

# Dry Binder Mixing of Field Trial Investigation Using Soil Mix Technology: A Case Study on Contaminated Site Soil

M. Allagoa, A. Al-Tabbaa

**Abstract**—The study explores the use of binders and additives, such as Portland cement, pulverized fuel ash, ground granulated blast furnace slag, and MgO, to reduce the concentration and leachability of pollutants in contaminated site soils. The research investigates their effectiveness and associated risks of binders, with a focus on Total Heavy Metals (THM) and Total Petroleum Hydrocarbon (TPH). The goal of this research is to evaluate the performance and effectiveness of binders and additives in remediating soil pollutants. The study aims to assess the suitability of the mixtures for ground improvement purposes, determine the optimal dosage, and investigate the associated risks. The research utilizes physical (unconfined compressive strength) and chemical tests (batch leachability test) to assess the efficacy of the binders and additives. A completely randomized design one-way ANOVA is used to determine the significance within mix binders of THM. The study also employs incremental lifetime cancer risk (ILCR) assessments and other indices to evaluate the associated risks. The study finds that Ground Granulated Blast Furnace Slag (GGBS): MgO is the most effective binder for remediation, particularly when using low dosages of MgO combined with higher dosages of GGBS binders on TPH. The results indicate that binders and additives can encapsulate and immobilize pollutants, thereby reducing their leachability and toxicity. The mean unconfined compressive strength of the soil ranges from 285.0-320.5 kPa, while THM levels with a combination of Ground granulated blast furnace slag and Magnesium oxide, Portland cement and Pulverised fuel ash were less than 10 µg/l. Portland cement was below 1 µg/l. The ILCR ranged from 6.77E-02 - 2.65E-01 and 5.444E-01 - 3.20 E+00, with the highest values observed under extreme conditions. The hazard index (HI), risk allowable daily dose intake (ADI), and risk chronic daily intake (CDI) were all less than 1 for the THM. The study identifies MgO as the best additive for use in soil remediation.

**Keyword**—Risk daily dose intake, risk chronic daily intake, incremental lifetime cancer risk, ILCR, novel binders, additives binders, hazard index.

## I. INTRODUCTION

SOIL serves as a perfect pointer for environmental pollution and environmental risk for human exposure. Soil is the primary environmental sink for PAHs in the terrestrial environment when compared to other sinks [1]. Soil TPH and PAHs contamination have a direct effect on public health via ingestion, inhalation, or dermal contact [2]-[5]. Petroleum hydrocarbons are prone to enrichment in soils where they are most retained for a long time as a result of their persistence and hydrophobicity [6]-[8]. As a result, the soil is usually

M. Allagoa is with Environmental Soil Science, University of Aberdeen, King's College, Aberdeen, AB24 3FX, Scotland, United Kingdom (e-mail: maryallagoa@gmail.com).

considered as the main reservoir for PAHs in the environment. Studies on soil contamination by PAHs are necessary to reduce the risk of human exposure and environmental pollution. Remediated land may improve the restoration of urban areas, as a result, decreases greenfield development [9]-[11]. Educational bodies have undertaken a significant amount of stabilization/solidification over the past two decades. The application of solidification/stabilization (S/S) contributes to reducing the level of toxins in the environment [12]. At present, US Environmental Protection Agency (USEPA) identifies S/S as one of the most demonstrated offered technologies for land removal of most contaminated and dangerous waste [13], [14]. S/S technology reduces the mobility of inorganic and organic compounds [15]. S/S technology mixing with dry binders requires more vigorous mixing when compared to wet binders. However, the strength of the samples may be greater in dry than wet binders. Zeolite, GGBS, and/or ash together with magnesia are likely alternatives to S/S binder application [12]. These alternative binders were efficient in SMiRT project field and laboratory trials when compared to the novel binders. The health risk assessment of heavy metals in Nigeria by [16] remunerated how the human body may be exposed to pollutants in soil via oral ingestion, dermal contact, and inhalation of soil particles.

The main objectives of this research were to determine the effectiveness of these binders and additives to reduce the concentration of total heavy metals and total petroleum hydrocarbon on polluted soil. The research addresses the following questions: What is the effectiveness of different binders and additives in soil remediation? What is the optimal dosage required to reducing pollutant concentration and leachability? Which binder or additive is the most effective?

## II. MATERIALS AND METHODS

This work determines the performance of field trials samples with dry binders.

### A. Binder Materials and Dosages

Binders vary from conventional to novel binders (see Tables I-IV).

### B. Soil Mix Process

In-situ soil mixing was employed in which a hollow rotating

A. Al-Tabbaa is with Department of Engineering, University of Cambridge, CB2 1PZ, United Kingdom.

shaft equipped with cutting and mixing augers, was placed above the tip of the shaft and blended into the soil with binders. The aim is to improve the physical, chemical, and mechanical properties of the soil without excavation. The use of augers or mixing tools is to break up the soil sufficiently before the binders are introduced. This is then followed by a number of mixing cycles depending on the soil type to ensure homogeneous mixing. Soil mixing can be deep or shallow: deep mixing can be carried out with the use of augers while shallow mixing uses several pieces of equipment such as blenders or mass stabilization and backhoes. Deep soil mixing augers have diameters between 0.6-1.2 m and can reach a depth of up to 35 m by using single or multi-shafted while shallow mixing augers have a diameter between 1 m to 4 m and up to 10 m.

TABLE I  
CONVENTIONAL AND NOVEL BINDERS

Binders	Obtained	Reference
Portland Cement (PC)	Blue Circle, Lafarge, UK	[12]
Pulverized Fuel Ash (PFA)	UK Quality Ash Association (UKQAA).	
GGBS	Civil and Marine Ltd, UK.	
MgO	Richard Baker Harrison Ltd, UK	
Zeolite used was a Clinoptilolite	Kentish Minerals, UK	

TABLE II  
COMPOSITION OF THE CEM I BASED MIXES APPLIED IN THE FIELD TRIALS USING DRY MIXING

Mix No.	Binder	Binder-content (wt%)	CEMI (%)
CFD1	CEM I	2.5	2.5
CFD2	CEM I	5	5
CFD3	CEM I	10	10

CFD2 not surfaced samples

TABLE III  
COMPOSITION OF THE CEM I-PFA-BASED MIXES APPLIED IN THE FIELD TRIALS USING DRY MIXING

Mix No	Binder	Binder Content (wt%)	CEMI (%)	PFA (%)	Zeolite (%)
CPFD1	CEM I:PFA (1:3)	5	1.25	3.75	-
CPFD2	CEM I:PFA <sup>1</sup> (1:3)	5	1.25	3.75	-
CPFD3	CEM I:PFA <sup>2</sup> (1:3)	5	1.25	3.75	-
CPFD4	CEM I:PFA <sup>3</sup> (1:3)	5	1.25	3.75	-
CPFD5	CEM I:PFA:ZEOLITE (2.2:6.7:1)	2.5	0.55	1.69	0.25
CPFD6	CEM I:PFA:ZEOLITE (2.2:6.7:1)	5	1.11	3.38	0.5

Only mix 6 was surface sampled; <sup>1</sup>: 2 × mixing speed; <sup>2</sup>: 2× mixing time; <sup>3</sup>: 4× treated area

TABLE IV  
COMPOSITION OF THE MgO-BASED MIXES APPLIED IN THE FIELD TRIALS WITH DRY MIX

Mix No.	Binder	Binder content (wt%)	MgO (%)	GGBS (%)
MgFD1	GGBS:MgO (4:1)	2.5	0.5	2
MgFD2	GGBS:MgO (4:1)	5	1	4
MgFD3	GGBS:MgO (4:1)	10	2	8
MgFD4	GGBS:MgO (9:1)	10	1	9
MgFD5	GGBS:MgO(9:1)	5	0.5	4.5
MgFD6	GGBS:MgO (9:1)	2.5	0.25	2.25
MgFD7	GGBS:MgO(19:1)	2.5	0.13	2.38
MgFD8	GGBS:MgO(19:1)	5	0.25	4.75
MgFD9	GGBS:MgO(19:1)	10	0.5	9.5



(a)



(b)

Fig. 1 The treated areas at the SMiRT project trials site (a) triple auger treatment areas and (b) mass stabilization areas courtesy of [17]

### C. Design Criteria

Design criteria provide insight into the performance of the binders and hence the effectiveness of the use of S/S treatment technology. These criteria are categorized into physical and chemical tests [18]. Physical tests determine the quality of the binders, the quantity required to be used, and homogeneity in mixing which include durability, permeability, and strength. Chemical tests involve determining the leaching behaviour of stabilized material [18]. The natural moisture content of the two soils was 10%. The soil and groundwater were contaminated with a mixture of heavy metal and organic contaminants including concentrations of up to 3000 mg/kg of lead and copper, 2000 mg/kg of mineral oil, and 9000 mg/kg of hydrocarbons. The soil had a water content of 24.9% with liquid and plastic limit of 29.6% and 23.8% respectively. Design criteria were chosen based on physical and chemical properties including unconfined compressive strength, leachability and leachate pH.

### D. Testing Procedures

$$\text{Plastic limit} = \frac{\text{weight of water}}{\text{weight of oven-dry soil}} \times 100 \quad (1)$$

$$\text{Plasticity index} = \text{Liquid limit} - \text{Plastic limit} \quad (2)$$

$$PI = LL - PL$$

$$MC = 100\% \times \frac{W_{wt} - W_{dt}}{W_{dt} - W_t}$$

where MC: the moisture content; Wwt: the weight of the moisture specimen with tare; Wdt: the weight of the dried specimen with tare; Wt: the weight of the container.

$$\text{Liquidity Index } LI = \frac{NM - PL}{PI} \quad (3)$$

where NM: the soils moisture content, in percent; PL: the calculated plastic limit; PI: the calculated plasticity index.

$$\text{Liquid limit} = MC \% \text{ Mass of oven - dried soil}$$

$$MC \% = \frac{\text{Mass of water}}{\text{Mass of oven-dried soil}} \times 100$$

$$\text{Water content } (\%) = \frac{\text{weight of wet samples} - \text{weight of dry samples}}{\text{weight of wet samples}} \times 100$$

#### i. Leachability Test

The batch leachability test is 24 hours to ensure that equilibrium conditions are reached to make the comparison applicable to a wider variety of materials. The experimental protocol followed British Standard BS 12457-2. The liquid-to-solid ratio (L/S) was kept at 10:1. The pH of the de-ionized water was between 6-7 and CO<sub>2</sub> was added. The bottles contained the liquid-to-solid ratio (L/S) of 10:1 and were on a roller table (rotation speed 10 rpm) for 24 hours at 20 °C. After the test, the bottles were on the table to allow the suspended solid of sorbent to settle. Once the sorbent settled the pH was measured with a Fisher Scientific accumet™ AP-71. Then the supernatant was filtered in a 0.45 μm filter and a syringe to measure 10 ml into a scintillating vial glass bottle and ready for chemical analysis using a typical optima 7000 DV ICP-OES inductively coupled plasma machine detection in μg/(ppb) based on three standard deviations. All values were obtained using axial viewing, a Gemcone™ nebulizer and cyclone spray chamber and a 10-second integration. The detection limit and wavelength of Cr, Cu, Pb, Ni and Zn were 0.25, 0.9, 1.4, 0.4 and 0.2 μg/l while the wavelength of 267.76, 224.70, 220.35, 231.60, 206.20 nm respectively. For the TPH analysis, 5 ml of Hydrochloric acid and 30 ml of Dichloromethane plus 400 ml of leachant were added into the conical flask for the first extract. The solutions were shaken by hand for about 1 min and settled. In total, 90 ml of dichloromethane was for three extracts and 10 ml was measured into a container. This process took place three times per sample in a fume hood and left for 24 h. After 24 h, the container with the dried TPH result was recorded on a weighed balance (where 0.3048 l = 1 kg).

#### ii. Unconfined Compressive Test

The UCS test specimens were 50 mm in diameter and 100 mm in height and have a UNIFRAME testing strength with 1.44 mm/mins displacement rate and an automatic

electromechanical compression/machine of 50 kN. The UCS test specimens were 50 mm in diameter and 100 mm in height. Both ends of the specimen were made flat to within ± 0.05 mm. The vertical load was applied axially at a constant rate of strain of 1.44 mm per minute until failure from which the strength was calculated.

$$\text{Strain } (\epsilon) = \frac{\Delta L}{L} = \frac{(\text{height of sample} - \text{failure weight})}{\text{height of sample}} \quad (4)$$

$$\text{Corrected load } (P)(kN) = \text{Machine failure} * \text{load gauge} \quad (5)$$

$$\text{Area of failed sample } (A_o) = \frac{V}{H} \quad (6)$$

$$\text{Stress } (\partial) \left( \frac{kN}{m^2} \right) = \frac{P(1-\epsilon)}{A_o} \quad (7)$$

#### E. Risk Assessment

The ILCR assessment (unitless) in terms of direct ingestion, dermal contact and inhalation are as follows:

$$ILCRS_{\text{Ingestion}} = CS \times (CSF_{\text{Ingestion}} \times \left( \frac{BW}{70} \right) SQRT(3) \times IR_{\text{soil}} \times EF \times ED) \div BW \times AT \times 10^6 \quad (8)$$

$$ILCRS_{\text{Dermal}} = CS \times (CSF_{\text{dermal}} \times \left( \frac{BW}{70} \right) SQRT(3) \times SA \times AF \times ABS \times EF \times ED) \div BW \times AT \times 10^6 \quad (9)$$

$$ILCRS_{\text{Inhalation}} = CS \times (CSF_{\text{Inhalation}} \times \left( \frac{BW}{70} \right) SQRT(3) \times IR_{\text{air}} \times EF \times ED) \div BW \times AT \times PEF \quad (10)$$

where CS is the pollutant concentration of soils (μgkg<sup>-1</sup>). CSF is carcinogenic slope factor (mgkg<sup>-1</sup>d<sup>-1</sup>)<sup>-1</sup>. BW is body weight (kg). AT is the average life span (year). EF is the exposure frequency (d year<sup>-1</sup>), ED is the exposure duration (year), IR<sub>air</sub> is the inhalation rate (m<sup>3</sup> d<sup>-1</sup>), IR<sub>soil</sub> is the soil intake rate (mg d<sup>-1</sup>), SA is the dermal surface exposure (cm<sup>2</sup> d<sup>-1</sup>), AF is the dermal adherence factor (mg cm<sup>-2</sup>), ABS is the dermal adsorption fraction, and PEF is the soil dust produce factor (m<sup>3</sup> kg<sup>-1</sup>).

The determination of carcinogenic slope factor was based on the cancer-causing ability of BaP; CSF Ingestion, CSF Dermal, and CSF Inhalation of BaP were 7.3, 25, and 3.85 (mg kg<sup>-1</sup> d<sup>-1</sup>)<sup>-1</sup>, respectively [19]-[21]. The normal and extreme conditions represent the average and maximal exposure time and exposure possibility, respectively.

Other body function related parameters were based on the Risk Assessment Guidance of Beijing Municipal Environmental Protection Bureau [22]. The normal and extreme conditions represent the average and maximal exposure time and exposure possibility, respectively. The total risks were the sum of risks associated with each exposure route [24], [25].

#### F. Heavy Metal Exposure Assessment Quantification

For dermal contact with soil, the allowable daily dose intake (ADI) was calculated with:

$$ADI = CS \times CF \times SA \times AF \times ABS \times EF \times ED \div (BW \times AT) \quad (11)$$

or ingestion of chemical in soil the chronic daily intake (CDI) was calculated using:

$$CDI = CS \times IR \times CF \times FI \times EF \times ED \div (BW \times AT) \quad (12)$$

where FI: Fraction Ingestion = 0.5 unitless [26]; DAF: Dilution Attenuation Factor = 1 [27]; CF: Conversion Factor = 0.000001 kg/mg [26], CS: Chemical Concentration in soil; Cancer Potential Factor (CPF); 1.7E-03, FI – 0.5 unitless; Conversion Factor: 0.000001; ORAL RfD: 6.72E-03, Dermal RfD: 1.50E-02.

TABLE V  
PARAMETERS USED IN ILCR ASSESSMENT [22], [23].

Exposure variables	Unit	child		adult	
		normal	extreme	normal	extreme
Body weight (BW)	kg	15	15	70	70
Exposure frequency (EF)	d year <sup>-1</sup>	350	350	350	350
Exposure duration (ED)	year	2	6	7	24
Inhalation rate IRair	m <sup>3</sup> d <sup>-1</sup>	5	5	20	20
Soil intake rate (IRsoil)	mg d <sup>-1</sup>	200	200	100	100
Dermal Surface Exposure (SA)	cm <sup>2</sup> d <sup>-1</sup>	1800	1800	5000	5000
Dermal Adherence factor (AF)	mg cm <sup>-2</sup>	0.2	1	0.2	1
Dermal Absorption fraction (ABS)	Dimensionless	0.1	0.1	0.1	0.1
Averaging Life Span (AT)	year	70	70	70	70
Soil dust produce factor (PEF)	m <sup>3</sup> kg <sup>-1</sup>	1.32du <sup>9</sup>	1.32du <sup>9</sup>	1.32du <sup>9</sup>	1.32du <sup>9</sup>

### 1. Exposure Hazard Assessment

Hazard quotient (HQ) was calculated using:

$$HQ = CDI \left( \frac{mg}{kg} \cdot day \right) \div RfD \left( \frac{mg}{kg} \cdot day \right) \quad (13a)$$

$$HI = \sum HQ_i \quad (13b)$$

where, I = increment; HI = Hazard Index for a specific exposure pathway; HQ<sub>i</sub> = Hazard Quotient for COPC I; HQ < 1 = Safe while HQ > 1 = Unsafe. The total chronic hazard attributable to exposure to all COPCs through a single exposure pathway is known as a Hazard Index (HI).

### 2. Exposure Risk Assessment

$$Risk = CDI \left( \frac{mg}{kg} \cdot day \right) \times \text{Cancer Potential Factor (CPF)} \left( \frac{mg}{kg} \cdot day \right) \quad (14)$$

or

$$Risk = ADI \left( \frac{mg}{kg} \cdot day \right) \times \text{Cancer Potential Factor (CPF)} \left( \frac{mg}{kg} \cdot day \right) \quad (15)$$

### G. Statistical Analysis

All experiments were conducted in triplicate.

$$STDEV (\sigma) = \text{SQRT} \sum (x_i - \mu)^2 \div N \quad (16)$$

F (The variance ratio for the overall test) = MST ÷ MSE (17)

$$MST(\text{mean squares due to groups}) = \frac{\sum_{i=1}^k (T_i^2 / n_i) - G^2 / n}{\{(K - 1)\}}$$

where G: the grand total of all observations, T<sub>i</sub>: a group total, n<sub>i</sub>: the number in group, n: total number of all observations.

$$MSE(\text{mean squares due to error}) = \frac{\left\{ \sum_{i=1}^k \sum_{j=1}^{n_i} Y_{ij}^2 - \sum_{i=1}^k (T_i^2 \div n_i) \right\}}{\{n - k\}}$$

The correlation theory was used to determine the degree of agreement between experimental results. From the correlation theory, the coefficient of correlation R is given by:

$$R^2 = \frac{N \sum xy - (\sum x)(\sum y)}{\{(N \sum x^2 - (\sum x)^2)(N \sum y^2 - (\sum y)^2)\}^{1/2}}$$

where N: No. of experimental points; X: Independent variable; Y – Independent variable.

## III.. RESULT AND DISCUSSION

The study collects physical and chemical data from the batch leachability test and the unconfined compressive strength test. The collected data are analysed using statistical tools, such as ANOVA, to determine the significance of differences between the binders. The ILCR and other indexes are also used to evaluate the associated risks, and the results are presented in Tables VIII and IX.

The metals investigated were Chromium (Cr), Copper (Cu), Nickel (Ni), Lead (Pb), and Zinc (Zn). Samples were produced in triplicate and then tested in the laboratory at 28 days. The treated soil sections were cored at 28 days with a window sampler at 0-4 m depth. The diameter of the samples obtained reduced per mm from 85 to 75 to 65 to 55, respectively. The cores were physically examined. Most cores were of high quality, it was clear that some cores were of better quality than others.

### CEM I

The leachability of all mixes with CEM I in the S/S treated are shown in Tables VI-VIII for Cd, Ni, Zn, Cu, Pb, and TPH, respectively. These tables demonstrate a significant effect of binder dosage of pH on the leaching trend of TPH in the binder mixes. However, CEM I binder mixes of 5% after the S/S mix immobilize with the lower amount of 21.6 mg/kg TPH when compared to 2.5% (23.7 mg/kg) and 10% (22.6 mg/kg) respectively. This may agree with some studies that the solubility of mainly organic pollutants may depend on the leachate pH [28]. In addition, the density obtained indicates that low density may lead to low pH with the addition of more CEM I which may affect the leachate pH, likewise the density of the sample mixes. More so, CEM I (2.5%) with a pH of 10.2 and density of 1797.5 kg/m<sup>3</sup>, CEM I (5%) and CEM I (10%) of pH 10.4 and 10.7 with a density of 1819.1 and 1840.7 kg/m<sup>3</sup> respectively, show the CEM I mixes had a positive correlation on the parameters investigated except TPH and UCS

parameters that were negative. For Cr, there was a significant difference ( $p = 0.015$ ), meanwhile, 5% CEM I increased significantly when compared to 2% and 10% of CEM I mixes. The effect of 2.5% and 10% CEM I was much lower when compared to 10% and were not significantly different. The leachability of Ni shows a highly significant difference in the mixes, however, CEM I 2.5% was found to have a higher value of Ni of the three mixes. For Pb, the mixes were not a significant difference but 5% CEM I mixes remain with the highest value while Zn with 5% CEM I mixes leached with higher concentration. Further to this, metal leachability decreased with an increase in binder dosage but 5% irrespective of leachate pH 10.4 was higher than 2.5% CEM I pH and exhibited a higher concentration of the heavy metals investigated when compared to 2.5% CEM I mixes. For CEM I individual metal, the highest concentration was in this order  $Cu > Ni > Cr > Zn > Pb$ . Lead, even at extremely low concentrations, is toxic and can cause many diseases, including an increased risk of cancer. Lead was evaluated with the lowest concentration, and still poses a great risk to humans and animals via ingestion of soil and dermal contact [16].

#### GGBS:MgO

In all the mixes, GGBS % mixes were more in quantity than MgO. The ratio of 4:1 of the mixes shows a significant difference in the TPH values. With the double addition of 8% GGBS and 2% MgO, TPH leachability remains lowest when compared to the lower percentage added to the other mixes. These may imply that an increase in binder dosage enhances a low TPH concentration as the decrease in density increases the strength of the sample, thereby minimizing the level of pollutant leached. More to this, the leachate pH may have an effect on the level of THMs, as higher pH in alkaline may be found to show a low level of THM [12]. The ratio of the mixes 9:1 shows a highly significant difference with the leachability trend. The mean UCS of 50.4-150.0 kPa was observed on some of the mixes. Again, the mixes with the highest leachate pH had the lowest THM concentration, however, TPH was generally below 9 mg/kg while the density accounted for between 2100.1-2379.9 kg/m<sup>3</sup>. For the ratio 19:1 of GGBS: MgO mixes, TPH was up above 9 mg/kg, indicating that too many differences in percentage between these binders could yield higher TPH concentration that may be leached. Additionally, a highly

significant difference in the mixes was observed, and a high average UCS of 80.0 – 1100.0 kPa.

#### CEM I: PFA

The TPH concentration of 4.0 – 60.1 mg/kg was between the mixes, however, the surface sample with the same amount of CEM I and PFA had the highest concentration level that may be leached. There was a highly significant difference in the mixes, as an increased percentage of Zeolite to 5% affected the level of TPH concentration to reduce from 28.7 to 10.2 mg/kg. Leachate pH was between 10.1-12.3 which may affect the level of THM (1.0-20.0 µg/l) as they were significantly different [28]. The double addition of Zeolite on mix 6 rather reduces the UCS value and increases the density slightly from 2000.0 to 2000.6 kg/m<sup>3</sup>. In addition, the extra mixing time of mix 4 reduces the level of THM where increasing the mixing speed may have no effect on the mix. The ANOVA results showed that a combined effect of the blended sample mixes with respect to binder dosage and type resulted in a significant difference. This implies that the interaction of the experimental design parameters significantly affected the mixes as  $p < 0.05$ .

#### Risk Assessment

The ILCR estimates the exposure risk for two age groups of adults, and children. Risk analysis indicates that the ILCR for adults in normal and extreme adult conditions were of 5.44 E-01 – 3.20 E+00 and 8.57 E-01 – 8.46 E+00, which may indicate high potential cancer risk; whereas for the children the risk values are less than 1, indicating less significant cancer risk.

We investigated the ILCR assessments associated with TPH exposure through three pathways: ingestion, dermal, and inhalation. Our results yielded 1.35 E+00, 1.43 E+01, and 7.56 E+01 for  $\sum ILCR_{\text{ingestion}}$ ,  $\sum ILCR_{\text{dermal}}$ , and  $\sum ILCR_{\text{inhalation}}$ , respectively. Ultimately, the three exposure pathways for humans are via ingestion of chemicals in the soil, ingestion in drinking water, and dermal contact with the soil were assessed. The order  $\sum ILCR_{\text{inhalation}} > \sum ILCR_{\text{dermal}} > \sum ILCR_{\text{ingestion}}$  of the ILCR pathway had the highest cancer value. As indicated, the HI values were all less than 1 [16]. In a nutshell, inhalation pathways contribute the most significantly to cancer risk compared to dermal and ingestion.

TABLE VI  
 THE PHYSICAL AND CHEMICAL PARAMETER RESULTS OF N ± 3 CEM I DRY MIX

Binder	Sample ID	TPH (mgkg <sup>-1</sup> )	Leachate pH	Density (kg/m <sup>3</sup> )	UCS (kPa)	Cr	Cu	Ni	Pb	Zn
CEM I	1A	24.3	9.8	1790	590	0.002	0.09	0.19	0.0001	0.002
	2A	22	10.4	1844	250	0.01	0.22	0.07	0.002	0.01
	3A	22.7	11	1855	23	0.002	0.07	0.02	0.001	0.001
	1B	22.5	9.5	1800	563	0.001	0.07	0.15	0.0002	0.003
	2B	21.9	10.7	1809	261	0.02	0.21	0.05	0.001	0.02
	3B	23.1	10.9	1820	20	0.004	0.06	0.04	0.003	0.002
	1C	24.1	9.7	1801	577	0.002	0.09	0.17	0.0001	0.001
	2C	20.9	10.8	1820	259	0.03	0.24	0.06	0.003	0.01
	3C	22.2	11.2	1833	22	0.003	0.08	0.03	0.001	0.001

TABLE VII  
CEM I:PFA PHYSICAL AND CHEMICAL TEST RESULT

Sample ID	TPH (mgkg <sup>-1</sup> )	Leachate pH	Density (kg/m <sup>3</sup> )	UCS (kPa)	THM (µg l <sup>-1</sup> )
CEM I:PFA 1A	60.3	11.1	1799.9	567	7.4
1B	8.9	10.1	1700.4	426.2	4.1
1C	21.7	12.3	1900.1	164.1	1.3
1D	4.2	11.8	2001.3	149.1	19.9
1E	28.1	12.6	1999.9	305.2	12.7
1F	10.5	11.8	2006.1	130	2.9
2A	59.9	10.9	1799.7	566.9	7.1
2B	8.6	9.9	1699.6	425.9	3.9
2C	20.9	12.4	1899.8	163.7	0.9
2D	4.1	11.2	2000.5	148.6	20.1
2E	29.3	12.1	1998.6	306.1	12.5
2F	9.8	11.3	2005.9	129.7	3.1
3A	60.1	11.4	1800.9	566.5	6.9
3B	7.9	10.2	1701.2	426.2	4.2
3C	22.1	11.9	1899.5	165.1	0.9
3D	3.8	11.1	2000.3	149.3	20.11
3E	28.7	12.1	2001.4	304.9	12.9
3F	10.3	11.6	2005.9	129.6	3.1

TABLE VIII  
THE MEAN RESULTS OF CEM I DRY MIXING S/S TECHNOLOGY

Parameters	Sample ID	mean	St.dev	P value	significant
CEM I TPH	A	23.63	0.99	P = 0.037	significant
	B	21.60	0.61		
	C	22.67	0.45		
Leachate pH	A	9.67	0.15	P = 0.001	significant
	B	10.63	0.21		
	C	11.03	0.15		
Density	A	1797.0	6.1	P = 0.046	significant
	B	1824.3	17.9		
	C	1836.0	17.7		
UCS	A	576.7	13.50	P = 0.001	significant
	B	256.7	5.86		
	C	21.67	1.53		
Cr	A	0.017		P = 0.015	significant
	B	0.020			
	C	0.003			
Cu	A	0.083		P = 0.001	significant
	B	0.223			
	C	0.070			
Ni	A	0.170		P = 0.001	significant
	B	0.060			
	C	0.030			
Pb	A	0.0001		P = 0.085	non-significant
	B	0.002			
	C	0.0017			
Zn	A	0.002		P = 0.008	significant
	B	0.013			
	C	0.001			

#### IV. CONCLUSION AND RECOMMENDATIONS

The research finds that binders and additives, such as GGBS: MgO, are effective in reducing pollutant concentration and leachability. The study identifies MgO as the best additive for the purpose of soil remediation when in combination with

GGBS. Furthermore, the results indicate that the associated risks are within safe limits for THM. Overall, the research supports the application of these mixtures for effective and safe soil remediation in contaminated sites.

TABLE IX  
THE GGBS:MGO MIX BINDER RESULTS

Binder	Sample ID	TPH (mgkg <sup>-1</sup> )	Leachate pH	Density (kg/m <sup>3</sup> )	UCS (kPa)	THM (µg l <sup>-1</sup> )
GGBS:MgO	1A	10.5	7.9	2113.1	101.1	3.1
	1B	8.7	10.9	1999.9	198.9	2
	1C	5.2	9	1800.2	1000.1	3.5
	1D	8.1	9.2	2380.1	149.8	4.1
	1E	2.3	8.1	2100.2	50.7	4
	1F	3.2	10.4	2113.1	101.9	2.5
	1G	10.1	8	2500.7	80.2	1.9
	1H	40.2	9.9	2199.9	100.6	2
	1I	29.7	10	1979.7	1099.9	1.5
	2A	10.1	8.1	2110.4	102.9	3
	2B	8.2	11.3	2000.1	200.3	1.8
	2C	5.1	9.2	1799.8	1001.1	3.4
	2D	8.5	9.1	2379.6	150.5	4
	2E	1.9	8	2099.9	49.8	3.7
	2F	3.1	9.9	2112.9	101.5	2.4
	2G	9.3	7.9	2499.8	79.9	2
	2H	39.7	9.8	2200.1	100.9	1.8
	2I	29.9	10.4	1979.9	1099.8	1.4
	3A	9.9	8	2111.4	100.8	3.3
	3B	7.9	10.9	2003.2	199.7	1.9
	3C	5.4	9.3	1800.2	1000.5	3.8
	3D	8.1	9	2380.1	149.5	4.3
	3E	2.1	8.3	2100.2	50.6	3.9
	3F	2.8	10	2113.1	101.2	2.6
	3G	9.7	8.2	2500	80.9	2
	3H	39.6	10.1	2200.3	99.9	1.9
	3I	29.6	10.3	1980.2	1100.2	1.6

TABLE X  
TOTAL ILCR ASSESSMENTS (ILCR PATHWAYS) OF TPH

Conditions	
Adult	
Normal	5.44 E-01 - 3.20 E+00
Extreme	8.57 E-01 - 8.46 E+00
Child	
Normal	6.77 E-02 - 2.65 E-01
Extreme	7.98 E-02 - 9.1E-01

TABLE XI  
HI, RISK (ADI AND CDI) OF THMS

Binders	∑ADI	∑CDI	∑HI
CEM I	1.42E-10	2.88E-08	4.78E-03
GGBS:MgO	2.08E-06	1.04E-06	1.73E-01
CEM I:PFA	4.08E-06	2.04E-06	3.39E-01

#### REFERENCES

- [1] Z. Wang, "Regional Study on Soil Polycyclic Aromatic Hydrocarbons in Liaoning: Patterns, Sources, and Cancer Risks. Dalian University of Technology, Dalian". 2007.
- [2] W.D. Hafner, D.L. Carlson, R.A. Hites, "Influence of local human population on atmospheric polycyclic aromatic hydrocarbon concentrations", Environ. Sci. Technol. 39, pp 7374-7379, 2005.
- [3] Y.X. Zhang, S.Tao, J. Cao, R.M. Coveney, "Emission of polycyclic



- aromatic hydrocarbons in China by county”, *Environ. Sci. Technol.* 41, pp 683–687, 2007.
- [4] W. Zhang, S. Zhang, C. Wan, D. Yue, Y. Ye, X. Wang. “Source diagnostics of polycyclic aromatic hydrocarbons in urban road runoff, dust, rain and canopy throughfall”, *Environ. Pollut.* 153, pp 594-601, 2008.
- [5] H.B. Zhang, Y.M. Luo, M.H. Wong, Q.G. Zhao, G.L. Zhang, “Distributions, Concentrations of PAHs in Hong Kong soils”, *Environ. Pollut.* 141 pp 107–114, 2006.
- [6] A.R. Johnsen, L.Y. Wick, H. Harms, “Principles of microbial PAH-degradation in soil,” *Environmental Pollution* 133 (1), pp 71–84, 2005.
- [7] Y. Liu, C-L. Ling, J. Zhao, Y. Wei, Z. Pan, X.Z. Meng, Q. Huang, W. Li, “Polycyclic aromatic hydrocarbons in the surface soil of Shanghai, China: Concentrations, distribution and sources”, *Organic Geochemistry* 41, pp 355–362, 2010.
- [8] S. Liu, X. Xia, L. Yang, M. Shen, R. Liu, “Polycyclic aromatic hydrocarbons in urban soils of different land uses in Beijing, China: distribution, sources and their correlation with the city's urbanization history”, *J Hazard Mater* 177, pp1085–92, 2010.
- [9] C.A. De Sousa, “Turning brownfields into green space in the City of Toronto”. *Landscape and Urban Planning* 62: 4; pp 181-198, 2003.
- [10] G. Thornton, M. Franz, D. Edwards, G. Pahlen, P. Nathanail, “The challenge of sustainability: incentives for brownfield regeneration in Europe”, *Environmental Science & Policy* 10:2; pp116-134, 2007.
- [11] A. Mehdipour, H.R. Nia. “The Role of Brownfield Development in Sustainable Urban Regeneration”. *Journal of Sustainable Development Studies* 4, 2;pp 78-87, 2013.
- [12] M. Allagoa, “Solidification/ Stabilization technology: Field versus Laboratory”. MPhil Thesis, University of Cambridge, 2011.
- [13] F. Jin, “Chapter 10 - Long-term effectiveness of in situ solidification/stabilization. Sustainable Remediation of Contaminated”. *Soil and Groundwater Materials, Processes, and Assessment* pp 247-278, 2020.
- [14] S. Kuppasamy, T. Palanisami, M. Megharaj, K. Venkateswarlu, R. Naidu, “Ex-Situ Remediation Technologies for Environmental Pollutants: A Critical Perspective”, *Reviews of Environmental Contamination and Toxicology* 236, pp 117-192, 2016.
- [15] V.R. Ouhadi, R.N.M. Yong, M. Deiranlou, Enhancement of cement-based solidification/stabilization of lead-contaminated smectite clay. *Journal of Hazardous Materials* 403, 123969, 2021.
- [16] R.N. Okparanma, A.S. Shedrack, J.M. Ayotamuno, Heavy metal human health risk assessment of stabilized/solidified low-temperature thermally desorbed oil-based drill cuttings. *European Journal of Engineering and Technology* 7:4, pp 42-52, 2019.
- [17] M. Liska, “Post-doctoral Researcher, University of Cambridge”, Personal Communication, 2011.
- [18] H.R. Harris. M.R. Herbert, S.M., Smith, M.A. (1995). Remedial treatment for contaminated land, Vol. IX: In-situ methods of remediation. Construction Industry Research and Information Association. Special Report No. 109, pp 121-131.
- [19] A. Knafla, K.A. Phillipps, R.W. Brecher, S. Petrovic, M. Richardson, “Development of a dermal cancer slope factor for benzo(a)pyrene”, *Regulatory Toxicology and Pharmacology* 45, pp 159-168, 2006.
- [20] USEPA, “Benzo[a]pyrene (BaP) (CASRN 50-32-8)” from <http://www.epa.gov/ncea/iris/subst/0136.htm>, 1994.
- [21] Z. Wang, “Regional Study on Soil Polycyclic Aromatic Hydrocarbons in Liaoning: Patterns, Sources and Cancer Risks”. Dalian University of Technology, Dalian, 2007.
- [22] BMEPRI, “Guidance of Site Environmental Assessment”, Municipal Environmental Protection Bureau, Beijing, 2007.
- [23] C. Peng, C. Weiping, X. Liao M. Wang, Z. Ouyang, W. Jiao, Y. Bai, Polycyclic aromatic hydrocarbons in urban soils of Beijing: Status, sources, distribution and potential risk. *Environmental Pollution* 159, pp 802-808, 2011.
- [24] C-M. Liao, K-C. Chiang, “Probabilistic risk assessment for personal exposure to carcinogenic polycyclic aromatic hydrocarbons in Taiwanese temples”. *Chemosphere* 63 pp 1610-1619, 2006.
- [25] I.C.T. Nisbet, P.K. LaGoy, “Toxic equivalency factors (TEFs) for polycyclic aromatic hydrocarbons (PAHs). *Regulatory Toxicology and Pharmacology*”, 16, pp 290-300, 1992.
- [26] USEPA, “IRIS (United States Environmental Protection Agency Integrated Risk Information System)”, 2004.
- [27] EPA, “Soil Screening Guidance: Users Guide. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency”. (EPA/540/R-96/018, April 1996).
- [28] M. Allagoa, “Effective use of Cementitious Materials, Ground Granulated Blast Furnace Slag and Bentonite in treating contaminants on polluted land”, Proceedings of the Shale Energy Engineering 2014 conference, held in Pittsburgh, Pennsylvania, July 21-23, 2014. Sponsored by the Energy Division of ASCE.