In Situ Solidification and Stabilization of Coal Combustion Residuals: Potential Applications and Cost Analysis

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ABSTRACT

In Situ Solidification and Stabilization (ISS) is a proven environmental remediation technology that has been implemented to address soil, sediment, and groundwater remediation projects throughout the United States and internationally. This remediation technology should serve as an alternative coal combustion residual (CCR) closure and corrective action strategy.

Using results from a recent bench scale study conducted by Geo-Solutions, Inc., the authors have performed preliminary evaluations of the regulatory acceptance, implementability, sustainability, and estimated costs to apply ISS as a CCR impoundment closure technology. Using the bench-scale mix design results substantially reduces the uncertainty in developing engineering cost estimates for ISS of CCR impoundments. The analysis also includes consideration of potential future uses of the former impoundment following application of the ISS treatment methods.

Specific closure applications evaluated include full depth/complete ISS of a CCR storage area, shallow ISS as an alternate to or in conjunction with multi-layer capping, and ISS for containment purposes (mixed cut-off wall versus other vertical barrier technologies).

INTRODUCTION AND BACKGROUND

The U.S. Environmental Protection Agency’s (USEPA’s) April 17, 2015 Final Rule for Disposal of Coal Combustion Residuals (CCR) from Electric Utilities (Parts 257 and 261 of Title 40 of the Code of Federal Regulations “Final Rule”) established nationally applicable minimum criteria for the safe disposal of CCR in landfills and surface impoundments as well as requirements for closure of inactive facilities. In response to the Final Rule, utilities began evaluating potential options related to maintaining or closing their existing CCR storage facilities (landfills and impoundments). Two primary closure strategies for impounded CCR currently being contemplated and/or implemented by utilities are removal of CCR with off-site disposition as a beneficial use or placement in a subtitle D landfill; or cap-in-place closure.

An alternative strategy for inactive CCR surface impoundment closure that promotes both in-place closure and beneficial use of CCR in accordance with the Final Rule is In Situ Solidification and Stabilization (ISS).

In general, ISS is a method of mechanically mixing soil-like material and typically includes the addition of reagents for treatment or stabilization of the material being mixed. Types of soil mixing include in situ and ex situ mixing and is accomplished through many different means including: single auger drills, multi auger drills, horizontal axis, cutter wheels, trenchers, jetting and hydraulic excavators with either a rotary tool attachment or just the bucket.[1] Soil mixing has been used as a form of ground improvement in the geotechnical field for over 50 years. Soil mixing originated in the United States for geotechnical applications such as foundation support and earth retention structures in the 1950s before becoming popularized in Europe and Japan in the 1960s through 1980s. Soil mixing became more popular in the United States in the 1980s and started to be used for environmental applications in the 1980s and 1990s. Soil mixing eventually became an accepted remediation method for agencies including the USEPA and in turn became a widely used method.[2]

ISS is a remediation technology that can support CCR storage facility closure and corrective action strategy.

By applying the environmental remediation principles associated with ISS, CCR impoundments can be closed in situ through transformation of CCR into a structural fill material. ISS is a proven method for strengthening and stabilizing loose and/or contaminated soils and sediments, and offers a cost-effective closure option for CCR impoundments that does not require dewatering, excavation, or off-site disposal.

In general, the transformation of the ponded CCR to an in-place structural fill could be completed using a combination of established soil mixing techniques historically used for ground improvement and environmental remediation. Following ISS, the ponded CCR is transformed from a loose, weak potentially unstable material into an encapsulated and solidified cementitious monolith. The resulting monolith is permanent, not susceptible to significant leaching through contact with precipitation or groundwater (i.e., due to binding and encapsulation of CCR and creation of a low permeability material similar to clay liner systems), and does not require placement in a lined basin or off-site landfilling, capping, or long-term maintenance. Following completion of the ISS process, the land area occupied by the former impoundments can be returned to a productive use. Potential land uses of stabilized impoundments could include energy generation (such as solar or combined cycle), redevelopment as a commercial or industrial facility, park or recreational area, or ecological restoration.

Because the application of ISS transforms the ponded CCR into a structural fill material, the impoundments do not require backfilling with imported soil fill materials. Additionally, the ISS process generates treated swell material that can be used as a surface grading material. Depending on the proposed future use for the stabilized impoundment, ISS can be applied to a portion of the ponded CCR (as a cap), as a perimeter barrier wall, localized ground improvement for foundation-specific support, or as a full-depth structural fill material.

As summarized in Table 1, the use of ISS as a closure method of inactive impoundments meets the Final Rule criteria presented in 40 CFR 257.100

Table 1. Criteria Analysis – Inactive Impoundment Closure by Leaving CCR in Place

Criteria (40 CFR Part 257.100)	Applicability to In Situ Beneficial Use Proposal
Control, minimize, or eliminate to the maximum extent feasible, post closure infiltration of liquids into the waste and releases of CCR, leachate, or contaminated runoff to the ground or surface waters or to the atmosphere.	Following treatment via ISS, the stabilized CCR will be encapsulated and a low permeability monolith (with hydraulic conductivity less than 1×10^{-5} cm/sec) that will significantly limit the potential for surface water or groundwater infiltration contact or infiltrate the treated CCR. In addition, the ISS process can be designed using a wet grout application method, which limits the potential for release of CCR to the atmosphere.
Preclude the probability of future impoundment of water, sediment, or slurry.	Depending on future site use, the stabilized CCR can be graded and paved with surficial drainage conveyance systems or covered with soil and vegetated to promote drainage and evapotranspiration thus providing long-term stormwater management and preclude future impoundment of water, sediment, or slurry.
Include measures that provide for major slope stability to prevent the sloughing or movement of the final cover system.	Following application of ISS, the CCR will be encapsulated and bound in a cementitious matrix that will limit the potential for sloughing or movement of the materials. The resulting unconfined strength of the treated CCR will be similar to native soils (25 pounds per square inch or higher).
Minimize the need for further maintenance of the CCR unit.	The ISS process is a permanent treatment, which effectively binds and encapsulates the CCR within a cementitious matrix. As a result, the treated CCR unit requires little to no long-term maintenance other than monitoring and maintenance of surface soil cover systems (if installed).

Notes:
CCR: coal combustion residual
cm/sec: centimeters per second
ISS: In Situ Solidification and Stabilization

The use of ISS as a closure strategy also meets the Final Rule’s definition of beneficial use as summarized in Table 2.

Table 2. Criteria Analysis – Beneficial Use of CCR

Criteria (40 CFR Part 257.53)	**Applicability to ISS Applications**
The use of CCR provides a functional benefit.	The creation of an encapsulated monolith will serve as the structural fill material to close the impoundments and allow for redevelopment and reuse of the former impoundment areas.
The CCR to be utilized as part of this approach is a substitute for the use of a virgin material, conserving natural resources that would otherwise need to be obtained through practices, such as extraction or mining.	The CCR stored within the impoundments will be transformed and serve as a structural fill material. Impoundments that undergo removal of CCR generally require some form of slope stabilization and closure, including backfilling some or all of the impoundment areas. The backfill materials are typically clean soil fill or other type of structure fill material, which would require extraction from an off-site area and transported to the site.
The use of CCR needs to meet relevant product standards, applicable government regulations (when available).	The end use of the CCR (following in situ beneficial use) will exceed typical compaction and strength standards associated with civil construction. The end product will have a permeability of less than 1 x 10^{-5} cm/sec, which will effectively isolate the end product from future contact of surface water or groundwater within the impoundments.
Encapsulated beneficial use.	Treatment of impounded CCR via ISS methods binds the CCR into a solid matrix consistent with the Final Rule's definition of an encapsulated beneficial use. Localized improvement of CCR through creation of perimeter barrier walls via ISS would also meet the encapsulated beneficial use criteria.

Notes:
CCR: coal combustion residual
cm/sec: centimeters per second
ISS: In Situ Solidification and Stabilization

Traditional ISS mix designs rely on a combination of reagents such as Portland cement, ground blast furnace slag, and bentonite. The dosages of reagents are typically determined on a site-specific basis via bench-scale treatability studies and specific performance criteria (such as reduction in constituent of concern mobility and leaching, compressive strength, and permeability).

CCR currently stored in impoundments varies not only by original coal source, but other physical and chemical factors including the coal combustion process (and air pollution controls that may have been used), fly ash content, in-place moisture content, organic content, and stratification of the materials overs the years of placement. A treatability study can be used to value engineer traditional ISS mix designs to reduce the reagent dosage, improve workability during mixing, and limit (or enhance as needed) the generation of swell materials. Finally, where controls on leaching of specific metals are required, the reagents can be modified to provide additional long-term chemical stabilization of the ash in addition to the physical encapsulation offered by the cementitious reagents.

POTENTIAL APPLICATIONS OF ISS TO CCR IMPOUNDMENT CLOSURE

To evaluate the potential application of ISS to impounded CCR, a bench-scale treatability study was performed using samples obtained from a former coal fired power station in the eastern United States. This power station burned bituminous coal and collected fly ash using electrostatic precipitators. Ash was sluiced to ponds where the material settled from the sluice stream by gravity.[3] Based on the results of the treatability study, CCR may be stabilized using PC, with successful mix designs demonstrated using as little as 5% PC (by weight), and resulting 28-day unconfined compressive strength greater than 25 pounds per square inch (psi) or 175 kilopascals (kPa). In addition, the treatability study demonstrated that target hydraulic conductivities less than 1×10^{-5} centimeters per second (cm/sec) were also achieved with the addition of 5% to 7% PC. The lowest measured hydraulic conductivity for a stabilized CCR sample (after 28-days curing) was 2×10^{-6} cm/sec. As discussed in Moran et al. (2017)[3], future treatability studies may optimize the design using different types of cements or additives.

Table 3 presents an evaluation of potential ISS applications to support CCR impoundment closure, along with an estimated cost for treatment.

Table 3. Implementability and Cost Analysis – ISS Applications

ISS Application and Assumptions[1]	Implementability	Estimated Application Cost Range[2]
Full-depth ISS of Impounded CCR		
• CCR would be stabilized into a monolith of tangential columns • ISS performed using 10-foot-diameter mixing augers • Assumed 5% PC addition. • Assumed depth of 50 feet • Assumed CCR storage volume of 2,000,000 CY/2,400,000 Tons	• Requires planning and sequencing of mixing/curing strategy to allow equipment to work across impoundment. • Because of the typical size of the CCR impoundments (10s of acres), scale of implementation would require multiple large mixing rigs and multiple years to complete stabilization. • Proximity to potable water, electricity, and Portland cement suppliers required to maximize cost effectiveness. • Some pre-work (such as embankment stabilization and site improvements) may be required before implementation. • Depending on final contemplated use of stabilized impoundment, may require site grading and placement of clean fill and vegetation layer to limit potential for ponding of surface water. • Full-depth ISS could be applied to localized areas within an impoundment to support targeted reuse within a portion of the impoundment.	Cost/CY: $35 – $45 Cost/Ton: $30 – $37

ISS Application and Assumptions[1]	Implementability	Estimated Application Cost Range[2]
Mixed-In-Place ISS Cap on CCR Impoundment		
• Assumed 5-foot-thick cap • 30-acre impoundment surface • Assumed 7% PC addition • Mixing performed using excavators with rotary tool attachments	• Similar implementability challenges and concerns as previously listed under full-depth ISS. • Physical conditions of underlying CCR may require additional design to create floating cap surface. • Additional testing and potential pilot studies needed to demonstrate longevity of stabilized cap and resistance to weathering/fracturing. • May require mix design optimization to enhance long-term stability and resistance to weathering. • To meet the surface cover requirements presented in 40 CFR 257.100, would need to demonstrate hydraulic conductivity of stabilized cap is less than or equal to permeability of any bottom liner system or natural subsoils, or $1x10^{-5}$ cm/sec, whichever is lower. • Final cover system may also require an infiltration layer that contains a minimum of 18 inches of earthen material and vegetative cover, or other surface water management system that meets 40 CRF 257.100 and is compatible with contemplated future use of the impoundment surface.	Cost/CY: \$25 – \$35 Cost/Ton: \$20 – \$30 Cost/SF: \$4 – \$7
Mixed-In-Place Containment and ISS Cap		
• Containment barrier constructed around 30-acre impoundment • Depth of barrier 60 feet; keyed into underlying confining layer • 5-foot-thick mixed-in-place cap • Assumed 7% PC addition • Barrier installed using 4-foot diameter augers, and consisting of overlapping columns • Cap installed using excavators with rotary tool attachments	• Similar implementability challenges and concerns as previously listed applications. • Could also be applied to support varied future uses on the impoundment surface, including providing access to wet areas within a large impoundment without first requiring dewatering.	Cost/CY: \$37 – \$45 Cost/Ton: \$30 – \$40 Cost/SF: \$7 – \$12

Notes:

1. Estimated range of costs include mobilization/demobilization, nonunion labor, equipment, and materials to perform the contemplated stabilization activities.
2. Baseline conditions for CCR to be treated assumed range of density from 1.2 – 1.4 Tons/cubic yard; in-place moisture content of up to 20%; and total organic content (as measured by loss on ignition) of up to 5%. Estimated costs do not include placement of clean fill, grading or revegetation of the treated impoundment.

CCR: coal combustion residual
CY: cubic yard
ISS: In Situ Solidification and Stabilization

SUSTAINABILITY

Use of ISS as a closure strategy is a sustainable alternative as compared with impoundment excavation or soil capping. Primary sustainability benefits associated with use of ISS as a closure strategy are:

- Reduced impoundment dewatering – ISS can be performed in a wide range of CCR moisture conditions. Little to no impoundment dewatering may be needed to implement ISS, short of removing ponded surface water.
- Reduces need for import of fill materials – because ISS transforms impounded CCR to a cementitious structural fill material, the Ponds do not require backfilling with imported materials. Additionally, the ISS process generates treated swell material that can be used as a surface grading material.
- Based on preliminary calculations, the overall carbon footprint of closing a CCR impoundment using ISS is approximately 60% less than the estimated greenhouse gases generated during a traditional excavation and backfill-type closure.

Based on the results of the bench scale treatability study, as well as the regulatory review and cost analysis, ISS can serve as an effective tool to support closure of CCR impoundments. In addition, the enhanced strength of the stabilized materials can support future redevelopment, allowing the former CCR impoundment land areas to return to a beneficial use of the utility and/or community.

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