STABILIZATION/SOLIDIFICATION OF IRON ORE MINE TAILINGS USING CEMENT, LIME AND FLY ASH

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Abstract

Current research emphasis is more on the utilization of materials that are considered as waste. Tailings and fly ash are major category of industrial wastes, whose disposal is problematic from environmental point of view. In this present research, Industrial byproducts, namely, lime (CaO) and class F type fly ash have been used as candidate materials along with the partial addition of ordinary Portland cement (OPC) in the Stabilization/solidification (S/S) of polymetallic iron ore mine tailings (TM). The effectiveness of S/S was assessed by comparing laboratory experimental values obtained from unconfined compressive strength (UCS), hydraulic conductivity and leaching propensity tests of S/S samples with regulatory standards for safe surface disposal of such wastes. Some S/S cured matrices were found unable to provide the required immobilization of pollutants. S/S and 28 days cured mine tailing specimens made with composite binders containing TM/10/0/0, TM/5/0/20, TM/10/0/40 and TM/0/10/40 significantly impaired the solubility of all contaminants investigated and proved successful in fixing metals within the matrix, in addition to achieving adequate UCS and hydraulic conductivity values, thus satisfying regulatory norms (U.S. EPA). Laboratory investigations revealed the TM blends (stabilized materials) were non-hazardous. The test results of this study are encouraging and it may be possible to undertake large-scale fill construction with stabilized tailing material that is sustainable and cost effective.

Keywords: *Tailing materials, Laboratory study, Compaction characteristics, unconfined compressive strength, Hydraulic conductivity, Heavy metal content.*

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1. INTRODUCTION

Mine tailings are the waste materials generated from the mining industry. These tailings are the residue of the milling process that is used to extract metals of interest from mined ores. During metallurgical process toxic chemicals are added to ore, which remains in tailings after the extraction process. Due to the above reason tailings are hazardous in nature. Leaching of heavy metals is another concern associated with tailings. Due to this the disposal of mine tailing is a serious environmental issue for any mining projects. In order to minimize the hazardous effect of mine tailing on the environment, remediation is found to be one of the effective methods. When remediation is achieved by addition of stabilizing agents they improve the overall characteristics of tailings and prevent environmental leaching. There by the tailing material dump yards can be effectively utilized for civil/geotechnical engineering constructions as well as to prevent the environmental hazards.

Stabilization/solidification prevents or minimizes the release of contaminant into the environment by limiting the mobility of contaminant when exposed to leaching fluids and chemically bonding the contaminant into a non-toxic form. This process limits the mobility of contaminant when exposed to leaching fluids (Kleppe, 1992). The two principle types of inorganic binders commonly used in stabilization are cement and pozzolanic materials (lime, fly ash, cement kiln dust and lime kiln dust). A pozzolana is a material containing silica and alumina that has a little or no cementitious value itself but, can react with lime or cement and water at ambient temperature to produce cementitious material (means, 1995, US EPA, 1989).

The basic solidification reaction in pozzolanic systems requires polyvalent metal ions in stoichiometric excess, so calcium compounds such as lime is most commonly added as setting agent (Malone and Lundquist., 1994). Stabilization/solidification is a proven technology for the treatment of hazardous materials. Stabilization refers to rendering a waste less toxic through fixation of the contaminants that contain and/or by providing a stable chemical environment. Solidification is related to those operations which improve the physical and handling characteristics of the waste (Conner, 1990).

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Tailing Material (Tm)

In the present study, mine tailing was procured from a tailing dam facility, situated in Kudremukha (latitudinal range $13^0$01'00" to $13^0$29'17" N, longitudinal range $75^0$00'55" to $75^0$25'00" E), Karnataka, India. The tailing samples were collected from a depth of 0.60 to 0.90 metre below the natural ground surface. After collection, the samples were sealed in polyethylene bags and transported to the geotechnical laboratory at National Institute of Technology, Karnataka, Surathkal, Mangalore. Laboratory tests were carried out on air dried samples to study the basic physical properties of the tailings. Table 1. shows the index properties of tailing material and Table 2. shows the chemical characteristics of tailing material.

In the present study, ordinary Portland cement (C), lime (L) in the form of calcium oxide and fly ash (FA) class F type were used as additives/stabilizing agents. The chemical characteristics of these reagents are presented in Table-2.

2.2 Methods

2.2.1 Compaction Characteristics

The compaction characteristic of tailing material was studied in the laboratory using Proctor light compaction test. The purpose of laboratory compaction test is to determine the proper amount of mixing water to be used, when compacting to the soil in the field and the resulting degree of denseness which can be achieved from compaction at Optimum moisture content. The equipment used in the test consists of cylindrical mould (with detachable base plate) having an internal diameter of 100 mm and 127 mm effective height. The rammer has a mass of 2.60 kgs with a drop of 310 mm. During the test, the TM was compacted into the mould in three layers of approximately equal mass, each layer being given 25 blows.

2.2.2 Unconfined Compressive Strength Test (UCS)

UCS test were conducted both on TM as well as blended TM. After mixing with additives in different proportions the UCS specimens were cured for 7 days, 28 days and 90 days. All the test specimens were compacted to maximum dry density (γ_{dmax}) and optimum moisture content (w_{opt}). The values of γ_{dmax} & w_{opt} were established initially. During the test the specimens were placed centrally on the lower plate of the compression testing machine and the load is applied to the ends of the specimen. The rate of deformation is kept uniform, approximately 1.25 mm/min. The maximum load (P) exerted is then recorded. The unconfined compressive strength (p) is calculated as: $p = P/A_n$ where P = Maximum recorded load (kN) and A_n is the cross sectional area (m^2).

2.2.3 Hydraulic Conductivity

Falling head permeability test was performed to study the hydraulic conductivity of tailing material. During the test samples were compacted to maximum dry density (γ_{dmax}) and optimum moisture content (w_{opt}) in the permeability mould using compaction energy equivalent to standard Proctor test. Similarly for stabilized tailing material, hydraulic conductivity tests were performed after mixing appropriate quantity of stabilizing agent (ie., C/L/FA) with tailing material. Saturation of the soil sample was ensured under steady state flow condition.

The hydraulic conductivity values were calculated using the following equation

$$k = \frac{2.303\ aL}{At} \log_{10}\left(\frac{h_1}{h_2}\right)$$

Where,
k - Coefficient of permeability in cm/sec,
a - Cross-sectional area of the stand pipe in cm^2,
L - Length of the sample in cm,
A - Cross-sectional area of the sample, in cm^2,
t - Time taken for the drop from height h_1 to h_2 in sec,
h_1- Initial height of the fluid in stand pipe in cm,
h_2 - Final height of the fluid in stand, pipe in cm after time t

2.2.4 Chemical Characteristics of the Tailing Material

The acidic or alkaline characteristics of a soil sample can be quantitatively expressed by means of the hydrogen ion-activity commonly designated as pH, The pH measurement of tailings: water ratio (1:2.5) extract was measured electrometrically by means of an electrode assembly consisting of one glass electrode and one calomel reference electrode with a saturated potassium chloride solution according to IS: 2720 (part-26)-1987. Electrical conductivity was measured by potentiometric method using conductivity meter. Silica oxide (SiO_2) and aluminium oxide (Al_2O_3) was measured by gravimetric method according to IS: 2720 (part-25)-1982. Iron oxide (Fe_2O_3) was measured by colorimetric method using spectrometer.

2.2.5 Water Leach Test (WLT)

Water leach test is a very useful test that can be used to study the migration and attenuation of heavy metals through a compacted soil and to study the interactions between soil and various contaminants. WLTs were performed on tailing material using Jacob's method (Jacob, 2012). 10 gms of solid material mixed with 200 ml of distilled water in glass bottles (liquid to solid (L: S) ratio of 20:1). The pH of the distilled water is reduced to pH 4 using ultrahigh-purity (UHP) nitric acid (HNO_3) before mixing it with the samples. The bottles were rotated continuously at 30±2 rpm and room temperature 25^0c for 18 hours. At the end of 18 hours extraction period, fluid in each bottle was separated from the soil phase by vacuum-filtration through 0.45 µm membrane filter. The pH of the extracts was then measured. The filtered supernatant was stored in 125 ml HDPE bottles. One of the supernatant samples was acidified to pH < 2 using ultrahigh-purity (UHP) nitric acid (HNO_3) for long term preservation. The sample bottles were washed with 2% UHP HNO_3 and rinsed with double distilled water prior to use. All samples were stored at 4^0 C prior to analysis.

2.2.6 Chemical Characteristics of Leachate

The leachate that was collected from the WLT has been stored in two 125 ml HDPE bottles. The sample in one of the bottles is acidified to pH < 2 using ultrahigh-purity(UHP) nitric acid (HNO_3) and stored at 4^0C is used for heavy metal analysis. The leachate collected in another bottle is used for testing pH, electrical conductivity, chlorides, sulphates, alkalinity, nitrate and nitrite. Tests were carried out as per Standard methods of water and wastewater examination (APHA, 2005). The chemical characteristics of the leachate are presented in Table-2.

3. RESULTS AND DISCUSSIONS

3.1 Geotechnical Properties of Tailing Material

Basic physical properties of tailing material are presented in Table 1. Based on the test results the TM is classified as non-plastic poorly graded sand (SP) with plasticity index, $I_P = 0$. Grain size distribution of tested TM is shown in Fig. 1. From grain size distribution curve it is observed that about 91% of the TM is greater than 75 µm sieve. Significant portion of the tailing material corresponds to sand size particles.

3.2 Chemical Characteristics of Tailing Material

The main chemical compositions of tailing material (TM), cement (C), lime (L) and fly ash (FA) used in this study are shown in Table 1. pH of the TM (soil to water ratio 1:2.5) is about 7.45. Iron content of the TM is about 28.59%. Main chemical composition of other additives used in this study is shown in Table 2. The heavy metal content of tested TM is presented in Table 3. Since TM contains heavy metals and to prevent environmental leaching (due to infiltration of rain water) remediation/stabilization of tailings is required. Hence this study is under taken to stabilize the TM using commonly used additives like cement, lime and fly ash.

Table -1: Index properties of tailing material

Properties	Average values
Color	Pale gray
Specific Gravity	3.24
Field density (kN/m^3)	18.54
Field moisture content (%)	10
Liquid limit (%)	NP
Plastic limit (%)	NP
Plasticity Index (%)	NP
Sand (75µ - 4.75 mm) %	91
Silt (2µ - 75µ) %	9
D_{10}	0.093
D_{30}	0.175
D_{60}	0.34
Soil classification	SP

NP – Non plastic,
SP – Poorly graded sand

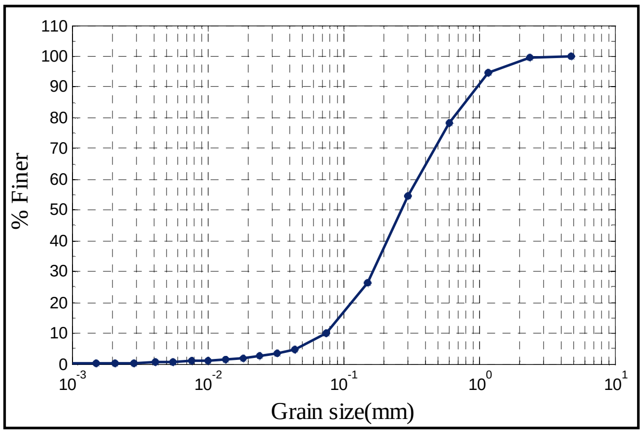

Fig-1: Grain size distribution of TM

Table 2: Chemical composition of test materials

Properties	TM	C	L	FA
pH	7.45	11.47	11.42	10.21
Electrical conductivity (ms)	0.145	6.95	6.90	0.35
Silica oxide (SiO_2) %	62.06	19.48	11.36	72.08
Iron oxide (Fe_2O_3) %	28.59	2.00	0.19	0.57
Aluminium oxide (Al_2O_3)%	3.08	8.25	5.08	5.15
Calcium oxide (CaO) %	0.073	56.08	72.90	12.34
Magnesium oxide (MgO)%	0.017	5.64	4.84	4.04
Loss on ignition (%)	2.32	4.77	4.24	0.76

TM – Tailing material, C – cement, L – lime, FA – fly ash

Table-3: Heavy metal content of tailing material (TM)

Elements	Result (w/w %)	Elements	Result (w/w %)
Lead (Pb)	0.00088	Copper (Cu)	0.001
Zinc (Zn)	0.003	Cobalt (Co)	0.01
Cadmium (Cd)	0.0001	Manganese (Mn)	0.08
Chromium (Cr)	0.0001	-	-

3.3 Mix Design

Compaction curves were developed for natural TM. The compaction energy used is equivalent to standard Proctor test (IS 2720 part-7) and modified Proctor test (IS 2720 part-8). The pozzolana dosing matrix is shown in Table-4. In Table-4, for example Mix ID TM/0/0/0 denotes 100% TM, 0% cement, 0% lime, 0% fly ash. Relevant literature is also referred while choosing the dosing matrix for stabilization purpose.

Table-4: Dosing matrixes of different additives

Mix ID	Tailing material (TM) (%)	Cement (C) (%)	Lime (L) (%)	Fly Ash (FA) (%)
TM/0/0/0	100	0	0	0
TM /5/0/0	95	5	0	0
TM /0/5/0	95	0	5	0
TM /10/0/0	90	10	0	0
TM /0/10/0	90	0	10	0
TM /5/5/0	90	5	5	0
TM /10/10/0	80	10	10	0
TM /5/0/20	75	5	0	20
TM /0/5/20	75	0	5	20
TM /10/0/40	50	10	0	40
TM /0/10/40	50	0	10	40

TM/0/0/0 denotes 100% TM

3.4 Compaction Behavior

Standard Proctor compaction test were carried out on TM and its blends after 24 hours after mixing with stabilizing agents. The results of compaction tests are plotted in Fig. 2 in the form of dry density versus moisture content. From Fig. 2 it is observed that maximum dry density (γ_{dmax}) and optimum moisture content (w_{opt}) values for natural TM are 20.65 kN/m^3 and 11.70 %. When TM is mixed with 5% cement alone (dry basis) the maximum dry density and optimum moisture content obtained were 20.50 kN/m^3 and 11.25 %. Similarly for mix ID TM/0/5/0 (i.e., 5% lime) same results were obtained i.e., γ_{dmax} = 20.50 kN/m^3 and w_{opt} = 11.25 %. All the standard compaction test results of different mixes are shown in Table 5. From Fig-2 it is also observed that when tailing is mixed with 20% fly ash and 40% fly ash (i.e., for Mix ID TM/5/0/20, TM/0/5/20), (TM/10/0/40) and (TM/0/10/40) there is a reduction in maximum dry density value of about 13% (i.e., γ_{dmax} = 17.76 kN/m^3). This reduction in dry density is attributed due to addition of fines in the form of fly ash. Fig-3 shows the effect of compaction energy on mine tailings.

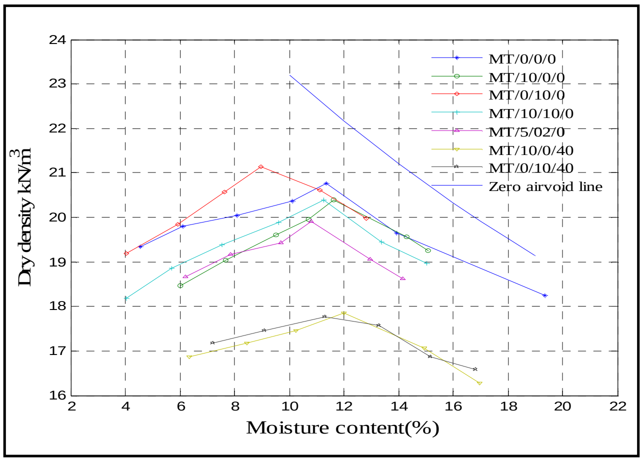

Fig- 2: Compaction curves for TM and its blends

Table-5: Standard Proctor test, modified Proctor test and specific gravity of tailing material & its blends

Mix ID	Standard Proctor test results		Modified Proctor test results		Specific gravity (G_s)
	γ_{dmax} (kN/m^3)	w_{opt} (%)	γ_{dmax} (kN/m^3)	w_{opt} (%)	
TM/0/0/0	20.65	11.70	21.29	10.25	3.24
TM/5/0/0	20.50	11.25	21.09	10.60	3.24
TM/0/5/0	20.50	11.25	21.97	9.60	3.27
TM/10/0/0	20.40	11.60	21.78	9.80	3.22
TM/0/10/0	21.17	9.50	22.37	8.25	3.27

TM/5/5/0	20.75	10.55	21.78	9.45	3.25
TM/10/10/0	20.40	11.10	21.58	9.65	3.27
TM/5/0/20	19.67	10.95	20.80	9.55	2.94
TM/0/5/20	19.82	10.55	20.65	9.50	2.97
TM/10/0/40	17.81	11.90	18.59	10.30	2.68
TM/0/10/40	17.76	11.85	18.90	10.25	2.69

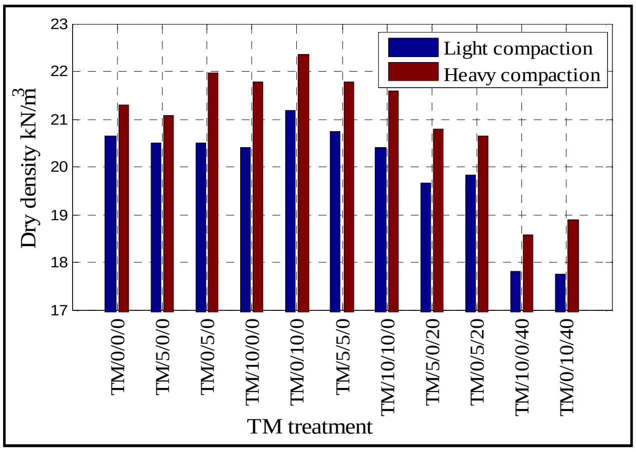

Fig- 3: Effect of additives on the compaction characteristics

3.5 Specific Gravity

Specific gravity tests were conducted on TM, cement, lime fly ash and blended samples. The results of the specific gravity are given in Table -5. From Table -5 we can observe that the specific gravity of TM is 3.24. After mixing with additives in different proportions to the TM, the specific gravity decreased. The specific gravity of Mix ID TM/10/0/40 is significantly decreased (i.e., from 3.24 to 2.68) because the TM is blended with the low specific gravity additives.

3.6 Unconfined Compressive Strength (UCS)

The results of UCS test with different curing period are shown in Table -5. For control sample UCS strength is about 17.22 kPa. After 28 days curing the UCS strength of control sample is marginal increase of about 19.35kPa.

Specimens of mine tailings stabilized with ordinary Portland cement as a sole binder (5% C and 10% C) attained UCS values of 1157.54 kPa and 1665.81 kPa at 28 days of curing as shown in Fig. 4. Strength development in a Portland cement based matrix is primarily due to the silicates tricalcium silicates (C_3S) & dicalcium silicates (C_2S) both of which produce similar hydration products, i.e., calcium hydroxide ($Ca(OH)_2$) and calcium silicates hydrates (C-S-H) (the silicates C_3S & C_2S are the most important compounds and are mainly responsible for the strength of the cement paste).

The addition of 5% lime to the tailings sample (TM/0/5/0) resulted in a gain of moderate strength after 7 days of hydration. These samples reached an unconfined compressive strength of 88.80 kPa after 28 days of curing. Further additions of 10% lime to the tailings sample; moderately increase the strength upto 111.50 kPa after 28 days of curing.

The main strength gain of lime-treated mine tailings waste is derived from two reactions, hydration and pozzolanic reaction (Mohamed & Antia, 1998). The calcium hydroxide resulting from the hydration of lime dissociates in the water. As a result the calcium concentration and pH of the pore fluid will increase. The hydrous alumina present in the water will then gradually react with the calcium ions liberated from the hydrolysis of lime to form insoluble compounds of calcium alumina hydrate (CAH) (secondary cementitious products). This secondary reaction is known as pozzolanic reaction, which has contributed to the increase in strength. In addition, the disintegration and loss of strength is attributed to the formation of gypsum. Therefore, it is postulated that the addition of lime alone could not instigate enough pozzolanic activities to generate a substantial amount of strength in the samples.

Specimens of mine tailings stabilized using a composite binder incorporating various proportions of cement and lime achieved compressive strength values lower than that obtained by specimens stabilized using ordinary Portland cement addition alone. At 28 days of curing (5% cement + 5% lime) i.e., (TM/5/5/0) produced unconfined compressive strength value of 815.72 kPa and (10% cement + 10% lime) i.e., (TM/10/10/0) produced UCS value of 1479.79 kPa.

The application of 5% lime + 20% of fly ash (TM/0/5/20) and 10% lime + 40% fly ash (TM/0/10/40) generated higher strength in the samples than in those that were treated with lime alone. After 7 days of curing, 52.12 kPa and 209.72 kPa of strength were increased in these samples. The generation of high early strength in these samples is attributed to the activation of lime’s pozzolanic properties in the presence of fly ash. The strength of these samples increased up to 251.16 kPa and 423.93 kPa after 28 days of hydration. The strength increase is attributed to i) the formation of cementitious products ii) the formation of ettringite iii) a reduction in gypsum content and iv) the formation of flocculated structure.

The formation of cementitious products can be explained based on the interaction between mine tailings waste, lime and fly ash. Upon the addition of these materials and mixing, hydration of both lime and fly ash occurs rapidly. The major hydration products are hydrated calcium silicates ($C_3S_2H_3$), hydrated calcium aluminates (C_3AH_6) and hydrated lime ($Ca(OH)_2$). The first two of these are the main cementitious products formed. The third, hydrated lime, i.e., deposited as a separate crystal line solid phases. These new products bind together and form a hardened skeleton matrix, so it is likely that none is completely crystalline part of the $Ca(OH)_2$ may also be mixed with other hydrated phases, as it is partially crystalline (Mohamed, 2003).

Specimens of mine tailings stabilized using a composite binder incorporating various proportions of cement and fly ash achieved compressive strength values higher than that obtained by specimens stabilized using cement alone. At 28 days curing MT/5/0/20 and MT/10/0/40 produced unconfined compressive strength values of 1100.87 kPa and 1903.89 kPa respectively. The presence of lime and silica in cement makes it a good soil stabilizer for low strength applications. The binder additive 5% cement and 20% fly ash and 10% cement and 40% fly ash with mine tailings produced the highest compressive strength at 28 days, as shown in Fig -4. The experimental results of the present study indicate that a cement-fly ash composite binder can be very effective in stabilizing iron ore mine tailings.

The mechanism of interaction between cement and fly ash in increasing the compressive strength of the resultant matrix of stabilized tailings is attributed to the reactivity of cement, cumulative calcium oxide content of individual additives and pozzolanic characteristics of fly ash. Also, the minimum recommended unconfined compressive strength for reusability of treated waste material is 345 kPa (U.S. EPA, 1986).

Table-6: UCC strength of cured test specimens (TM and its blends)

Mix ID	Unconfined compressive strength (kN/m^2)		
	0 day	7 days	28 days
TM/0/0/0	17.22	18.83	19.35
TM/5/0/0	36.70	705.40	1157.54
TM/0/5/0	31.06	40.46	88.80
TM/10/0/0	31.76	1529.20	1665.81
TM/0/10/0	38.99	54.22	111.50
TM/5/5/0	46.74	422.49	815.72
TM/10/10/0	67.54	780.99	1479.79
TM/5/0/20	35.21	680.12	1100.87
TM/0/5/20	30.60	52.12	251.16
TM/10/0/40	65.22	1698.20	1903.89
TM/0/10/40	80.75	209.72	423.93

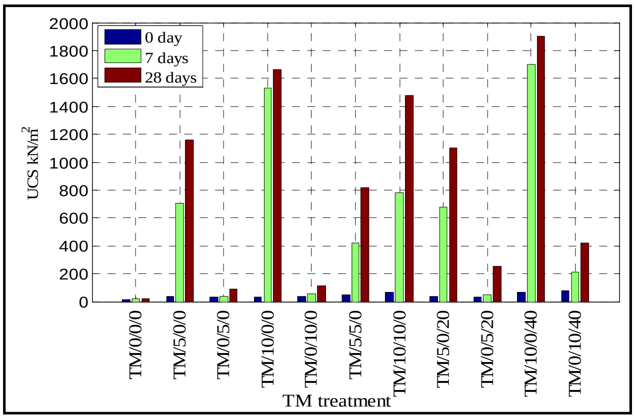

Fig-4: Average UCC strength of TM and blends

3.7 Hydraulic Conductivity

The hydraulic conductivity of stabilized mine tailings is one of the most important properties of the solidified material. Typical hydraulic conductivities for stabilized wastes range from $1.0x10^{-4}$ cm/s to $1.0x10^{-8}$ cm/s. Hydraulic conductivity of less than $1.0x10^{-5}$ cm/sec are recommended for stabilized waste destined for land disposal by the U.S. EPA, 1986. Reduction of hydraulic conductivity of the cement, lime & fly ash treated tailings to $1.0x10^{-5}$ cm/sec is the target value for this treatment procedure.

The hydraulic conductivity of particulate media such as tailings is influenced by physical and chemical factors related to the media and permeant (Yong, 1992). The measured value of hydraulic conductivity is representative of the material (tailings) only for a given state (compacted at OMC) and is not a constant material property (Mitchell, 1993). The observed hydraulic conductivity of compacted pure tailing materials was $2.4x10^{-3}$ cm/sec which is less than the usual range ($1.0x10^{-4}$ to $1.0x10^{-6}$ cm/sec) for homogenized tailings (Pettbone and Kealy, 1971: Qui and Sego, 2001).

Mine tailing – cement specimen incorporating 5% cement and 10% cement by dry mass of tailings achieved hydraulic conductivity values of $5.26x10^{-4}$ and $1.40x10^{-5}$cm/sec respectively. The addition of cement resulted in the formation of hydration products, filling the pores of the stabilized matrix. When cement is mixed with waste material such as mine tailings, water in the tailings chemically reacts with cement to form hydrated silicate and aluminates compounds, solids in the wastes acts as aggregates to form a low strength concrete (Conner, 1990).

The hydraulic conductivity of the 5% cement treated sample is slightly higher than the hydraulic conductivity of compacted pure mine tailings. The increase in the percentage of cement to 10% induced a corresponding decrease in hydraulic conductivity, apparently, the additional cement product increased hydration products that filled more pores, better encapsulated the tailing particles and thus increased the water holding capacity of the stabilized matrix. The decrease in the hydraulic conductivity of cement stabilized tailings is a synergistic effect of the consolidation of the cement-mine tailing mixture using a compactive effort, the high CaO content of the cement (56.08%) and its cementitious properties. The production of C-S-H gel is responsible for the blockage of flow paths and matrix densification.

The addition of 5% lime and 10% lime (TM/0/5/0 & TM/0/10/0) to the mine tailings achieved hydraulic conductivity values of $3.01x10^{-4}$ and $7.73x10^{-5}$ cm/sec respectively, which is slightly higher than the hydraulic conductivity of compacted mine tailings.

Further addition of 5% cement + 5% lime (TM/5/5/0) achieved hydraulic conductivity values for stabilized mine tailings specimens of $8.94x10^{-5}$ cm/sec and also 10% cement + 10% lime (TM/10/10/0) achieved hydraulic conductivity of $5.06x10^{-5}$ cm/sec. Using this composite binder resulted in a monolith having a modified pore structure of the stabilized material due to synergistic effects between the cementitious and pozzolanic lime. Matrix densification due to such cementitious and pozzolanic reaction lowered the hydraulic conductivity of the stabilized tailings. Yet, the resulting hydraulic conductivity value is still higher than that permitted by standards.

The addition of 5% cement + 20% fly ash (TM/5/0/20) and 5% lime + 20% fly ash (TM/0/5/20) to mine tailings achieved hydraulic conductivity values of $7.65x10^{-6}$ and $4.64x10^{-6}$ cm/sec respectively. The addition of fly ash effectively reduced the hydraulic conductivity of the resulted monolith, turning into an effective barrier against water percolation. A combination of several mechanisms, such as cementitious and pozzolanic reactivity, particle packing effect and densification of the interfacial transition zone between tailings particles and the cementing paste, can drastically reduce the permeability of cement based material (Nehdi & Mindess, 1999).

The hydraulic conductivity of $1.07x10^{-6}$ and $2.63x10^{-6}$ cm/sec produced by the addition of 10% cement + 40% fly ash (TM/10/0/40) and 10% lime + 40% fly ash (TM/0/10/40) is a result of combined effect of cement hydration products and compaction of the treated specimen. Eliminating large pores, increasing the bonding particles and maintaining of the particle arrangements as a result of treatment with lime and fly ash have contributed to the reduction of permeability (Mohamed, 2007).

The result of the permeability analysis shows that using cement & fly ash and lime & fly ash has reduced the permeability of the stabilized waste. Such a low permeability is an indicative for the safe disposal of the tailings sample in the environment after treatment.

Table-7: Hydraulic conductivity of the TM and blends

Mix ID	Hydraulic conductivity (k) cm/sec	Void ratio
TM/0/0/0	2.40E-03	0.55
TM/5/0/0	5.26E-04	0.56
TM/0/5/0	3.01E-04	0.57
TM/10/0/0	1.01E-05	0.56
TM/0/10/0	7.73E-05	0.52
TM/5/5/0	8.94E-05	0.55
TM/10/10/0	5.06E-05	0.58
TM/5/0/20	7.65E-06	0.48
TM/0/5/20	4.64E-06	0.48
TM/10/0/40	1.07E-06	0.49
TM/0/10/40	2.63E-06	0.49

3.8 Leaching studies on TM and blends

In order to determine the effectiveness of the stabilization process, the stabilized tailings were subjected to a leach test. This gives an understanding of leaching of heavy metals from the stabilized material. Leaching studies on TM and stabilized tailing material were performed using GBC-932 plus ver. 1.33 Atomic Absorption Spectroscopy (AAS). During leach tests, the material was mixed with distilled water in a ratio 1:20 (solid: liquid). Buffer was added to maintain pH of the soil solution. Then the test specimens were mixed continuously for about 18 hours in a rotary shaking machine at 30±2 rpm and room temperature 25^0c as required in D3987. After mixing the solution was filtered through 0.45 µm membrane filter. 100 ml of filtrate was stored in HDPE bottles and used for heavy metal analysis using AAS. The above leach test procedure in accordance with the U.S. EPA (1996) regulations and the method adopted by Jacob, 2012 were performed on specimen from the control mine tailings sample and 28 days cured blended mine tailings. The results of leaching tests of pH, conductivity, chloride, sulphate and alkalinity are presented in Table-8. The results of heavy metal analysis using AAS are presented in Table-9. From the Table-8 and Table-9 it is observed that the leached constituents from the stabilized material are in consistent with the TCLP criteria for each metal as shown in Fig-8a to Fig-8d.

Table-8: Chemical characteristics of leachate

Element	Regulatory limits[1] ppm	Control sample[2] TM/0/0/0 ppm	TM/5/0/0	TM/0/5/0	TM/10/0/0	TM/0/10/0	TM/5/5/0	TM/10/10/0	TM/5/0/20	TM/0/5/20	TM/10/0/40	TM/0/10/40
pH	6.5-8.5	7.45	11.53	12.16	11.64	12.25	12.21	12.25	11.36	12.06	11.25	12.07
Conductivity (ms)	-	0.233	0.879	4.54	1.39	5.46	4.37	5.08	0.731	3.41	0.63	3.41
Chloride (mg/l)	1000	30	30	680	10	805	650	795	10	480	20	330
Sulphate (mg/l)	400	110	210	52	120	42	62	46	168	35	91	37
Alkalinity (mg/l)	500	124.80	395	1040	437	1206	1383	1477	187	322	146	520
Nitrate (mg/l)	10	13.09	ND	5.18	ND	ND	ND	1.94	ND	ND	0.46	ND
Nitrite (mg/l)	1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

[1] Indian Standard tolerance limits for drinking water and its inland surface water source, class A: specification for drinking water as per IS: 10500-1991 (permissible)

[2] Tailings sample without additives (untreated), ND – Not detected

Table-9: Concentration of heavy metals in leachate for EPA testing procedure

Element	EPA regulatory limits[1] ppm	Control sample[2] TM/0/0/0 ppm	TM/5/0/0	TM/0/5/0	TM/10/0/0	TM/0/10/0	TM/5/5/0	TM/10/10/0	TM/5/0/20	TM/0/5/20	TM/10/0/40	TM/0/10/40
Lead (Pb)	0.015	5.51	ND	0.89	ND	0.76	ND	ND	ND	ND	ND	0.008
Chromium (Cr)	0.10	1.56	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Copper (Cu)	1.30	0.41	0.28	ND	0.30	ND	0.19	0.22	0.24	0.14	0.05	0.08
Manganese (Mn)	0.05–0.10	4.84	ND	ND	0.06	ND	0.08	ND	0.02	ND	ND	ND
Iron (Fe)	0.30–0.60	3.24	0.13	0.17	0.10	0.02	ND	0.11	0.10	0.21	0.15	0.16

[1] U.S. EPA regulatory limits NDEP Profile II (Misra et al., 1996)

[2] Tailing sample without additives (untreated), ND – Not detected

Concentration of Pb in control sample: 5.51 ppm

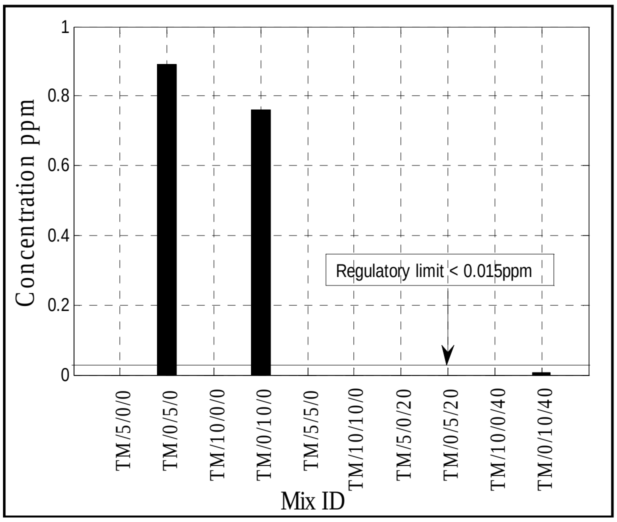

Fig-3.8a: Concentration of Pb in 28 days cured TM -additive mixtures & EPA regulatory limit

Concentration of Cu in control sample: 0.41 ppm

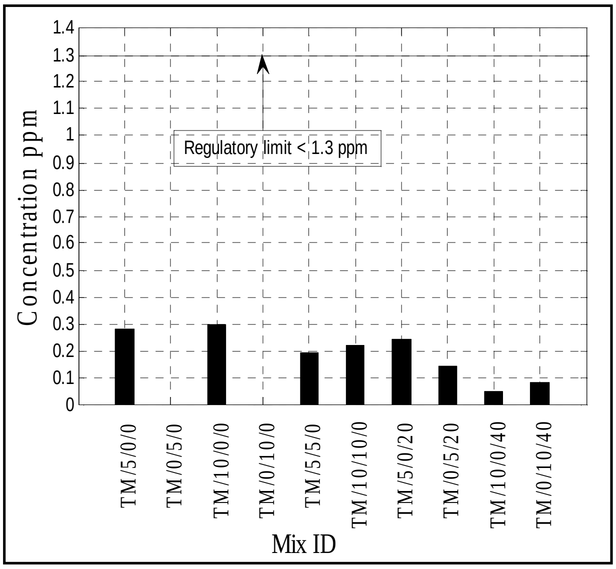

Fig-3.8b: Concentration of Cu in 28 days cured TM - additive mixtures & EPA regulatory limit

Concentration of Mn in control sample: 4.84 ppm

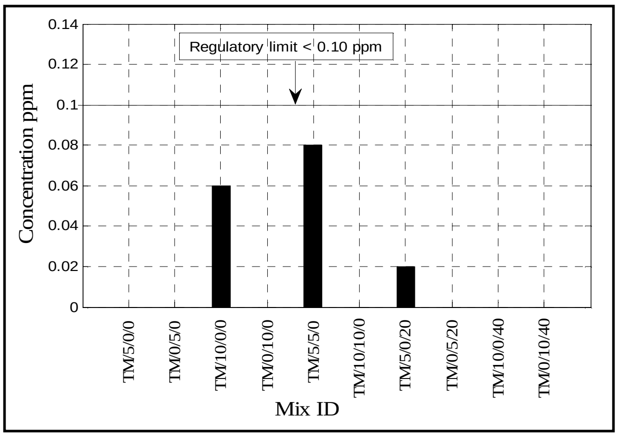

Fig-3.8c: Concentration of Mn in 28 days cured TM-additive mixtures & EPA regulatory limit

Concentration of Fe in control sample: 3.24 ppm

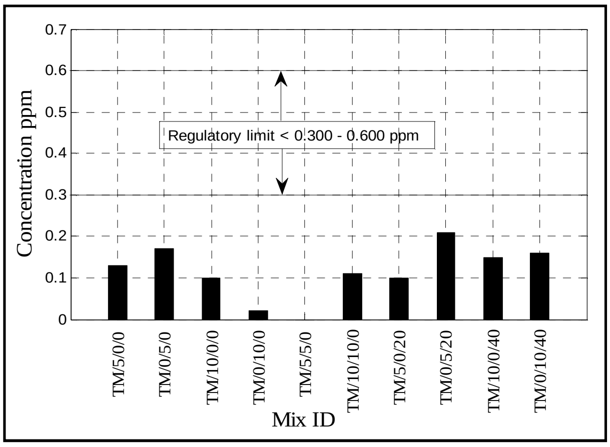

Fig-3.8d: Concentration of Fe in 28 days cured TM -additive mixtures & EPA regulatory limit

SUMMARY & CONCLUSIONS

The tailing material (TM) used in this study contains high concentrations of Pb, Cr, Mn and Fe leading to leaching of these elements above the respective regulatory limits. The land filling of such tailings, even after compaction, constitutes an environmental risk as substantiated by a high hydraulic conductivity value of compacted mine tailings exceeding regulatory standard limits. Solidification/stabilization of such polymetallic mine tailings using ordinary Portland cement (OPC), lime (CaO) and Fly ash (class F) as binder/additives was evaluated from a regulatory perspective. The performance of ten binder combinations in S/S of the tailing material was compared to study the effect of type and dosage of the additives/binder on selected parameters.

Based on the results presented in this paper, the following conclusion can be drawn:

1. The experimental results of the present study indicate that a cement-fly ash composite binder can be very effective in stabilizing iron ore mine tailings.
2. Test specimen with Mix ID TM/5/0/0, TM/5/5/0, TM/10/10/0 produced adequate compressive strength values >345 kPa, but failed in achieving the required hydraulic conductivity < $1.0\text{x}10^{-5}$ cm/sec. Two specimens TM/0/5/0 and TM/0/10/0 in TM -lime mixtures failed in achieving the required both compressive strength of > 345kPa and hydraulic conductivity of < $1.0\text{x}10^{-5}$ cm/sec. A specimen with Mix ID TM/0/5/20 produced hydraulic conductivity < $1.0\text{x}10^{-5}$ cm/sec, but failed in achieving the required compressive strength of > 345kPa.
3. Four design mixes namely TM/10/0/0, TM/5/0/20, TM/10/0/40 and TM/0/10/40 produced hydraulic conductivity values of $1.40\text{x}10^{-5}$, $7.65\text{x}10^{-6}$, $1.07\text{x}10^{-6}$ and $2.63\text{x}10^{-6}$ cm/sec respectively and qualified for further leaching test.
4. Composite design mixes prepared using cement, lime and fly ahs i.e., TM/10/0/0, TM/5/0/20, TM/10/0/40 and TM/0/10/40 significantly impaired the solubility of all contaminants investigated and proved successful in fixing metals within the matrix, thus satisfying the regulatory requirements.
5. The design mixes with mix ID's TM/10/0/0, TM/5/0/20, TM/10/0/40 and TM/0/10/40 provided good strength, lower hydraulic conductivity value and provided the best immobilization efficiency on Pb, Cr, Cu, Mn and Fe leaching.

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