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Valorization of Dredged Sediments from Cameron Highlands Reservoirs: Characterization and Pollution Risk Assessment for Sustainable Construction Materials Recovery

Lee-Woen Ean
Sunway University

Bashar S. Mohammed
Universiti Teknologi PETRONAS

Marlinda Abdul-Malek
Imam Abdulrahman Bin Faisal University

Chao-Wei Tang
Cheng Shiu University

Wong Leong Sing
Universiti Tenaga Nasional

Nur Aishah Abbas
Kawasan Institusi Penyelidikan

Isyaka Abdulkadir
Universiti Tenaga Nasional

Abstract: Sustainable management of dredged sediments from hydroelectric reservoirs is critical for environmental protection and resource conservation, aligning with circular economy principles. This study addresses the knowledge gap hindering the beneficial reuse of sediments from Cameron Highlands, Malaysia, by conducting a comprehensive characterization to evaluate recycling feasibility and identify specific applications. Sediments from eight representative sites were rigorously analyzed (particle size, Atterberg limits, specific gravity, SEM-EDX, XRD, heavy metals via Igeo, CF, DC, and regulatory benchmarks). Results revealed two distinct groups: Sand-Dominant Sediments (78-85% sand, high quartz) suitable as fine aggregate or fill, and Silt-Dominant Sediments (12-49% silt, quartz/kaolinite) potentially viable for bricks or soil amendment. Critically, all sediments exhibited heavy metal concentrations below Malaysia's hazardous waste limits and showed low pollution indices, supporting safe reuse in many applications. Statistical analysis quantified property variability, essential for application-specific feasibility assessments. This work provides the foundational data and analysis needed to transform Cameron Highlands' dredged sediment from a landfill burden into a valuable resource, directly contributing to sustainable infrastructure development and environmental goals. Future work will focus on pilot-scale validation of proposed recycling pathways.

Keywords: Sediment, Sediment characterization, Sustainable material recovery, Waste Valorization.

Introduction

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

Sedimentation in hydroelectric reservoirs is a critical global challenge that reduces water storage capacity and impairs power generation efficiency. Peninsular Malaysia hosts three major hydroelectric schemes, including the Cameron Highlands reservoirs, which collectively operate 21 dams reliant on large impoundments. The Cameron Highlands region (elevation 1070–1829 m) has experienced increased soil erosion due to intensified agricultural practices and land development, which has accelerated sediment accumulation in these reservoirs and jeopardised their ecological balance and operational lifespan (Eisakhani et al., 2011; Khairiah et al., 2006). For example, the Cameron Highlands Hydroelectric scheme's Ringlet reservoir generates 300,000 to 400,000 m^3 of dredged sediment annually. Due to the limited reservoir holding capacity caused by sedimentation, these reservoirs have garnered a lot of attention lately for causing mudslides and flash floods, which are frequently caused by controlled water releases from dams to prevent dam bursts (Bernama, 2013; Loghun Kumaran, 2015; Manjit Kaur et al., 2013). The increasing volume of dredged sediment also makes it more challenging to find suitable landfills. This situation is exacerbated by the fact that the region is hilly and that the land is being prioritized for development, as the population in the Cameron Highlands is growing. The Ringlet reservoir loses 52% of its gross storage capacity every year because of sediment deposition at a rate of 200,000 m^3 (Noh et al., 2019).

There have been reports of similar sedimentation problems all over the world. Each year, the Shihmen Dam in Taiwan dredges about 4 million m^3 of sediment (Cheng et al., 2014), whereas the Bakhadda Dam in Algeria withstands up to 32 million m^3 (Serbah et al., 2018). Nevertheless, inappropriate disposal of dredged sediments can result in secondary environmental pollution and land scarcity, particularly in geographically limited areas like Cameron Highlands. Dredging is still the main intervention to restore reservoir capacity.

The sustainable valorisation of dredged sediments has drawn more attention in recent years. Shihmen Dam sediments have been effectively used as raw materials for pressed and sintered building bricks in Taiwan (Chiang et al., 2008; Liang & Li, 2015; Tang et al., 2011). Similarly, Tunisian marine sediments have been used in the production of paving blocks using high-frequency vibration compaction (Said et al., 2015), and studies in northern France have shown that dredged river sediments stabilise in fired clay bricks (El Fgaier et al., 2013; Samara et al., 2009). These initiatives, which seek to lessen reliance on landfills and preserve natural resources, are in line with the ideas of the circular economy.

In order to determine whether dredged sediments are suitable for reuse, a thorough characterisation is required due to their heterogeneous nature, which is influenced by their source environments. Harbour sediments frequently contain more clay (Mezencevova et al., 2012), dam sediments are richer in silty fractions (Serbah et al., 2018), seaport sediments usually contain more sandy particles (Mymrin et al., 2017), and lagoon sediments contain more clayey particles(Almeida et al., 2001). For example, the sediments of Bakhadda Dam in western Algeria are silty (Serbah et al., 2018), while the sediments of Shihmen Dam in Taiwan are primarily clayey (Tang et al., 2011). The physical behaviour and possible uses of sediments as building materials are greatly influenced by their mineralogical composition, which is frequently dominated by quartz and kaolinite. In certain cases, additives such as clay, steel slag, or gypsum are needed to maximize the mechanical properties while mitigating contamination risks. (Baruzzo et al., 2006; Liang & Li, 2015; Wei et al., 2014).

Reusing sediments raises serious concerns about heavy metal contamination. Due to their larger surface area, affinity for clay minerals, and plately shape, metals like mercury, cadmium, lead, nickel, copper, zinc, chromium, and manganese (positive charged cations) tend to accumulate in finer sediment fractions (<75 µm) (Almeida et al., 2001; Mezencevova et al., 2012; Northcott et al., 2003). Heavy metal concentrations are generally higher in reservoir and lagoon sediments than in river sediments because finer sediments are carried and suspended in reservoirs or lagoons, causing siltation and posing a risk to environmental safety, while coarser particles settle along riverbanks (Mezencevova et al., 2012). The use of fertilisers and pesticides in agriculture has led to increased levels of metals like Cu, Cd, Pb, Fe, Zn, and Cr in soils and sediments in the Cameron Highlands. These soils' low organic matter content makes metal mobility and leaching potential even worse.

Agricultural practices have greatly impacted the quality of the soil and sediment in the Cameron Highlands region. (Wan Abdullah, 2001) reported that the Ringlet River has high phosphate and nitrate levels, attributed to extensive fertiliser use. In 2006, it was further confirmed by (Khairiah et al., 2006) that the soils in the Cameron Highlands were contaminated with heavy metals such as Fe, Zn, Cd, Mn, Cu, and Cr. This contamination was probably caused by long-term agricultural activities, which were linked to the use of fertilisers and farmyard manure. Additionally, these soils had low levels of organic matter, which is linked to higher metal mobility because organic complexes usually bind metals and lessen their leachability. Contamination levels have increased due to the widespread use of chemical fertilisers and pesticides, such as phosphate fertilisers that contribute to the buildup of Cd and copper-based fungicides that contain copper sulphate and copper oxychloride, which add arsenic (As), copper (Cu), and lead (Pb). Furthermore, the movement of heavy metals from soil to rivers and reservoir sediments has been made easier by soil erosion in open farming, which is accelerated by rain splash. Metal concentrations in these sediments are further increased by a significant amount of fine-grained particles with a large surface area (Khairiah et al., 2006; Rahim et al., 2006).

To address these challenges, this study aims to describe the dredged sediments from eight landfill sites near rivers and reservoirs in the Cameron Highlands. It focuses on the sediments' physical properties, mineral composition, and heavy metal contamination. The purposes of this study are to investigate whether the sediments are safe for possible repurpose in civil engineering applications and whether the properties are comparable to natural building materials such as sand and clay. In highland reservoir systems, this work offers fundamental data to support resource recovery and sustainable sediment management.

Methodology

Sediment samples were collected from eight designated landfill sites (Sites A – H) in Cameron Highlands, Malaysia, representing a range of upstream and downstream locations. Figure 1 shows the sampling locations, with Site A at downstream and Site E at upstream. Sites F - H were dredged from the reservoirs, while Sites A - E were dredged from nearby rivers. Each disturbed or bulk sample collected roughly 200 kg. The bulk sampling was carried out in compliance with (“ASTM D420-18,” 2018), to make sure enough material was on hand for thorough testing and accurate characterisation.

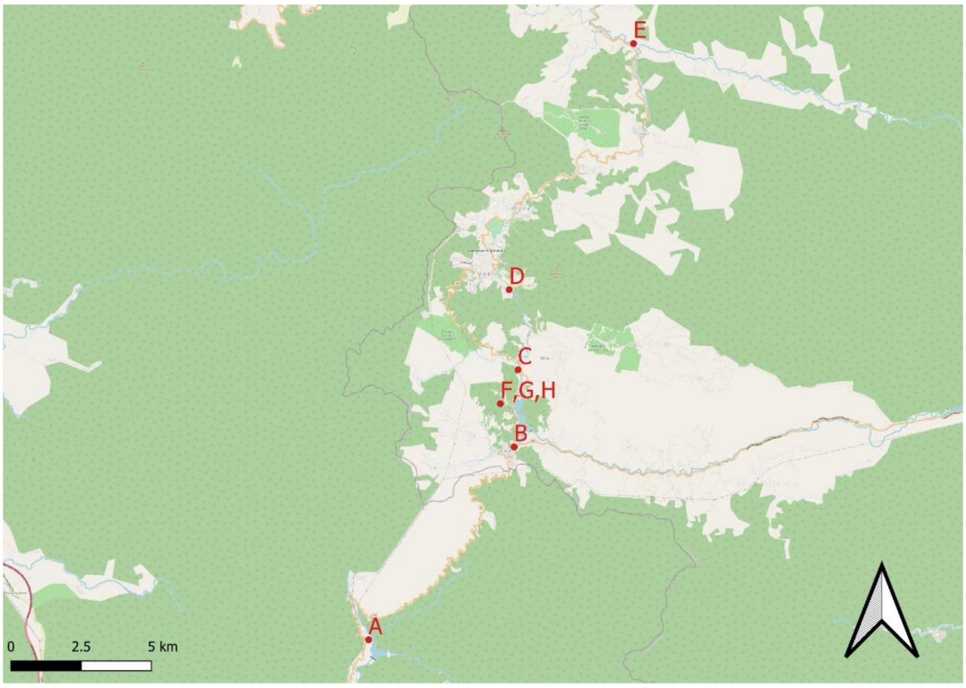


Figure 1. Sampling locations in Cameron Highlands, Malaysia

The main objective of this study is to describe the physical, mineralogical, and chemical properties of the dredged sediments to evaluate if they can be reused in building materials and other applications. A range of standard soil tests and analytical methods were employed to achieve this objective. In order to group the sediments into fractions of clay, silt, sand, or gravel, physical characterisation that involves particle size distribution analysis was conducted. Besides that, specific gravity tests were performed to determine the specific gravity value for the sediments. The plasticity behaviour of the fine-grained sediment fractions was also evaluated using the Atterberg limit tests (plastic limit and liquid limit), which are essential to understand the workability characteristics. The organic matter content was determined using loss on ignition (LOI) tests, and the microstructure and morphology of the sediment were observed in detail using scanning electron microscopy (SEM).

Meanwhile, mineralogical analysis was performed using X-ray diffraction (XRD) to determine the mineral phases in the sediments, which is very important for determining their suitability for various industrial and construction applications. X-ray fluorescence (XRF) analysis was used to determine the chemical composition, especially the amount of heavy metals. This assessment is essential to check for environmental risks and ensure compliance with regulatory standards. These techniques provide a thorough grasp of the sediments' properties, allowing for well-informed choices about their sustainable management and possible value addition in civil engineering projects.

Results and Discussion

Physical Characterization

Particle Size Distribution

Sieve analysis was primarily used to determine the particle size distribution (PSD) of sediment samples in accordance with ("ASTM C33/C33M-18," 2018) and ("ASTM C136/C136M-14," 2014), which are typically used to evaluate the grading of aggregates. However, for samples from Site F, Site G, and Site H where more than 50 percent of the sediments passed through the 75 µm sieve, additional wet sieving and hydrometer analyses were performed to characterize the fine particle fractions accurately.

For the sieve analysis, an initial 300 g of dried sediment was used. The nested sieves, arranged from largest to smallest opening, included sizes of 5.00 mm, 4.75 mm, 2.36 mm, 2.00 mm, 1.18 mm, 0.85 mm, 0.6 mm, 0.3 mm, 0.15 mm, 0.075 mm, and a pan at the bottom. The sediment sample was poured onto the top sieve, and the stack was mechanically shaken for 15 minutes (Figure 2a). The material retained on each sieve was weighed individually (Figure 2b), and the data were recorded to construct particle size distribution curves. This procedure aligns with the standard practice of separating a known dry sample mass through progressively smaller sieve openings to determine the particle size distribution.

(a) (b)

Figure 2. Equipment for Sieve Analysis Test; a) Sieve set with shaker b) Weighing machine and pan

For particles smaller than 75 µm, ("ASTM D422-63," 1998) recommends sedimentation analysis using a hydrometer. This process began with wet sieving through a 63 µm sieve to separate fine particles. Samples passing the 63 µm sieve were collected and allowed the sediment in a pail for 24 hours. The retained coarser particles on the 63 µm sieve underwent further sieve analysis. The fine particles settled at the bottom of the pail were oven-dried at 110°C for 12 hours before being dispersed in a cylinder filled with saline water and a dispersing agent (carbon solution). A hydrometer was gently immersed to measure suspension density at specified intervals (2, 4, 8, 15, 30, 60, 120, 240, 480, 1440, and 4320 minutes), allowing determination of particle size distribution in the fine fraction. The particle size distribution curves for all sampling sites are presented in Figure 3. Sediments were classified based on grain size according to the criteria summarized in Table 1.

Table 1. Soil classification (Whitlow, 2001)

Particle	Size
Gravel	>2mm
Sands	0.06mm to 2mm
Silts	0.002mm to 0.06mm
Clays	<0.002mm

Further classification considered the percentage passing specific sieve sizes. Soils with over 65% of particles larger than 0.06 mm were classified as coarse (sand or gravel), while those with more than 35% finer than 0.06 mm were classified as fine (silt or clay). Particle fractions below 5% were considered negligible for classification purposes (Whitlow, 2001).

The results indicate that sediments from Sites A, B, C, D, and E (Figure 3) are well-graded gravely sands, exhibiting a wide range of particle sizes from coarse to fine without significant fine fractions (Table 2). Well-graded soils are characterized by a continuous distribution of particle sizes, which enhances compaction and mechanical stability. Conversely, sediments from Sites F, G, and H (Figure 4) show a more complex distribution including significant fine fractions. Site F is classified as well-graded clayey sandy SILT, Site G as well-graded silty gravely SAND, and Site H as well-graded sandy SILT (Table 3).

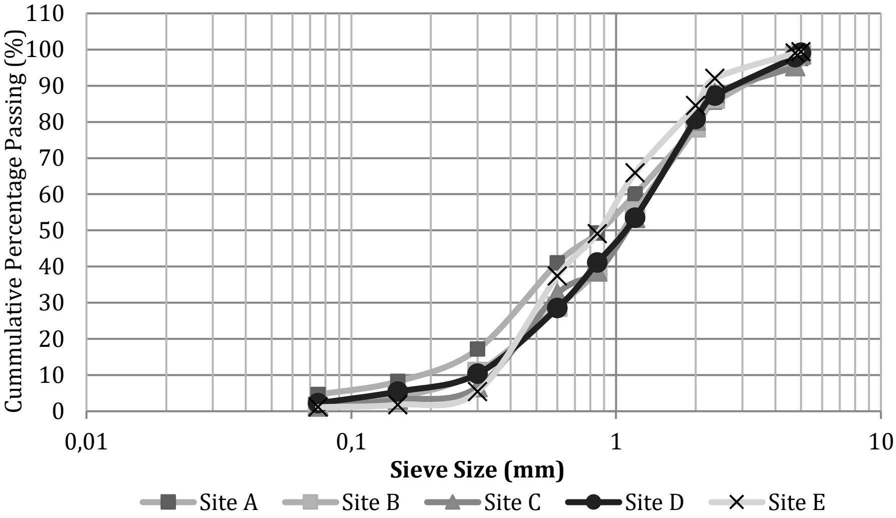


Figure 3. Particle size distribution curves for Site A, Site B, Site C, Site D, and Site E.

Table 2. Particle Size classification for Site A, Site B, Site C, Site D, and Site E

Classification	Site A	Site B	Site C	Site D	Site E
Gravel (%)	14.58	21.53	19.67	19.20	15.50
Sand (%)	85.47	78.47	80.33	80.80	84.50
Soil Classification	Well-graded gravelly SAND	Well-graded gravelly SAND	Well-graded gravelly SAND	Well-graded gravelly SAND	Well-graded gravelly SAND

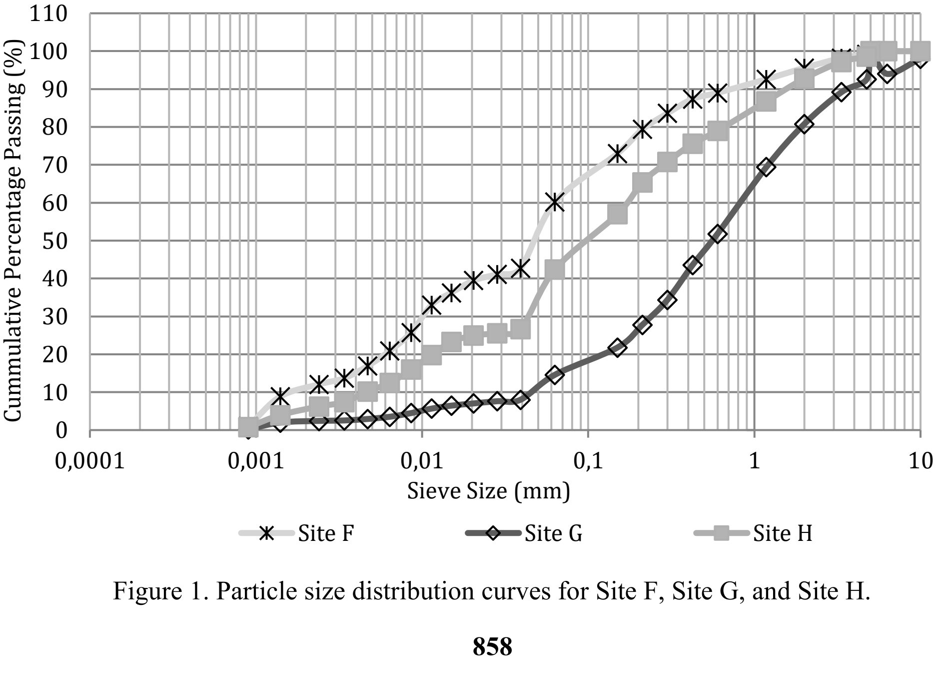


Figure 1. Particle size distribution curves for Site F, Site G, and Site H.

Table 3. Particle size classification for Site F, Site G, and Site H.

Classification	Site F	Site G	Site H
Gravel (%)	4.4	19.2	7.2
Sand (%)	35.4	66.2	50.4
Silt (%)	49.5	12.37	37.24
Clay (%)	10.7	2.23	5.16
Soil Classification	Well-graded clayey sandy SILT	Well-graded silty gravelly SAND	Well-graded sandy SILT

These findings align with general sedimentological observations reported in the literature. The sediments collected from Sites A through E are predominantly well-graded gravely sands, characterized by a wide range of particle sizes and minimal fine fractions. This granulometric profile is consistent with sediments typically found in high-energy riverine environments, where greater flow velocities facilitate the transport and deposition of coarser, angular sand and gravel particles. Dredged river sediments are predominantly sandy and coarser compared to lagoon and lake sediments, which tend to be sludgy with higher fine particle content. This is attributed to the greater flow velocity in rivers, which transports and deposits angular, light-coloured sand-sized particles. In contrast, sediments from reservoirs and lagoons accumulate finer silts and clays due to slower water movement (Sultan & Shazili, 2010) which is observed in sediments from Sites F, G, and H, exhibited a higher proportion of fine particles, including silts and clays, indicative of lower-energy depositional environments such as reservoirs or slow-moving river reaches. The presence of significant fine fractions in these sediments is typical of lacustrine or reservoir settings where reduced flow velocities allow finer particles to settle and accumulate. Similar trends have been observed in harbour sediments, where the middle harbour and reservoir sediments are richer in clay and silt, while sandy particles dominate the lower and higher areas (Mezencevova et al., 2012). The variation in particle size distribution across the Cameron Highlands sampling sites reflects these depositional dynamics, influenced by local hydrology and geomorphology.

Specific Gravity

The specific gravity test was conducted to determine the particle density of the sediments, an essential parameter in understanding the physical characteristics of soil materials. It is important to distinguish between specific gravity and density, as these terms are often confused. Soil density refers to the mass of soil per unit volume, whereas specific gravity is the ratio of the mass of soil solids to the mass of an equal volume of water at a specified temperature. Specific gravity pertains specifically to the solid particles constituting the soil mass rather than the bulk soil (Whitlow, 2001).

Soils are typically composed of a mixture of mineral particles, each with its specific gravity. For example, quartz, a common mineral in many soils, has a specific gravity of approximately 2.65, while minerals such as anhydrite and barytes have higher values, as summarized in Table 4. The specific gravity of most soils generally falls between 2.60 and 2.80, with quartz-dominant sands often assumed to have a specific gravity of 2.65. Clay minerals, which are typically heavier than quartz, tend to have specific gravities ranging from 2.68 to 2.72. The presence of heavy metals or oxides can further increase specific gravity values, whereas soils containing organic matter, such as peat, may have significantly lower values, sometimes below 2.0 (Head & Epps, 1980).

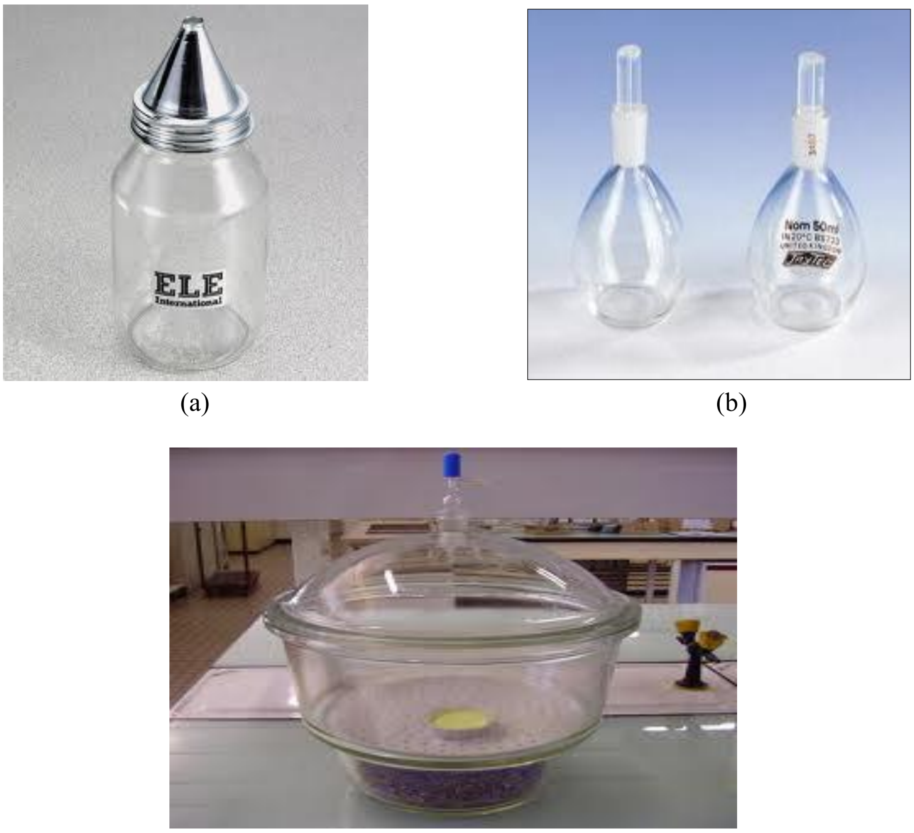
Table 4. The range of specific gravities of some common minerals (Hartlén, 1996).

Mineral	Specific Gravity
Anhydrite	2.9
Barytes	4.5
Calcite, chalk	2.71
Feldspar	2.6-2.7
Gypsum	2.3
Haematite	5.2
Kaolinite	2.6
Magnetite	5.2
Quartz (silica)	2.65
Peat	1.0 or less
Diatomaceous earth	2

In soil testing, different types of specific gravity measurements are used depending on the moisture condition of the sample. Saturated surface dry (SSD) specific gravity is commonly used when the aggregate is wet, but surface moisture is removed, while oven-dry (OD) specific gravity applies when the sample is completely dry. The absorption value, which indicates the water content held within the pores of soil particles, is also derived from these measurements and is important for understanding moisture interactions in soils.

In this study, the specific gravity of sediments from Sites A, B, C, D, and E was determined following ("ASTM C128-22," 2022), as these samples predominantly consist of sand-sized particles (0.06 mm to 2 mm). For sediments from Sites F, G, and H, which contain more than 50% fine particles passing the 75 µm sieve, ("ASTM D854-23," 2023) was employed to accommodate the fine-grained nature of these samples better.

For the ("ASTM C128-22," 2022) procedure, a 500 g sample was immersed in water to remove unwanted particles and dried using a hairdryer to reach the SSD condition. The sample was then placed in a pycnometer (Figure 5a), filled with water, and weighed. Subsequently, the sample was oven-dried to a constant weight, and specific gravity was calculated according to the standard. In contrast, it requires only 10 g of sample, which is placed in a density bottle filled three-quarters full with water (Figure 5b). The bottle is subjected to a partial vacuum in a desiccator (Figure 5c) for six hours to remove entrapped air, after which it is filled with water, sealed, and weighed. Each test was repeated three times to ensure accuracy.



(a) (b)

(c)

Figure 5. Equipment for specific gravity test (a) Pycnometer (b) Density bottle with stopper (c) Desiccator with vacuum system

The specific gravity results are summarized in Table 5. Sediments from Sites A through E exhibited apparent specific gravity values ranging from 2.49 to 2.54, slightly lower than the specific gravity of pure quartz (2.65) . This deviation likely reflects the presence of a mixture of minerals within the sediments, each contributing differently to the overall specific gravity. In contrast, sediments from Sites F, G, and H showed higher specific gravity values, ranging from 2.69 to 2.74, consistent with typical values for fine-grained soils such as silts and clays (2.65-2.9). All sediment samples had specific gravity values above 2.0, confirming their predominance of inorganic mineral matter rather than organic material.

Table 5. Specific gravity for the sediments

Sediments	Specific Gravity (SSD)	Specific Gravity (OD)	Apparent Specific Gravity	Absorption (%)
Site A	2.41	2.36	2.49	2.329
Site B	2.48	2.44	2.54	1.665
Site C	2.44	2.40	2.50	1.630
Site D	2.33	2.28	2.40	2.026
Site E	2.42	2.37	2.49	1.947
Site F	2.74			-
Site G	2.69			-
Site H	2.73			-

* Samples from Site F, G and H are tested accordance to ASTM D854 since the samples consist of a significant amount of silt, while samples from other sites were tested in accordance to ASTM C 128.

These findings are consistent with the mineralogical diversity expected in natural sediments. The lower specific gravity values in sandy sediments (Sites A-E) suggest a composition dominated by quartz and lighter minerals, while the higher values in fine-grained sediments (Sites F-H) may indicate the presence of heavier clay minerals and possibly trace metal oxides. The specific gravity values also provide useful information for engineering applications; for example, soils with higher specific gravity typically exhibit greater strength and stability, which is relevant when considering sediment reuse in construction or land reclamation.

Plastic and Liquid Limits

Plasticity characteristics of the fine-grained sediments were evaluated through liquid limit (LL) and plastic limit (PL) tests, conducted in accordance with (“ASTM D4318-17e1,” 2017). The liquid limit test determines the moisture content at which soil transitions from a plastic to a liquid state, while the plastic limit test identifies the moisture content at which soil changes from plastic to semi-solid.

The liquid limit was measured using the Casagrande cup method. Soil passing the 425 µm sieve was mixed with distilled water to form a uniform paste, which was placed in the cup (filled almost half) to a thickness of approximately 10 mm. A groove was cut through the soil, and the cup was repeatedly dropped at a rate of two blows per second until the groove closed over (Figure 6). The number of blows required to close the groove was recorded at different moisture contents, and the liquid limit was defined as the water content corresponding to 25 blows. The plastic limit was determined by rolling soil threads on a glass plate until they reached a diameter of about 3 mm and began to crumble, indicating the transition to a semi-solid state. The moisture content at this point was recorded as the plastic limit.

(a) (b)

Figure 2. Casagrande cup for Liquid Limit test. (a) The sample was divided into two halves using a grooving tool in the Casagrande cup. (b) The two halves of the soil were in contact after being dropped by turning the handle of the apparatus.

The plasticity index (PI), calculated as the difference between the liquid and plastic limits, quantifies the plastic range of the soil and provides insight into its engineering behavior, including shear strength and compressibility, Fine-grained soils with flaky particle shapes, such as those found at Sites F, G, and H, typically exhibit plasticity due to their mineralogy and particle morphology ("ASTM D7348-21," 2021; C.-L. Ho et al., 2011).

Table 6 summarizes the plastic and liquid limit results for the fine-grained sediments. Site F exhibited the highest liquid limit, plastic limit, and plasticity index (17.4%), although this value remains relatively low, indicating a low plasticity range overall. According to the Unified Soil Classification System and the plasticity chart, these soils fall within the low to intermediate plasticity silt categories (symbols ML to MI), consistent with their particle size distribution and mineralogical composition.

The low plasticity indices suggest that while these sediments possess some plastic behavior, their engineering properties are likely to be more stable compared to highly plastic clays. This has positive implications for their potential reuse in construction materials, where moderate plasticity can aid compaction without excessive shrink-swell behavior. These findings align with the influence of particle shape and mineralogy on soil plasticity and mechanical characteristics.

Table 6. Classification of fine-grained soil of the soil samples based on the plasticity chart

Soil Sample	Plastic Limit (%)	Liquid Limit (%)	Plasticity Index (%)	Fine-Grained Soil Classification	Subgroup Symbol
Site F	27.2	44.6	17.4	SILT of intermediate plasticity	MI
Site G	24.8	39.1	14.3	SILT of low plasticity	ML
Site H	25	34.8	9.8	SILT of low plasticity	ML

Loss on Ignition (LOI)

The Loss on Ignition (LOI) test is a widely used method in soil science to estimate organic matter content by measuring the mass loss of a sample upon controlled heating. In this study, LOI was determined according to ("ASTM D7348-21," 2021), where 1 g of sediment passing the 250 µm sieve was dried at 80°C for 12 hours, then ignited in a furnace with a temperature ramp from 450°C to 750°C at a rate of one volume per minute. The mass loss after ignition corresponds primarily to the combustion of organic matter, as well as dehydroxylation of clay minerals and decomposition of carbonates, sulphides, hydroxides, and other compounds (Mezencevova et al., 2012).

Organic matter in soils originates from plant and animal residues and is known to be highly compressible and water-absorbent, often causing significant volume changes and settlement under load or moisture variation. High-organic soils tend to have low bearing capacity and shear strength, which may compromise construction procedures such as cement setting and soil stabilization (Ahmed & Jasim, 2024; Ge et al., 2020). Therefore, determining the organic content is essential to decide if the sediment is suitable for engineering applications.

Soils with LOI values greater than 10% are classified as organic soils ("BS 1377-3," 2021). Table 7 shows that all sediment samples displayed values below this cutoff, ranging from 1.73% to 9.58%. This indicates that the sediments contain only minor amounts of organic matter and can be classified as inorganic soils. Such low organic content suggests that these sediments are less likely to pose problems related to compressibility or cement hydration, enhancing their potential for reuse in construction and soil improvement applications.

Table 7. Loss on Ignition

Sample	LOI (%)
Site A	9.5814
Site B	3.6741
Site C	8.2445
Site D	2.7156
Site E	3.6875
Site F	9.1690
Site G	1.7250
Site H	4.8108

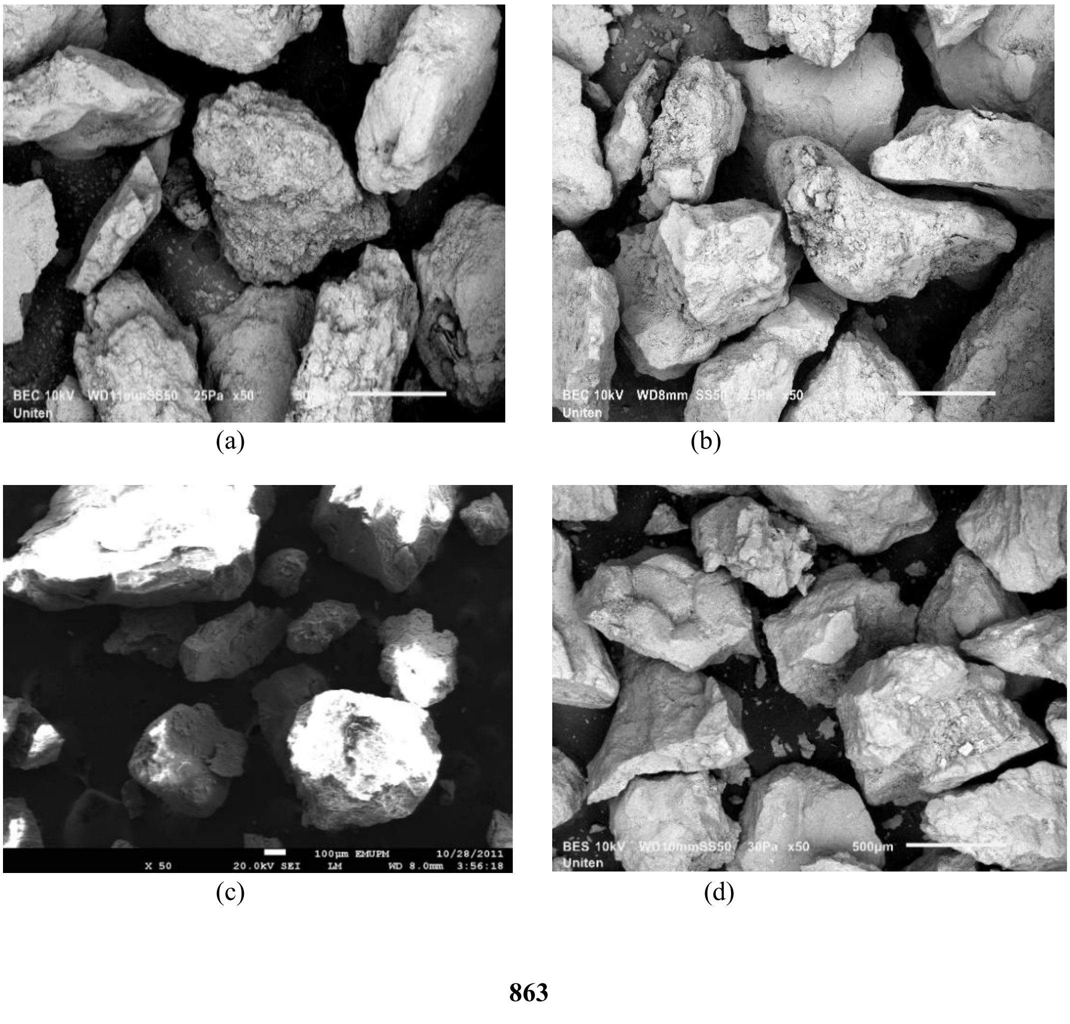
Scanning Electron Micrograph (SEM)

Scanning Electron Microscopy (SEM) was employed to analyze the morphology and surface topography of sediment particles, which significantly influence their engineering properties. Morphology refers to particle shape and size, while topography describes surface texture. For SEM imaging, sediment particles were dispersed onto carbon tape mounted on specimen holders and coated with a thin platinum layer to prevent charging and enhance electron imaging. The samples were then examined using a JSM-6010Plus/LV SEM.

Figures 7(a) to 7(e) present micrographs at 50× magnification to allow direct comparison of particle size and shape across samples, while Figures 7(f) to 7(h) show higher magnifications (250× and 500×) for finer sediments. The particles generally exhibit irregular, angular, and somewhat flaky shapes. The flakiness observed in sediments from Sites F, G, and H correlates with their plastic behavior demonstrated in plastic limit tests. Flaky particles typically impart plasticity to soils, where applied stress results in irreversible deformation without cracking or disruption (Whitlow, 2001), consistent with the low plasticity indices observed for these samples, which explained the shape of the sediments obtained from the locations that are not totally flaky.

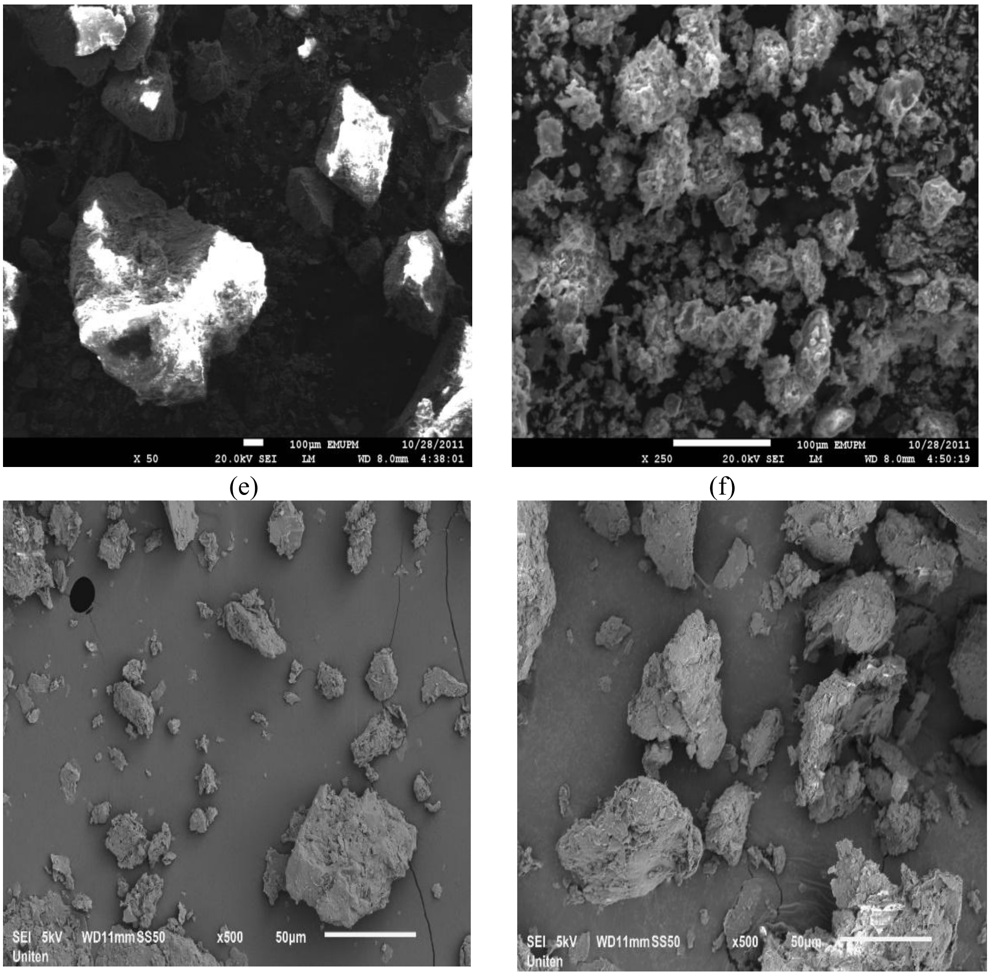
The SEM images align well with particle size distribution results. For instance, sediments from Sites B and D (Figures 7a and 7b) display similar particle sizes, corroborating their nearly identical size distribution curves (Figure 3). Sediments from Site C (Figure 7d) contain smaller particles relative to Sites B and D, while Site E (Figure 7c) shows a broader range of particle sizes, including both smaller and larger grains. Site A sediments (Figure 7e) contain a higher proportion of fine particles compared to other sites.

The finer sediments from Sites F, G, and H (Figures 7f to 7h) exhibit a wide particle size distribution dominated by very fine particles and smaller coarse particles than those found at other sites. Their shapes are predominantly flaky and irregular, consistent with their classification as fine-grained soils. Notably, Site F sediments contain more intermediate-sized particles and fewer extremes than Sites G and H. Overall, the SEM observations provide visual confirmation of the particle size distribution analyses and support the interpretation of sediment texture and plasticity characteristics.



(a) (b)

(c) (d)



(e) (f)

(g) (h)

Figure 3. Scanning Electron Micrograph Image of (a) Site B (b) Site D (c) Site E (d) Site C (e) Site A (f) Site F (g) Site G (h) Site H.

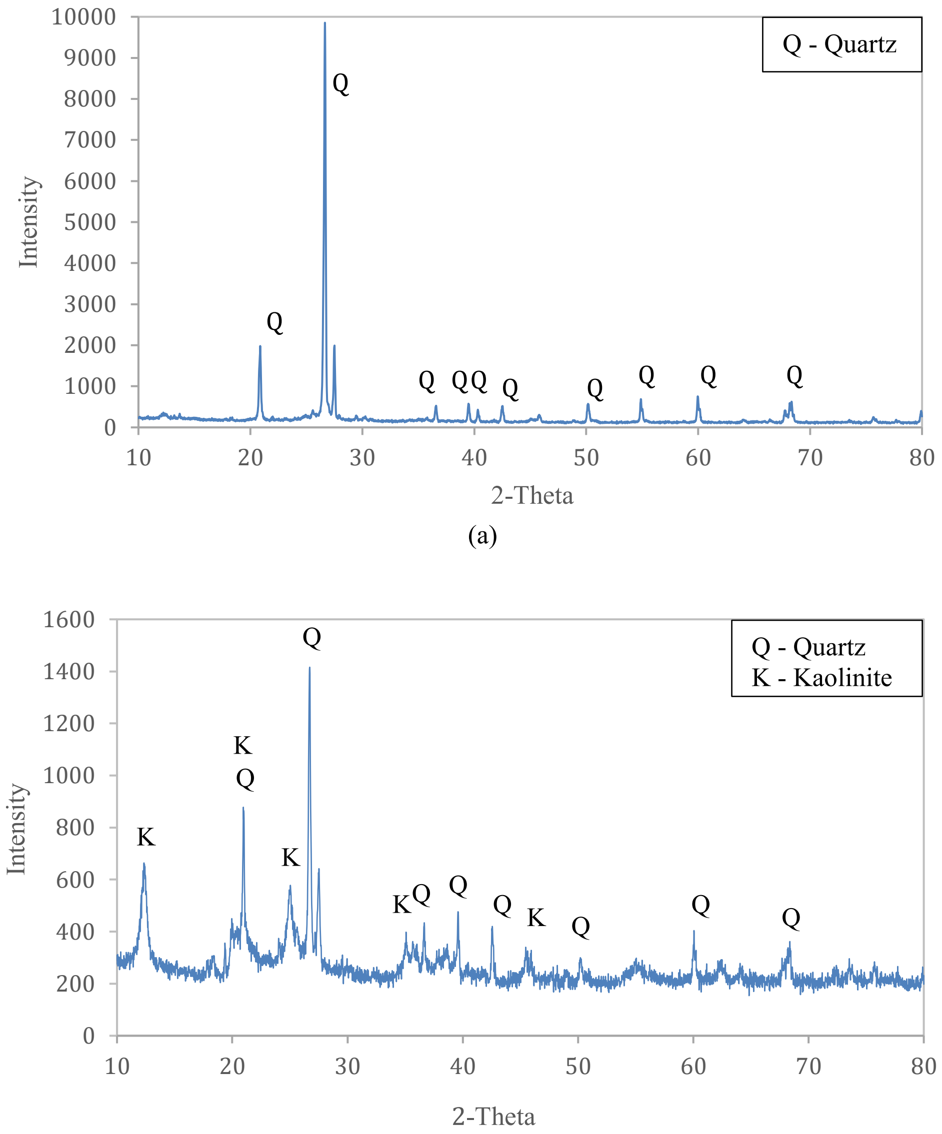
Mineralogy Analysis

Mineralogical characterization of the sediments was performed using X-Ray Fluorescence Spectroscopy (XRF) to determine oxide composition and X-Ray Diffraction (XRD) to identify mineral phases. Site C was selected to represent sandy sediments, while Site F represented silty sediments. XRF analysis, conducted with a Bruker S4-Explorer X-Ray Fluorescence (1 kW) and SPECTRAPLUS V1.64 software, revealed that both sites contain significant amounts of silica (SiO_2) and alumina (Al_2O_3), with Site C exhibiting 71.6% SiO_2 and 14.3% Al_2O_3, and Site F showing lower silica (46.6%) but higher alumina (27.2%) and iron oxide (Fe_2O_3) content (Table 8).

Table 8. Chemical composition of the sediments (% wt)

Sediment	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	MgO	Na_2O	TiO_2
Site C	0.56	71.60	14.30	4.41	-	5.34	0.96	0.44	0.879
Site F	1.22	46.60	27.20	14.40	0.30	4.63	0.52	-	1.680

XRD patterns (Figure 8) indicate that Site C sediments are predominantly quartz, a non-clay mineral lacking pozzolanic activity, as noted by (Chakchouk et al., 2006). In contrast, Site F contains a substantial proportion of kaolinite, a clay mineral recognized for its pozzolanic potential. The higher alumina content in Site F corresponds to the greater clay mineral presence, suggesting enhanced reactivity for cementitious applications. However, as emphasized by (Chakchouk et al., 2006; Pourkhorshidi et al., 2010) chemical composition alone does not fully determine pozzolanic reactivity; physical properties and strength activity indices are also critical factors influencing material performance. These findings highlight the mineralogical differences between sandy and silty sediments in the study area and their implications for potential valorization in construction materials.



(a)

(b)

Figure 4. XRD for (a) Site C and (b) Site F.

Assessment of Heavy Metal Pollution in the Sediments

Heavy Metals Assessment based on Marine Sediments Pollution Evaluation Method

Heavy metals in sediments originate from both natural sources, such as parent rock weathering, and anthropogenic activities (Barbieri et al., 2014). In Cameron Highlands, (Khairiah et al., 2006) reported contamination of soils with heavy metals, including Fe, Zn, Cd, Mn, Cu, and Cr, primarily attributed to agricultural practices. Compared to coastal sediments from the Port of Singapore, the elemental concentrations in Cameron Highlands sediments are generally lower. Tang et al. (1998) found notably high concentrations of heavy metals in Singapore's coastal sediments, such as 7 mg/kg Sn, 300 mg/kg Cu, 108 mg/kg Pb, and 530 mg/kg Zn; largely due to pollution from vessel maintenance activities, where antifouling paints contribute significant Cu, Zn, Sn, and Pb.

In this study, heavy metal concentrations were determined using X-Ray Fluorescence (XRF) and evaluated against the (GB 18668-2002 Marine Sediment Quality (English Version) - Code of China, n.d.). This standard defines three pollution criteria for marine sediments: the primary criterion aims to protect marine habitats and recreational areas; the secondary criterion regulates general industrial and coastal tourism zones; and the tertiary criterion applies to harbors and ocean exploration sites. The appropriate pollution threshold depends on the intended use of the sediment Yu et al., 2008).

Table 9 summarizes the concentrations of key heavy metals in the sediments relative to these standards. Notably, copper (Cu) levels in dredged sediments from Site F exceed the tertiary standard, while Sites G and H exceed the secondary but meet the tertiary standard. Zinc (Zn) concentrations at Sites F, G, and H similarly exceed the secondary standard but comply with the tertiary standard. Arsenic (As) concentrations at Sites F and H surpass the tertiary standard, likely to reflect pesticide and insecticide contamination from nearby plantations. These findings highlight localized heavy metal enrichment in sediments associated with anthropogenic inputs, emphasizing the need for site-specific risk assessments when considering sediment reuse or disposal

Table 9. Summary of metal concentrations (mg/kg) of sediments from Cameron Highlands

Sediment	Copper (Cu)	Zinc (Zn)	Chromium (Cr)	Arsenic (As)
Site A	100	70	-	-
Site D	60	60	-	-
Site C	70	90	80	-
Site B	100	90	-	-
Site E	80	130	-	-
Site F	300	390	140	220
Site G	180	360	120	-
Site H	180	360	-	240
Primary Standard [45]	**35**	**150**	**80**	**20**
Secondary Standard [45]	**100**	**350**	**150**	**65**
Tertiary Standard [45]	**200**	**600**	**270**	**93**

Heavy Metal Assessment

Several risk assessment indices, such as the geo-accumulation index (Igeo), contamination factor (CF), and degree of contamination (DC), were used to determine the amount that heavy metal contamination in the sediments compared to natural background levels (Muller, 1969; Müller, 1979) first suggested the Igeo, which is now widely used to measure metal accumulation by comparing measured concentrations (Cn) to background shale values (Bn), with a factor of 1.5 to account for natural lithological variability. The geo-accumulation index (Igeo) is a common classical assessment model that shows how heavy metals build up in sediment, shown in the following equation.

$$I_{geo} = \log_2\left(\frac{C_n}{1.5B_n}\right)$$

where Cn is the measured concentration of heavy metal in sediments, Bn is the crustal shale background content of the metal, the constant of 1.5 is introduced because of the possible variations in the background data due to the lithological changes. The common background values in average shale were used in the calculation (Turekian & Wedepohl, 1961).

Despite Igeo, CF, and DC were also examined in order to avoid biases in the risk assessment (Barbieri et al., 2014; El-Sayed et al., 2015; Hakanson, 1980; Muller, 1969; Peña-Icart et al., 2017; Yu et al., 2011). CF and DC, as formulated by (Hakanson, 1980), are to assess contamination levels by comparing sediment concentrations (Ms) to background values (Mb), with DC reflecting the cumulative contamination from multiple metals. The equations for the CF and the DC were as follows:

$$CF = \frac{M_s}{M_b}$$

and,

$$DC = \sum_{i=0}^{n} CF$$

Where M_s is the measured concentration of the sediments, M_b is the background value of the same metal. The same background value as described by (Turekian & Wedepohl, 1961) were used as a reference. n is the number of selected metals. Table 10 presents the classification criteria for Igeo, CF, and DC used in this study.

Table 10. Classification of heavy metals assessment (Peña-Icart et al., 2017).

$\mathbf{I_{geo}}$ **index**	**Description**
$I_{geo} \leq 0$	uncontaminated
$0 < I_{geo} < 1$	uncontaminated to moderately contaminated
$1 < I_{geo} < 2$	moderately contaminated
$2 < I_{geo} < 3$	moderately to strongly contaminated
$3 < I_{geo} < 4$	strongly contaminated
$4 < I_{geo} < 5$	strongly to extremely contaminated
$I_{geo} > 5$	extremely contaminated
Contamination factor, CF	**Description**
$CF < 1$	Low
$1 \leq CF < 3$	Moderate
$3 \leq CF < 6$	Considerable
$CF \geq 6$	Very high
Degree of contamination, DC	**Description**
$DC < 7$	Low
$7 \leq DC < 14$	Moderate
$14 \leq DC < 21$	considerable
$DC \geq 21$	Very high

Representative results for sandy sediment (Site C) and silty sediment (Site F) are summarized in Table 11. Site C generally exhibits negative Igeo values, indicating uncontaminated conditions for most metals, except copper (Cu), which shows an uncontaminated to moderately contaminated status. In contrast, Site F reveals a more complex contamination profile: nickel (Ni) is uncontaminated, chromium (Cr) is uncontaminated to moderately contaminated, zinc (Zn) is moderately contaminated, cobalt (Co) and copper (Cu) range from moderately to strongly contaminated, and arsenic (As) is strongly contaminated. The CF values corroborate these findings, with Site C showing moderate contamination only for Cu and low contamination for other metals. Site F displays low to moderate contamination for Ni, Cr, and Zn, but high contamination for Co, Cu, and As. The DC further differentiates the sites, classifying Site C as low contamination (DC < 7) and Site F as very high contamination (DC ≥ 21).

Arsenic, notably, exhibits the highest contamination factor at Site F (16.92), significantly exceeding the indicated index of 6. This high level of arsenic is likely caused by the use of insecticides and agricultural pesticides, which are common in the Cameron Highlands. These findings show how human activity influences sediment contamination, especially in agricultural areas, and highlight the value of multi-index assessments in accurately assessing environmental risks.

Table 11. Concentration based on geo-accumulation index (I_{geo}), contamination factor (CF) and degree of contamination (DC) of specific heavy metals in the sediments.

Sediment	Trace Metals	Background value	Concentrations (mg/kg)	I_{geo}	CF	DC
Site C	Cr	90	80	-0.755	0.889	3.392
	Cu	45	70	0.052	1.556	
	Zn	95	90	-0.663	0.947	
Site F	Cr	90	140	0.052	1.556	36.449
	Co	19	120	2.074	6.316	
	Ni	68	60	-0.766	0.882	
	Cu	45	300	2.152	6.667	
	Zn	95	390	1.452	4.105	
	As	13	220	3.496	16.923	

Heavy Metal Assessment based on Local Regulatory Limit

Although indices such as those proposed by Muller (1969) and Hakanson (1980) are widely used for evaluating sediment contamination, the heavy metal concentrations detected in sediments from Sites C and F in this study remain below the hazardous waste regulatory limits set by the (Malaysia Department of Environment, 2005). The

Total Threshold Limit Concentrations (TTLC) for relevant metals are summarized in Table 12, confirming that these sediments do not exceed national safety standards for hazardous waste disposal.

Table 12. Total threshold limit concentration, TTLC (mg/kg), compared with the (Malaysia Department of Environment, 2005) threshold limit

Sediment	Cr	Co	Ni	Cu	Zn	As
Site C	80	0	0	70	90	0
Site F	140	120	60	300	390	220
Threshold limit	2500	8000	2000	2500	5000	500

Remarks on Heavy Metal Contamination and Stabilization

The geo-accumulation index (Igeo) is an effective method to measure the amount of metals accumulated in sediments compared to the background value. (Yu et al., 2011) mentioned that this occurs because of human activities such as farming and industry. Grain size is also very important for retaining the metals. For example, sediments at Site F, with smaller particles, had greater amounts of heavy metals than sediments at Site C, which had larger particles. This is in line with what was reported by Ho et al. (2011), Head & Epps (1980) whereby smaller grain sizes are better at adsorbing and retaining the heavy metals because they have a larger specific surface area. Visual observations also supported this, as the darker color of sediment lumps at Site F showed that they had more metal in them. Heavy metal levels may not change much across the study area, but finer sediments with more organic matter tend to retain more metal ions. It is important to know the difference between total and bioavailable metal concentrations. The bioavailable part, which mostly comes from human activities, is easier to transport, while metals derived from parent rock are less likely to leach out in mild conditions.

Solidification and stabilization are two examples of immobilization technologies that have been widely studied to reduce the environmental risks of heavy metal contamination. Researchers often use ordinary Portland cement (OPC) as a cheap and effective way to do this. (Almeida et al., 2001; Voglar & Leštan, 2010) have demonstrated that using OPC to solidify soil not only reduces metals mobility, but also significantly enhances the mechanical strength, making them suitable for use in construction materials. Recent research shows that mixing OPC with other supplementary cementitious materials or industrial by-products such as lime, GGBS, or clay can make heavy metals less mobile and make the stabilization process last longer (Amar et al., 2021; Zhang et al., 2020). The techniques not only improve the effectiveness of heavy metal stabilisation but also contribute to resource conservation and the circular economy. Additionally, it lowers the carbon footprint linked to the production of OPC, supporting global sustainability goals. Furthermore, innovative amendments like biochar and nanomaterials have shown promise in further immobilizing heavy metals and improving soil quality. These are advanced stabilization methods to manage contaminated sediments in a way that is good for the environment and make sure that construction materials are always available (Gondek et al., 2023; Guo et al., 2024; Luo et al., 2025).

In summary, the integration of heavy metal contamination assessment with stabilization technologies provides a robust framework for the safe reuse of dredged sediments. The finer sediments from Site F, while exhibiting higher contamination levels, can be effectively treated, mitigating environmental risks and enabling their valorization in civil engineering applications.

Discussions

Characterization of sediments is fundamental for their sustainable utilization, especially when anthropogenic activities and rapid development influence sedimentation origins. Particle size distribution is equally important in sediment assessments as heavy metal contamination and organic pollution (Barbieri et al., 2014; Besser et al., 2015; Casado-Martínez et al., 2006; Chau, 2006;. Ho et al., 2002; Stronkhorst et al., 2003) when taking into account the reuse of sediment in building materials such as bricks and aggregates (Said et al., 2015). Heavy metals assessment not only guarantees environmental safety but also recommends suitable stabilisation or pozzolanic treatments to immobilise pollutants efficiently. The particle size distribution results from this study revealed that sediments from Sites A to E are predominantly well-graded gravely sands (78–85% sand fraction), suitable to replace natural sand in construction applications. Conversely, sediments from Sites F and H are silty, with Site G presenting a mixed texture containing approximately 66% sand alongside silts and clays. These granulometric distinctions were corroborated by SEM imaging, where Sites A–E exhibited irregular, larger particles, while Sites F–H contained more flaky particles, consistent with their higher plasticity as confirmed by liquid and plastic limit tests. Specific gravity measurements further differentiated these groups, with Sites A–E showing mineral diversity beyond quartz, and Sites F–H dominated by fine-grained soils such as silt and clay. These results were confirmed by XRF and XRD analyses, which showed that the primary mineral in Site C was quartz (71%), while the main mineral in Site F was kaolinite clay (27%). This highlighted the mineralogical variability that is essential for the performance of building materials (Chakchouk et al., 2006; Pourkhorshidi et al., 2010).

The sediments were classified as inorganic soils by the Loss on Ignition (LOI) tests, which showed that the organic matter content was less than 10% in all samples. This is favourable because a moderate amount of organic matter can improve fired brick quality by increasing plasticity and acting as pore formers during the firing process, while an excessive amount of organic matter can result in surface defects and attract pollutants (Samara et al., 2009). Collectively, these physical and mineralogical properties suggest that the Cameron Highlands sediments, especially those from sandy sites, have great potential for use in the manufacturing of fired bricks and other building materials. Heavy metal contamination assessment remains important because the sediments come from many different places and are exposed to anthropogenic pollutants. The geo-accumulation index (Igeo), contamination factor (CF), and degree of contamination (DC) analyses revealed that finer sediments (e.g., Site F) tend to accumulate higher heavy metal concentrations, which is in line with established findings that smaller grain sizes with larger surface areas retain more metals (El-Sayed et al., 2015; Ho et al., 2011).

This observation aligns with visual evidence of darker inner sediment lumps at Site F, indicating that metals are accumulating. However, it is important to distinguish between total metal concentrations and bioavailable fractions, as the latter comes mostly from human activities and is more dangerous to the environment, while metals from parent rock are less mobile (Barbieri et al., 2014; Yu et al., 2011). Similar patterns of trace metal and ecological risk have been reported in other coastal areas, such as Sepetiba Bay in Brazil, where both natural and anthropogenic factors contribute to levels of potentially toxic elements in sediments and make the environment potentially hazardous (da Silva et al., 2022).

Recent developments show that using ordinary Portland cement (OPC) for solidification or stabilization can effectively lower heavy metal mobility and increase mechanical strength for the reuse of sediment in construction(Voglar & Leštan, 2010). Additional cementitious materials (SCMs) and cutting-edge additives like biochar and nanomaterials are added to improve stabilisation effectiveness and sustainability (Cai et al., 2019; Pavoni et al., 2025; da Silva et al., 2023).

Furthermore, waste river sludge has been successfully stabilised into unfired green bricks with good mechanical and environmental performance by combining cement with industrial by-products like phosphogypsum and slag (Maierdan et al., 2020). Overall, the viability of using dredged sediments from the Cameron Highlands for construction is demonstrated by combining heavy metal assessments with physical, chemical, and mineralogical characterisation. Customised stabilisation and treatment can lessen negative effects on the environment and lessen reliance on natural clay and sand, promoting environmentally friendly sediment management in developing nations.

Conclusion and Recommendations

Dredged sediments from the Cameron Highlands were described in this study, revealing unique characteristics affecting their potential for reuse as building materials. While the finer, more plastic sediments (Sites F–H) are rich in kaolinite, indicating their use in pozzolanic or stabilised applications, the sandy sediments (Sites A–E) show characteristics appropriate for direct sand replacement. The low organic content of all sediments makes them useful for material processing. While the study confirms that solidification and stabilization using Ordinary Portland Cement (OPC) and advanced amendments are effective for immobilising metals and improving mechanical properties, finer sediments exhibit higher accumulations of heavy metals, especially from anthropogenic sources. Therefore, it is advised to apply sandy sediments directly, while finer, metal-enriched sediments need to be stabilised or pre-treated. To ensure the safe and sustainable value-adding of these dredged materials, future research should concentrate on comprehensive leaching studies and pilot-scale trials to optimise treatment techniques and validate long-term performance.

Pilot-scale trials are advised to validate laboratory results by producing construction materials such as bricks and paving blocks using treated sediments, assessing their long-term durability and environmental safety. Finally, the development of integrated sediment management guidelines that combine sediment characterization, contamination assessment, and treatment strategies will support circular economy principles and reduce dependence on natural resources. Implementing these recommendations will help optimize the reuse of Cameron Highlands dredged sediments, contributing to sustainable construction practices and environmental protection.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Lee Woen Ean
Sunway University, Faculty of Engineering and Technology, School of Engineering, No. 5, Jalan Universiti, Bandar Sunway, 47500 Selangor Darul Ehsan, Malaysia
Contact e-mail: *leewoene@sunway.edu.my*

Bashar S. Mohammed
Universiti Teknologi PETRONAS, Department of Civil and Environmental Engineering, , Seri Iskandar, Perak Darul Ridzuan 32610, Malaysia

Marlinda Abdul-Malek
Imam Abdulrahman Bin Faisal University (University of Dammam), College of Engineering, Environmental Engineering Department, PO Box: 1982, Dammam 31441 Kingdom of Saudi Arabia.

Chao-Wei Tang
Cheng Shiu University, Department of Civil Engineering and Geomatics, No. 840, Chengching Road, Niaosong District, Kaohsiung 83347, Taiwan.

Wong Leong Sing
Universiti Tenaga Nasional, Institute of Energy Infrastructure, Jalan IKRAM-UNITEN, Kajang, Selangor 43000, Malaysia

Nur Aishah Abbas
Kawasan Institusi Penyelidikan, TNB Research Sdn. Bhd., No 1, Lorong Ayer Itam, , 43000 Kajang, Selangor, Malaysia.

Isyaka Abdulkadir
Institute of Energy Infrastructure, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, Kajang, Selangor 43000, Malaysia

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