 2. Physical properties of low- and high-calcium fly ash

Reference	Grain size <20 μm, %	Mean grain size, μm	Specific surface area, m^2/g	Specific gravity, g/cm^3	Bulk density, g/cm^3	CaO, wt%	Ash type and origin
37	30	39.9	3.07	2.42		47.2	PFA*, Greece
38			3.82	2.22		14.8	PFA, lignite, Soma, Turkey
39	97		4.14	2.51	2.51	34.9	PFA, lignite, Neyveli, India
40	22		2.85	1.84		15.1	PFA, Turkey
42		40.5	12.40	2.40	0.70	11.8	PFA, Meirama, Spain
42		32.8	4.30	2.60	0.50	27.3	PFA, lignite, Greece
41				2+/–0.15		<10	PFA as concrete additive, British standard BS EN 450:1995
21	55–70	50–75		2.15	1.5–1.8	3.0	PFA, UK
40	43		3.35	2.34		1.6	PFA, Catalağzı, Turkey
43		8.0	1.58	2.53		2.3	PFA, Masontown, USA
43		11.0	9.25	2.38		4.0	PFA, Springdale, USA

* PFA – fly ash from pulverized fuel boilers

better flowability but can cause excess bleed water, particle segregation during pumping, and reduced strength of the hardened backfill [36].

Various applications for paste and grout fills require mixtures with different flowability. Flowability is often assessed by paste consistency, and the standard consistency test with the Vicat apparatus is commonly used to assess the water demand of mortars and the cement replacement percentage in concrete [44, 45]. A higher standard consistency value indicates that the material requires more water in grouts. For example, coal fly ash from various sources requires 27–34% water to achieve standard consistency, whereas oil shale fly ash requires 51–64% water to reach the same consistency (Table 3). However, comparing water demand of different raw materials can be problematic because paste components are rarely tested separately. More user-friendly tests exist for onsite quality control of backfills, such as the grout flow-through test [46]. This method is suitable for high-flow grouts that have a maximum aggregate size of 4 mm. Test readings for grouts used to stabilize abandoned workings should be between 300–600 mm [24].

Alternatively, the consistency of paste backfills used in active mining is usually evaluated by the slump test [32], which is suitable for mixes with a maximum aggregate size of 40 mm [47]. Paste with a slump between 150–250 mm is considered optimum for underground applications that require pumping [32]. The slump test provides an empirical measure of consistency that depends on paste yield stress and density. Although yield stress would more accurately describe paste consistency, it is difficult to measure onsite. Some research has shown a correlation between the slump test and yield stress [48]. This relation would make the slump test the easiest and most valuable method for measuring paste consistency [32].

Table 3. Flow properties of coal fly ash and oil shale fly ash grout, important parameters in pumping operations

Reference	Standard consistency, %	Slump, mm	Flow channel, mm	Ash type and origin
49	64			OS FA*, CFB**, Auvere power plant, Estonia
49	51			OS FA, CFB, Enefit280 oil production, Estonia
21			>450	PFA***, UK
36		250		PFA, Jinchuan power plant, China
50			520	PFA, UK
50			419	PFA, UK
50			416	PFA, UK
50			570	PFA, UK
51	32			PFA, Ennore power plant, India
52	27			PFA, UK
37	34			PFA, Greece
53		220		CFB, China

* OS FA – oil shale fly ash

** CFB – fly ash from circulating fluidized bed combustion boilers

*** PFA – fly ash from pulverized fuel boilers

Cementation and the development of compressive strength are essential properties of backfill materials used for land stabilization [54]. The strength characteristic of backfills is often measured by the uniaxial compressive strength test (UCS) and is usually evaluated after 28 days of hardening [55]. The required strength of hardened backfill depends on the properties of mine workings, overlying strata, and the designed usage of stabilized land [10]. For instance, active cut and fill mines, where hardened backfill replaces support structures, require greater support compared to abandoned mines, where backfill adds support to original ore pillars left unmined [32]. However, a uniaxial compressive strength (UCS) of 1–2 MPa after 28 days of curing is considered sufficient for most new developments above mined land [10], and a UCS of 0.7–2 MPa is considered adequate for backfill in typical Canadian mines [34]. Calculations for paste backfill mining in Estonian room and pillar mines indicate that a compressive strength of 1.32 MPa would be sufficient to replace ore pillars left to support the mine roof [56]. The self-cementing properties of some low-calcium coal fly ash-based grouts are insufficient to achieve the desired strength and require adding cement in a proportion exceeding 10:1 (ash/cement) [21]. Moreover, cement accelerates the early setting of backfill and is often used as a binder in active mines, where hardening time is crucial to the mining cycle [28, 32]. However, fast hardening and high strength are usually not essential for infilling abandoned mines. Therefore, to improve grout flowability, strength characteristics are somewhat sacrificed and lower strength grouts are used [23]. A slow setting time of grout, while undesirable in active mines, can be advantageous in backfilling abandoned workings, allowing to hold fresh backfill longer from setting prior to pumping it into treatment holes.

The mineralogical and chemical composition of backfill materials significantly influences its cementing properties [57, 58]. The composition of fly ash is determined by the type of fuel and combustion technology used [28, 49]. Fly ash from coal-fed pulverized fuel boilers, which reach combustion temperatures of 1500 °C [59], contains a high amount of glassy material with average contents of CaO (1.1–5.4%), SiO_2 (45–51%), Al_2O_3 (24–32%), Fe_2O_3 (7–11%), and MgO (1.5–4.4%) [60, 61].

The American Society for Testing and Materials (ASTM) classifies fly ash based on CaO content into class C and class F. Currently, ashes with a CaO content over 18% are classified as class C and ashes with a CaO content below 18% as class F [62]. In literature, this classification has not always been consistently followed, as previous versions of the standard set the limit between F and C class ashes at a lower CaO content (e.g., 10%) [63]. The characterization of ashes based on low and high CaO content is relevant to backfilling because the CaO content often determines their self-cementing properties [49]. Notably, class F coal fly ash-based grouts usually require the addition of cement to achieve the desired strength [21].

5. Stabilization methods applicable in Estonian abandoned mines

In Estonia, most stability problems in mined land are associated with old shallow mines that ceased operations decades ago [1–3, 5, 64]. Land stability is primarily affected by the thickness and quality of the layers above the mine roof, the thickness of the extracted seam, and the mining method used [10, 65–67]. In Estonia, these parameters are usually well-documented in mining plans. Subsidence near buildings and roads was often minimized by leaving support pillars during mining. The relatively simple mine setup, where only a single, nearly horizontal seam set between limestone beds is excavated, facilitates the planning of stabilizing works. The absence of dangerous mine gases and acid mine drainage, common in hard coal mining, further simplifies backfilling in Estonian OS mines [68, 69]. However, there are about a thousand residential or public buildings in quasi-stable areas, where ground stability problems could arise unexpectedly [70]. Most of these buildings are in populated regions along the Kiviõli–Kohtla-Järve–Jõhvi line, where mine workings are shallow and longwall mining with partial backfilling and shortwall stoping were used [4, 5].

Partial solid backfilling was employed in early longwall mining, where manually separated limestone tailings were laid out as artificial support (Fig. 8). Otherwise, backfilling cases in Estonia are rare. In the second half of the 1980s, large-scale paste backfilling experiments were carried out in the

Fig. 8. Partial backfilling with manually laid limestone supports in an Estonian longwall mine, a common practise at the beginning of industrial mining. Note that the supporting rock piles do not reach the mine roof. Photo: Urbex Estonia.

Fig. 9. Consolidation of the Sillamäe uranium mine using the earthworks method. The whole mine area in the foreground is excavated down to the mine floor, and coarse material is placed back to fill the area on the far left. Photo: Kalmer Sokman.

Kiviõli and Viru mines. Limestone tailings and sand were used as filler, while OS ash from pulverized fuel combustion was used as a binder material. In the Kiviõli mine, over 30,000 m^3 of workings were filled using different backfilling methods [11]. Despite promising study results for applying backfill mining, room and pillar mining was implemented instead as a cheaper solution.

The bulk backfill method was employed for the consolidation of the abandoned Sillamäe uranium mine area from 2003 to 2005. During this project, 3 ha of shallow mine area were excavated and backfilled for railway construction (Fig. 9) [12].

Additionally, blasting was suggested as a land stabilization method during the remediation of the Kukruse OS tailings heap to stabilize shallow, unstable workings beneath it [71]. This project did not receive official approval and the plans to blast the remnant support structures at the mine level were dropped. Recently, blasting was tested near the town of Kiviõli, where 990 m^2 of ground above a shallow longwall mine was stabilized [72]. The initial plan involved blasting remnant pillars at the mine level to cause roof collapse and prevent later ground instability from unpredictable pillar breakage. As this did not collapse the roof, a second blasting in the approximately 7 m thick limestone roof strata above the workings was conducted (Fig. 10). The test report concluded that pillar blasting would give better results in larger areas and additional roof blasting is preferred to generate more rubble for filling mining voids.

Fig. 10. Stabilization of land above a shallow mine using the blasting method. Test site after blasting pillars at the mine level and strata above the mine roof. Photo: Hendrik Klaas.

The most common stabilization method for foundations above land affected by Estonian OS mining is piling. In contrast, injecting backfill has been the least used method in Estonia, despite its wide usage in consolidating old workings elsewhere. The only known remedial backfill injection in Estonia occurred in 2009, when the addit in the Kukruse mine was backfilled during road construction. Twenty-seven treatment boreholes were drilled at a spacing of 7–8 m, with 40–60 m^3 of paste backfill, consisting of OS ash and limestone tailings, pumped into each borehole, forming grout columns. The resulting backfill was reported to form a cone with an inclination angle of 20–30°, reaching and supporting the mine roof. The compressive strength of the tested backfill mixture was 6.2 MPa (Fig. 11) [13].

The vicinity of existing buildings limits the choice of stabilization methods, making injectable backfilling the most promising in Estonia. Point support features like grout columns made from OS industry materials (e.g., crushed limestone tailings, sand, and OS fly ash) would be applicable where large remnant voids exist (addits, roadways, etc.). Mixtures with a large proportion of fines (OS fly ash) could be used for backfilling where better flow characteristics of backfill are required, such as filling voids under buildings or remediating large areas. While the strength of hardened OS fly ash backfill is likely to be sufficient for both high fly ash and coarser crushed limestone tailings mixtures, the latter has better overall workability (mechanical properties) [73]. On the other hand, ash-based backfill requires less preparation and is thus more

Fig. 11. Stabilization of the addit in the Kukruse mine using the backfill injection method during road construction. Photo taken both from the ground level and from inside the addit during ongoing backfill injection [13].

economical. Nevertheless, in some sparsely populated shallow mining areas, such as Kukruse or Ubja OS mines, earthworks may be the economically soundest consolidation method [74].

Hydraulic backfills require access to workings and are known to generate significant bleed water, making them unsuitable for Estonian conditions. Problematic mining areas often lack accessible workings, and constructing perimeter barriers and drains for hydraulic backfill is difficult, making this consolidation method ineffective. Additionally, a high amount of bleed water is undesirable, as groundwater is the primary drinking water source and contributes significantly to surface water outflow into rivers.

6. OS fly ash suitability for injectable backfill

Oil shale mining for power and oil production accounts for 99% of Estonia's underground mining areas. At the same time, the OS industry generates abundant production waste, mainly limestone tailings, ash, and semicoke. With the modernization of the industry, the former pulverized fuel combustion has been replaced by circulating fluidized bed (CFB) combustion – a shift that has had a notable effect on OS fly ash properties. This paper compares Estonian CFB ash properties with similar materials used in backfilling. Compared to widespread waste materials used in backfills, Estonian OS fly ash is most similar to class C coal fly ash [75]. Previous research shows that most Estonian CFB fly ashes possess sufficient self-cementing properties and are also environmentally acceptable [49, 76–78]. While various experiments have included crushed limestone tailings and sand added to OS ash backfills, these aggregates might not be needed for ground stabilization purposes. Untreated OS fly ash and water mortar hardens to a compressive strength of over 7 MPa, well exceeding the usual requirements of mine stabilizing projects [10, 34, 79, 80].

Furthermore, backfills commonly contain a large amount of fillers (bulk aggregates) due to their availability and lower cost compared to binder materials (Portland cement, fly ash, tailings, etc.). However, the primary waste from the Estonian OS industry is fine-grained ash, which could replace other bulk materials in backfills. Keeping the number of components low, avoiding preparation steps such as crushing and screening, can make backfill more cost-effective. Additionally, increasing the fines content in backfill mixtures positively affects the flowability (yield stress and viscosity) of backfills and reduces setting time [34].

Most OS fly ashes have a medium fines fraction (35–60% of fines <20 µm), with a mean grain size between 17–37 µm (Table 4). The particle size of coal fly ash is similar, with the proportion of fines under 20 µm in most coal fly ashes around 40% (ranging between 18–97%) [39, 44, 50, 81]. In the UK, coal fly ash used for backfill grouting in abandoned mines has a fines proportion of 45–75% [21]. There is no obvious difference in particle size distribution between coal fly ash and OS fly ash that could notably affect backfill workability.

Due to the lower temperatures of CFB combustion boilers currently used in Estonian OS power plants, the main difference between OS fly ash and coal fly ash lies in particle shape. Coal fly ash particles are typically spherical and glassy [21, 41, 50], whereas OS fly ash from CFB boilers has an irregular shape [83]. An irregular particle shape usually results in a greater surface area and thus higher water demand.

Table 4. Physical properties of OS fly ash

Reference	Grain size <20 µm, %	Mean grain size, µm	Specific surface area, m^2/g	Specific gravity, g/cm^3	CaO, wt%	Ash type and origin
49, 82	ca 50	17–23	3.5–6	2.8	35–39	OS FA*, CFB**, Auvere power plant, Estonia
82, 83		37–40	2.2–3.5	2.83	30	OS FA, CFB, Eesti power plant, Estonia
49, 82	ca 50	21–34	5.5–5.8	2.74	29–30	OS FA, Enefit280 oil production, Estonia

* OS FA – oil shale fly ash

** CFB – fly ash from circulating fluidized bed combustion boilers

Backfill grout should range between 300–600 mm in a flow channel test. OS fly ash-based grout requires a water/solid ratio of 65–70% to provide suitable grout [our unpublished data]. However, with a water/solid ratio between 35–50%, the water demand of coal fly ash backfill grout is considerably lower [21].

Finer particles with a greater surface area of backfill increase water demand, as more surface needs to be wetted [84]. Additionally, the irregular shape of OS fly ash from CFB combustion corresponds to a greater surface area compared to spherical coal fly ash of the same grain size. OS fly ashes with a mean grain size of 17 to 34 μm have a specific surface area between 2.2 to 6 m^2/g (Table 5), whereas coal fly ash with a similar grain size possesses a surface area between 1.8 to 4.3 m^2/g (Table 3). Furthermore, class C fly ash is noted for its low bleeding due to pozzolanic properties, where some water is used in chemical reactions and crystal structure formation. A study conducted with 100% class C coal fly ash and water mix showed bleeding rates below 1% at a water/solid ratio as high as 1/1, compared to 24% bleed water in a Portland cement mixture with the same water content [85]. There are no published data on the amount of bleed water in OS fly ash mixtures, but it is an important parameter in backfilling. Similarly, the segregation of an OS fly ash-water mixture and its influence on infilling pipes is another important parameter to be tested prior to large backfilling projects.

Most Estonian OS fly ashes harden to strength requirements for mine backfills without the need for additional cement, which is a significant advantage of OS fly ash-based backfills (Table 5). In modern CFB combustion ash, this is mainly due to its pozzolanic effect [49]. The self-cementing properties of OS fly ash are influenced by its mineralogical and chemical compositions [82], which depend on the fuel composition and combustion technology [49, 59]. The chemical composition of OS fly ash from CFB combustion includes CaO (28–38%), SiO_2 (21–31%), Al_2O_3 (5–8%), Fe_2O_3 (3–4%), and MgO (3–5%) [49]. It is also important that mineralogically, Estonian OS fly ash contains considerable amounts of quartz, lime, and anhydrite. The hardening of OS fly ash grout is observed through the early formation of ettringite and, in the long term, through the transformation of Ca-silicates to gel-like Ca-Si-hydrate, which fills voids between particles and increases the density of the settled grout [76, 86].

The initial setting time of Portland cement is around two hours, whereas cement replacement with coal fly ash is known to delay the initial setting time of concrete mixtures [87]. Estonian OS fly ash sets somewhat faster than Portland cement (Table 5). This fast setting of OS fly ash grout can be problematic during infilling operations and needs to be tested prior to large-scale works. In general, high-calcium silicate fly ashes have been noted for stiff behavior in mixtures with higher solid content [88, 89]. It is not yet well researched how OS fly ash grout maintains its pumpability during longer periods of stirring in agitator tanks for backfill distribution.

Table 5. Setting time and uniaxial compressive strength (UCS) of OS fly ash

Reference	Initial setting, min	Final setting, min	UCS (28-day), MPa	Ash type and origin
49, 82	20–80	30–190	10–14*	OS FA**, Auvere power plant, Estonia
79, 83	90	460	4.8	OS FA, Eesti power plant, Estonia
49, 82	40–360	348–1560	0.7–7*	OS FA, Enefit280 oil production, Estonia

* 1:3 ash/sand mortar

** OS FA – oil shale fly ash

7. Conclusion

This article reviews consolidation methods applicable to land stabilization in Estonian shallow mining areas. The stabilization of buildings located on or near quasi-stable areas, where the collapse of mine workings may cause sudden settlements on the ground surface, is the most urgent priority. While earthworks could be considered for sparsely populated mining areas with very shallow working depth, backfill injection through infill boreholes appears to be the most promising stabilization method. Additionally, backfill injection could help utilize the most widespread industrial solid wastes.

Finding suitable backfill that is environmentally acceptable, cost-effective, and possesses good infilling properties is essential. Due to high groundwater usage, low bleeding of backfill and very limited leaching of dangerous substances are important considerations in Estonian conditions. Local waste material from OS-powered energy production, OS fly ash, possesses suitable chemical and mineral properties to be used as a main component in Estonian backfilling grouts. Although OS fly ash properties are well-researched, this material has not been much used in backfills. With the modernization of the Estonian OS industry, the former pulverized fuel combustion has been replaced by CFB combustion – a shift that has had a notable effect on OS fly ash properties. OS fly ash properties from CFB combustion are compared to coal fly ash that is a well-known binder and bulk material in mine backfilling. Prior to applying OS fly ash in backfill grout, it is necessary to determine the backfill's flow parameters and its potential influence on groundwater. Further research is needed to establish optimum strength requirements for hardened backfill to be used to stabilize a typical Estonian mine. Unlike coal fly ash, OS fly ash-based grouts beneficially possess sufficient self-cementing properties commonly required for mine stabilization. However, the water demand of

OS fly ash is significantly higher than that of most coal fly ashes used in backfilling. Sufficient water supply is thus relevant for OS fly ash-based backfilling projects. On the positive side, the high water demand of OS fly ash-based grouts suggests low bleeding values. However, this assumption, as well as the grout's interactions with groundwater, must yet be confirmed with further experiments.

Data availability statement

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments

The publication costs of this article were partially covered by the Estonian Academy of Sciences.

References

1. Karu, V., Valgma, I., Kolats, M. Mine water as a potential source of energy from underground mined areas in Estonian oil shale deposit. *Oil Shale*, 2013, **30**(2S), 336–362. https://doi.org/10.3176/oil.2013.2S.12
2. Vassiljev, J., Aarniste, M., Rebane, K., Urtson, K. *Põlevkivi altkaevandatud alade varingute uuring. Lõpparuanne.* Tallinn, 2018. https://fond.egt.ee/fond/egf/8911
3. Reinsalu, E., Valgma, I. Geotechnical processes in closed oil shale mines. *Oil Shale*, 2003, **20**(3S), 398–403.
4. Karu, V. Stability problems in undermined areas. In: *8th International Symposium "Topical Problems in the Field of Electrical and Power Engineering. Doctoral School of Energy and Geotechnology II"*, January 11–16, 2010, Pärnu, Estonia (Lahtmets, R., ed.). Elektriajam, 2010, 134–137.
5. Väizene, V., Valgma, I. Methods for digitizing mine plans and data of mined out areas. In: *Closing Conference of the Project "Doctoral School of Energy and Geotechnology II"*, January 12–17, 2015, Pärnu, Estonia (Zakis, J., ed.). Tallinn University of Technology, 241–244.
6. Whaite, R. H., Allen, A. S. *Pumped-Slurry Backfilling of Inaccessible Mine Workings for Subsidence Control*. Vol. 8667. United States Bureau of Mines, 1975.
7. Roy, R., Chakraborty, S., Bisai, R., Pal, S. K., Mishra, S. Gravity blind backfilling of abandoned underground mine voids using suitable mix proportion of fill materials and method of filling. *Geotech. Geol. Eng.*, 2023, **41**, 1801–1819. https://doi.org/10.1007/s10706-022-02371-8

8. Kawalec, J., Grygierek, M., Koda, E., Osiński, P. Lessons learned on geosynthetics applications in road structures in Silesia mining region in Poland. *Appl. Sci.*, 2019, **9**(6), 1122. https://doi.org/10.3390/app9061122
9. Gray, R. E. Subsidence over abandoned mines: US experience. In: *Surface Subsidence Engineering: Theory and Practice* (Peng, S. S., ed.). CSIRO Publishing, Clayton, Victoria, 2020, 131–160.
10. Watson, P. D., Dennehy, J. P., O'Neill-Gwilliams, S., Parry, D. N., Fraser, I. W. Ground treatment and remediation of workings. In: *Abandoned Mine Workings Manual* (Parry, D. N. and Chiverrell, C. P., eds). Vol. C758D. CIRIA, London, 2019, 354–414.
11. Sevastjanova, A. Научно-технический отчет по теме «Разработать технологии заполнения выработаванного пространства сланцевой шахты». Silbet, Estonia, 1988. https://fond.egt.ee/fond/egf/4466
12. Valgma, I., Kattel, T. Low depth mining in Estonian oil shale deposit – Abbau von Ölschiefer in Estland. In: *Kolloquium Schacht, Strecke und Tunnel 2005*, April 14–15, 2005, Freiberg, Germany. TU Bergakademie, Freiberg, 2005, 213–223.
13. Valgma, I., Kolats, M., Karu, V. Streki toestamine põlevkiviaherainebetooniga. In: *Maapõue kasutamise arengud* (Västrik, A., Reinsalu, E., Vesiloo, P., Pastarus, J. R., Kõpp, V., Sein, O., Soosalu, H., Viilup, H., Tohver, T., eds). Tallinna Tehnikaülikooli Kirjastus, Tallinn, 2010, 33–38.
14. Walker, J. S. *State-of-the-Art Techniques for Backfilling Abandoned Mine Voids*. Information circular/1993. Vol. 9359. United States Department of the Interior, Bureau of Mines, 1993.
15. Brook, D. Reclamation of abandoned underground mines in the United Kingdom. In: *International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage: Abandoned Mine Lands and Topical Issues*. Vol. 4. United States Department of the Interior, Bureau of Mines, 1994, 163.
16. Zięba, M., Kalisz, P., Grygierek, M. The impact of mining deformations on road pavements reinforced with geosynthetics. *Arch. Min. Sci.*, 2020, **65**(4), 751–767. https://doi.org/10.24425/ams.2020.134145
17. Workman, J. L., Thompson, J. *Blasting for Abandoned-Mine Land Reclamation (Closure of Individual Subsidence Features and Erratic, Undocumented Underground Coal-Mine Workings). Final Report*. Calder and Workman, Inc., Washburn, USA, 1991. https://www.osti.gov/biblio/5788957
18. Potvin, Y., Thomas, E., Fourie, A. *Handbook on Mine Fill*. Australian Centre for Geomechanics, 2005.
19. Moser, A. K. *State of the Art of Backfill Technology in Underground Mining Excavations*. Master's thesis. Montanuniversität Leoben, Austria, 2015.
20. Sivakugan, N., Veenstra, R., Naguleswaran, N. Underground mine backfilling in Australia using paste fills and hydraulic fills. *Int. J. Geosynth. Ground Eng.*, 2015, **1**, 18. https://doi.org/10.1007/s40891-015-0020-8
21. UK Quality Ash Association. *Technical Data Sheet 3. Pulverised Fuel Ash for Grouting*, 2006.

22. Giacinto, J. F., Petzrick, P., Rafalko, L. G. Cost optimization for mine void stabilization projects: a deep mine case study. In: *2007 World of Coal Ash (WOCA*), May 7–10, 2007, Covington, USA, 13.
23. Johnson, D. Cementitious grouts – standards update 1999. In: *Specialist Techniques and Materials for Concrete Construction: Proceedings of the International Conference Held at the University of Dundee*, September 8–10, 1999, Scotland, UK (Dhir, R. K., Henderson, N. A., eds). Thomas Telford, Dundee, 1999, 41–48.
24. Scott, J. T. Sustainable alternatives to PFA in Scotland. In: *Procedia Environmental Science, Engineering and Management*, **4**, 2017, 301–307.
25. Colaizzi, G. J., Whaite, R. H., Donner, D. L. *Pumped-Slurry Backfilling of Abandoned Coal Mine Workings for Subsidence Control at Rock Springs, Wyo*. Information Circular 8846, United States Department of the Interior, Bureau of Mines, 1981.
26. Stone, D. The evolution of paste for backfill. In: *Mine Fill 2014. Proceedings of the Eleventh International Symposium on Mining with Backfill*. Australian Centre for Geomechanics, Perth, 2014, 31–38. https://doi.org/10.36487/ACG_rep/1404_0.3_Stone
27. Udd, J. E. Backfill research in Canadian mines. In: *Innovations in Mining Backfill Technology* (Hassani, F. P., Scoble, M. J., Yu, T. R., eds). CRC Press, Boca Rotan, Florida, 1989.
28. Behera, S. K., Mishra, D. P., Singh, P., Mishra, K., Mandal, S. K., Ghosh, C. N., Kumar, R., Mandal, P. K. Utilization of mill tailings, fly ash and slag as mine paste backfill material: review and future perspective. *Constr. Build. Mater.*, 2021, **309**, 125120. https://doi.org/10.1016/j.conbuildmat.2021.125120
29. Sheshpari, M. A review of underground mine backfilling methods with emphasis on cemented paste backfill. *Electron. J. Geotech. Eng.*, 2015, **20**(13), 5183–5208.
30. Shen, B., Poulsen, B., Luo, X., Qin, J., Thiruvenkatachari, R., Duan, Y. Remediation and monitoring of abandoned mines. *Int. J. Min. Sci. Technol.*, 2017, **27**(5), 803–811. https://doi.org/10.1016/j.ijmst.2017.07.026
31. Mahmadoliev, A. K., Makhmudov, D. R., Nurboboev, Y. T., Pardaev, F. S. Reducing the cost of backfill in the Kauldi gold mine. *IOP Conf. Ser.: Earth Environ. Sci.*, 2020, **614**, 012058. https://doi.org/10.1088/1755-1315/614/1/012058
32. Belem, T., Benzaazoua, M. Design and application of underground mine paste backfill technology. *Geotech. Geol. Eng.*, 2008, **26**(2), 147–174. https://doi.org/10.1007/s10706-007-9154-3
33. BRE Building Technology Group. *Stabilising Mine Workings with PFA Grouts: Environmental Code of Practice (BR 509)*. BREPress, 2009.
34. Choudhary, B. S., Kumar, S. Underground void filling by cemented mill tailings. *Int. J. Min. Sci. Technol.*, 2013, **23**(6), 893–900. https://doi.org/10.1016/j.ijmst.2013.11.003
35. De Souza, E., Archibald, J. F., Dirige, A. P. Economics and perspectives of underground backfill practices in Canadian mines. In: *Proceedings of the 105th*

Annual General Meeting of CIM. Canadian Institute of Mining, Metallurgy and Petroleum, Montreal, 2003.

36. Yin, S., Yan, Z., Chen, X., Wang, L. Effect of fly-ash as fine aggregate on the workability and mechanical properties of cemented paste backfill. *Case Stud. Constr. Mater.*, 2022, **16**, e01039. https://doi.org/10.1016/j.cscm.2022.e01039
37. Anastasiou, E. K. Effect of high calcium fly ash, ladle furnace slag, and limestone filler on packing density, consistency, and strength of cement pastes. *Materials*, 2021, **14**(2), 301. https://doi.org/10.3390/ma14020301
38. Nalbantoğlu, Z. Effectiveness of Class C fly ash as an expansive soil stabilizer. *Constr. Build. Mater.*, 2004, **18**(6), 377–381. https://doi.org/10.1016/j.conbuildmat.2004.03.011
39. Mohan, S., Gandhimathi, R. Removal of heavy metal ions from municipal solid waste leachate using coal fly ash as an adsorbent. *J. Hazard. Mater.*, 2009, **169**(1–3), 351–359. https://doi.org/10.1016/j.jhazmat.2009.03.104
40. Uysal, M., Akyuncu, V. Durability performance of concrete incorporating Class F and Class C fly ashes. *Constr. Build. Mater.*, 2012, **34**, 170–178. https://doi.org/10.1016/j.conbuildmat.2012.02.075
41. McCarthy, M. J., Dhir, R. K. Towards maximising the use of fly ash as a binder. *Fuel*, 1999, **78**(2), 121–132. https://doi.org/10.1016/S0016-2361(98)00151-3
42. Moreno, N., Querol, X., Andrés, J. M., Stanton, K., Towler, M., Nugteren, H., Janssen-Jurkovicová, M., Jones, R. Physico-chemical characteristics of European pulverized coal combustion fly ashes. *Fuel*, 2005, **84**(11), 1351–1363. https://doi.org/10.1016/j.fuel.2004.06.038
43. Mohebbi, M., Rajabipour, F., Scheetz, B. E. Evaluation of two-atmosphere thermogravimetric analysis for determining the unburned carbon content in fly ash. *Adv. Civ. Eng. Mater.*, 2017, **6**(1), 258–279. http://dx.doi.org/10.1520/ACEM20160052
44. Cao, D., Selic, E., Herbell, J.-D. Utilization of fly ash from coal-fired power plants in China. *J. Zhejiang Univ. Sci. A*, 2008, **9**(5), 681–687. https://doi.org/10.1631/jzus.A072163
45. EN 196-3:2016 – Methods of testing cement – Part 3: Determination of setting times and soundness, 2016.
46. EN 13395-2:2002 – Products and systems for the protection and repair of concrete structures – Test methods – Determination of workability – Part 2: Test for flow of grout or mortar, 2002.
47. EN 12350-2:2019 – Testing fresh concrete – Part 2: Slump test, 2019.
48. Clayton, S., Grice, T. G., Boger, D. V. Analysis of the slump test for on-site yield stress measurement of mineral suspensions. *Int. J. Miner. Process.*, 2003, **70**(1–4), 3–21. https://doi.org/10.1016/S0301-7516(02)00148-5
49. Uibu, M., Tamm, K., Viires, R., Reinik, J., Somelar, P., Raado, L.-M., Hain, T., Kuusik, R., Trikkel, A. The composition and properties of ash in the context of the modernisation of oil shale industry. *Oil Shale*, 2021, **38**(2), 155–176. https://doi.org/10.3176/oil.2021.2.04
50. Rice, G., Miles, N., Farris, S. Approaches to control the quality of cementitious

PFA grouts for nuclear waste encapsulation. *Powder Technol.*, 2007, **174**(1–2), 56–59. https://doi.org/10.1016/j.powtec.2006.10.022

51. Dave, N., Misra, A. K., Srivastava, A., Kaushik, S. K. Setting time and standard consistency of quaternary binders: the influence of cementitious material addition and mixing. *Int. J. Sustain. Built Environ.*, 2017, **6**(1), 30–36. https://doi.org/10.1016/j.ijsbe.2016.10.004
52. Snelson, D., Wild, S., O'Farrell, M. Setting times of Portland cement–metakaolin–fly ash blends. *J. Civ. Eng. Manag.*, 2011, **17**(1), 55–62. https://doi.org/10.3846/13923730.2011.554171
53. Zhang, S., Shi, T., Ni, W., Li, K., Gao, W., Wang, K., Zhang, Y. The mechanism of hydrating and solidifying green mine fill materials using circulating fluidized bed fly ash-slag-based agent. *J. Hazard. Mater.*, 2021, **415**, 125625. https://doi.org/10.1016/j.jhazmat.2021.125625
54. Singh, P., Ghosh, C. N., Behera, S. K., Mishra, K., Kumar, D., Buragohain, J., Mandal, P. K. Optimisation of binder alternative for cemented paste fill in underground metal mines. *Arab. J. Geosci.*, 2019, **12**(15), 462. https://doi.org/10.1007/s12517-019-4623-6
55. ASTM D7012-23. *Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures*, 2023.
56. Siitam, L.-O. *Researches and Analysis of Technological Solutions for Oil Shale Underground Longwall Mining with Backfilling of Outmined Areas in Conditions of Narva Opencast Mine*. Master's thesis. Tallinn University of Technology, Estonia, 2016. https://digikogu.taltech.ee/et/Item/c5e3e29b-3dae-44b1-b62b-2b0344eb04a3
57. Benzaazoua, M., Belem, T., Bussière, B. Chemical factors that influence the performance of mine sulphidic paste backfill. *Cem. Concr. Res.*, 2002, **32**(7), 1133–1144. https://doi.org/10.1016/S0008-8846(02)00752-4
58. Moon, G. D., Oh, S., Choi, Y. C. Effects of the physicochemical properties of fly ash on the compressive strength of high-volume fly ash mortar. *Constr. Build. Mater.*, 2016, **124**, 1072–1080. https://doi.org/10.1016/j.conbuildmat.2016.08.148
59. Barnes, D. I. Understanding pulverised coal, biomass and waste combustion – a brief overview. *Appl. Therm. Eng.*, 2015, **74**, 89–95. https://doi.org/10.1016/j.applthermaleng.2014.01.057
60. Woolley, G. R., Simpson, D. T., Quick, W., Graham, J. *Ashes to Assets? Studies of the Usefulness and Environmental Management of Ash from Coal Fired Power Stations*. UK, 2000.
61. Sear, L. K. A., Coombs, R., Yong, R. N., Thomas, H. R. The use of PFA as a fill material and the environment. In: *Geoenvironmental Engineering: Geoenvironmental Impact Management* (Yong, R. N., Thomas, H. R., eds). Thomas Telford, London, 2001, 33–38. https://doi.org/10.1680/gegim.30336.0006
62. ASTM C618-23e1. *Standard Specification for Coal Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, 2023.

63. ASTM C618-03. *Standard Specification for Coal Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, 2003.
64. Valgma, I. Mapping potential areas of ground subsidence in Estonian underground oil shale mining district. In: *Environment. Technology. Resources. Proceedings of the International Scientific and Practical Conference*, June 25–27, 1999, Rēzekne, Latvia, 227–232. https://doi.org/10.17770/etr1999vol1.1869
65. Karu, V. Dependence of land stability on applied mining technology. In: *11th International Symposium "Topical Problems in the Field of Electrical and Power Engineering. Doctoral School of Energy and Geotechnology"*, January 16–21, 2012, Pärnu, Estonia (Zakis, J., ed.). Tallinn University of Technology, 16–21.
66. Toomik, A. Assessment of the impact of underground mining on ground surface. In: *Impact of Oil Shale Mining and Processing on the Environment in North-East Estonia* (Liblik, V., Punning, J.-M., eds). Institute of Ecology, Tallinn, 1999, 109–129.
67. Sahu, P., Lokhande, R. D. An investigation of sinkhole subsidence and its preventive measures in underground coal mining. *Procedia Earth Planet. Sci.*, 2015, **11**, 63–75. https://doi.org/10.1016/j.proeps.2015.06.009
68. Backhaus, C., Mroz, A., Willenbrink, B. Coal mine gas from abandoned mines. *Pol. Geol. Inst. Spec. Pap.*, 2002, **7**, 33–40.
69. Selberg, A., Viik, M. Relationship between water quality and oil-shale mines in northern Estonia. In: *Water Quality Monitoring and Assessment* (Voudoris, K., Voutsa, D., eds). InTech-Open Access Publisher, 2012, 391–406.
70. Järvan, A. *Endistel põlevkivialadel asuvatele hoonetele kaevandamisega põhjustatud kahjustuste hindamine. Aruanne nr 2107-118*. EKIF OÜ, Tallinn, 2021.
71. Tamberg, I., Hansen, R. *Kukruse A-kategooria jäätmehoidla (Kukruse aherainemäe) korrastamiseks ettevalmistava projekti koostamine. Teostatavusuuring*. AS Infragate Eesti, IPT Projektijuhtimine OÜ, Ministry of Environment of the Republic of Estonia, Tallinn, 2015. https://docplayer.gr/43621451-Kukruse-a-kategooria-jaatmehoidla-kukruse-aherainemae-korrastamiseks-ettevalmistava-projekti-koostamine-projekti-sfos-kood.html
72. Klaas, H. *Stabilization of Post-Mining Areas and Expansion of Land Use Opportunities: A Case Study of the Kiviõli Oil Shale Mine*. Master's thesis. Tallinn University of Technology, Estonia, 2024.
73. Pastarus, J. R., Šommet, J., Valgma, I., Väizene, V., Karu, V. Paste fills technology in condition of Estonian oil shale mine. In: *Environment. Technologies. Resources. Proceedings of the International Scientific and Practical Conference*, June 20–22, 2013, Rēzekne, Latvia, 182–185. https://doi.org/10.17770/etr2013vol1.823
74. Tamm, I. *Uuring Ubja põlevkivi kaevanduskäikude püsivuse ja maapinna stabiilsuse hindamiseks*. Eesti Keskkonnauuringute Keskus, Tallinn, 2023. https://www.kik.ee/sites/default/files/uuring_ubja_polevkivi_kaevanduskaikude_pusivuse_ja_maapinna_stabiilsuse_hindamiseks.pdf
75. Lees, H., Järvik, O., Konist, A., Siirde, A., Maaten, B. Comparison of the ecotoxic properties of oil shale industry by-products to those of coal ash. *Oil Shale*, 2022, **39**(1), 1–19. https://doi.org/10.3176/oil.2022.1.01

76. Uibu, M., Somelar, P., Raado, L.-M., Irha, N., Hain, T., Koroljova, A., Kuusik, R. Oil shale ash based backfilling concrete – strength development, mineral transformations and leachability. *Constr. Build. Mater.*, 2016, **102**, 620–630. https://doi.org/10.1016/j.conbuildmat.2015.10.197
77. Siirde, A., Pihu, T., Konist, A., Järvik, O., Nešumajev, D., Maaten, B., Rannaveski, R., Sulg, M., Kirsimäe, K., Paiste, K., Liira, M., Mõtlep, R., Somelar, P., Leben, K., Paaver, P. *Põlevkivituhkade ohtlikkuse uuring*. University of Tartu, Tallinn University of Technology, Tallinn, 2019. http://www.digar.ee/id/et/nlib-digar:399360
78. Irha, N., Reinik, J., Jefimova, J., Koroljova, A., Raado, L.-M., Hain, T., Uibu, M., Kuusik, R. PAHs in leachates from thermal power plant wastes and ash-based construction materials. *Environ. Sci. Pollut. Res.*, 2015, **22**(15), 11877–11889. https://doi.org/10.1007/s11356-015-4459-x
79. Paaver, P., Paiste, P., Liira, M., Kirsimäe, K. Mechanical activation of the Ca-rich circulating fluidized bed combustion fly ash: development of an alternative binder system. *Minerals*, 2020, **11**(1), 3–19. https://doi.org/10.3390/min11010003
80. Pastarus, J.-R., Otsmaa, M., Šommet, J., Pototski, A., Kuusik, R. Improvement of current mining technology in Estonian oil shale mines. In: *Proceeding of the V-Th International Geomechanics Conference*, June 18–21, 2012, Varna, Bulgaria. Scientific and Technical Union of Mining, Geology and Metallurgy, Sofia, 2012, 275–279.
81. Lanzerstorfer, C. Fly ash from coal combustion: dependence of the concentration of various elements on the particle size. *Fuel*, 2018, **228**, 263–271. https://doi.org/10.1016/j.fuel.2018.04.136
82. Usta, M. C., Yörük, C. R., Hain, T., Paaver, P., Snellings, R., Rozov, E., Gregor, A., Kuusik, R., Trikkel, A., Uibu, M. Evaluation of new applications of oil shale ashes in building materials. *Minerals*, 2020, **10**(9), 765–783. https://doi.org/10.3390/min10090765
83. Raado, L.-M., Kuusik, R., Hain, T., Uibu, M., Somelar, P. Oil shale ash based stone formation – hydration, hardening dynamics and phase transformations. *Oil Shale*, 2014, **31**(1), 91–101. https://doi.org/10.3176/oil.2014.1.09
84. Fall, M., Benzaazoua, M., Ouellet, S. Effect of tailings properties on paste backfill performance. In: *Proceedings of the 8th International Symposia on Mining with Backfill*, September 19–21, 2004, Beijing, China, 193–202.
85. Pekrioglu Balkis, A. Properties and performance of a high volume fly ash grout. *Mar. Georesour. Geotechnol.*, 2020, **38**(1), 73–82. https://doi.org/10.1080/1064119X.2018.1552999
86. Leben, K., Mõtlep, R., Paaver, P., Konist, A., Pihu, T., Paiste, P., Heinmaa, I., Nurk, G., Anthony, E. J., Kirsimäe, K. Long-term mineral transformation of Ca-rich oil shale ash waste. *Sci. Total Environ.*, 2019, **658**, 1404–1415. https://doi.org/10.1016/j.scitotenv.2018.12.326
87. Dias, W. P. S., Nanayakkara, S. M. A., Ekneligoda, T. C. Performance of concrete mixes with OPC–PFA blends. *Mag. Concr. Res.*, 2003, **55**(2), 161–170. https://doi.org/10.1680/macr.2003.55.2.161

88. Fatema, N., Bhatia, S. K., Palomino, A. M. Flow behavior of impounded fly ash slurries using flow test. *Fuel*, 2023, **339**, 126906. https://doi.org/10.1016/j.fuel.2022.126906
89. Rakngan, W., Williamson, T., Ferron, R. D., Sant, G., Juenger, M. C. G. Controlling workability in alkali-activated Class C fly ash. *Constr. Build. Mater.*, 2018, **183**, 226–233. http://dx.doi.org/10.1016/j.conbuildmat.2018.06.174