International Journal of Research in Engineering and Applied Sciences(IJREAS)
Available online at http://euroasiapub.org/journals.php
Vol. 7 Issue 6 , June-2017, pp. 1~9
ISSN (O): 2249-3905, ISSN(P): 2349-6525 | Impact Factor: 7.196 | Thomson Reuters Researcher ID: L-5236-2015

Use of Base Metal Tailings from Mining Industry in Concrete: A Review

Arushai Sheoran
PG Student,Department of Civil Engineering,
Birla Institute of Technology & Science,Pilani,Rajasthan- 333031,India

Abstract
Natural sand and cement are the prime materials used for preparation of concrete. Scarcity of sand due to various environmental factors and cement production causing green house effect has affected sustainability. Thus there is need for alternate materials to replace them. Mine tailings are in the present times one of the largest industrial corollary, requires immediate attention to assess its reuse prospectives. Number of studies and experiments has been carried out to examine the use of this mining waste as building construction material. Such studies have shown that mine tailings have great potential to be used in concrete, thus making construction a green activity. This paper reviews the use of base metal tailings in concrete.

Keywords: Concrete, Sand Replacement, Cement Replacement, Mining Waste, Base Metal Tailings

INTRODUCTION
Concrete is among most widely consumed man-made artifact in the world. After water, it is the most exploited commodity in the world. It offers numerous advantages, which includes good workability along with mechanical strength and high durability and rigidity along with low cost. Over the past divers decennium, the demand of concrete has shot up and will keep on increasing rapidly because of growth in infrastructural development. Global production of concrete is about 12 billion tons a year corresponding to almost 1 m3 per person per year, causing it to acquire a status quo of highest level along with ranking as the largest users of the natural resources in the world. (Prabhu et al., 2014; Siddique et al., 2011). It is predicted that concrete need will further rise to more than 7.5 billion m3 (about 18 billion tons) a year by 2050 (Monteiro,2015).Such extensive consumption of concrete is the genesis for extortionate use of natural aggregates and cement which eventually causes detrimental effect on the environment.

The worldwide utilization of natural sand as fine aggregate in mortar/concrete production is very high and several developing countries are having problems with the supply of natural sand so as to meet the increasing demands of civil construction industry. In many countries there is a shortage of natural fine aggregate which is appropriate for construction as natural sand is the most commonly used material. The shortage of the resources of natural sand is the cause for sliding the barrier for by-products and cementitious materials being used as the source. Reuse of by-products as a partial or full replacement of natural fine aggregate in construction reduces both the exploitation of natural resources and sustainability issues faced by wastes. (Ji et a., 2013, Rashad, 2013,2016).

Similarly, Portland cement is popular and an essential binder for most of the building constructions while at the same time it is causing emission of a huge amount of carbon dioxide (CO_2) in its production which is responsible for carbon foot printing and greenhouse effect. Global

Climate change being the most significant environmental impacts in recent years is causing big threats for subsequent build-outs which includes rising of sea level and causing numerous natural disasters. According to the IPCC,(2007), 11of the last 12 years (1995–2006) are ranked as 12 of the warmest years in instrumental record of global surface temperatures since 1850. Global average sea levels have been raised since 1993 at the rate of 3.1 mm/year which has a considerable effect on future development greatly (IPCC, 2007). If immediate actions are not taken so as to reduce the emission of green house gas (GHG) then the inclusive costs and risks of climate change will be analogue to losing more than 5% of global GDP per year from present time onwards. The civil construction industry has a great contribution towards increase of greenhouse gases emissions level, of cement manufacture being the major shareholder and so there is need to search for alternate viable materials to be used in place of cement(Wu et al., 2010a,b). Reuse of by-products as a partial/ full replacement of cement in construction reduces both the GHG and sustainability issues faced by wastes, thus considering its potential as of great significance in the future.

Over the erstwhile assorted decades, an expansive consignment of research has been conducted on the use of industrial waste as substitute/replacement material for fine aggregate/cement by the construction industry. Industrialization and population growth has ushered to the production of vast amount of wastes and by-products, disposal of which is a gargantuan task. Thus, making Green construction an important aspect to be considered, as it is valuable both economically and ecologically as by replacing some of the elements with waste materials effects the cost economics and environmentally by clean ejection of waste materials (Moustafa and ElGawady, 2015).

MINING WASTE

One of the major industries which is among the largest producer of industrial by products is Mining industry. Millions of tons of mill tailings are produced as by-product of metal ore processing and are dumped every year in landfills, quarries, rivers, oceans among others places thereby giving rise to huge environmental issues. To fashion mining activities in more eco-friendly manner, it is paramount to conduct mining operations in a fashion that is more environmentally amiable, economically admissible and socially amiable. The huge quota of solid waste generated which includes tailings produced from mineral processing activities is among the major concerns faced by the mining industry (Yellishetty et al., 2008). The recourse of trade of natural fine aggregate/cement with industrial by-product such as Base Metal Tailings(BMT) propound technical, economic and environmental boon which are of exceptional importance in present state of affairs regarding sustainability in the civil construction sector.

Metalliferous mining activities have deleterious effects on the environment due to exploration and beneficiation process of metal ore. Various mining and ore beneficiation operations generates waste that may consist of natural materials (Overburden and topsoil) as waste .Waste generated during the action of ore-processing and enrichment juncture contains chemical, inorganic and organic additives. This whole process is depicted in Fig. 1 (BRGM, 2001). In the mining activities, once the minerals are dealt with and recovered from the ore the remaining rock waste becomes another form of mining waste which are called mine tailings. It is gauged that more than 1150 million tons of heavy metals (copper, zinc, cobalt chromium, cadmium and lead) have been mined since the Stone Age with appraises of contemporary mine tailings production (Lu and Wang, 2012;

Mudd and Boger, 2013). Generally the production of tailings is about 50 to 1000 times the metal production depending upon the cost of the metal. Copper metal produces 100 times where as gold produces 1000 times. To quantify it we could say that each ton of cooper and gold produces about 100 and 1000 tonnes of tailings respectively. By appraised judgment it is guessed that mass of mine tailings production is more than 18 billion m^3/year and by next 20 years this valuation is about to be doubled. (Aswathanarayana, 2003).

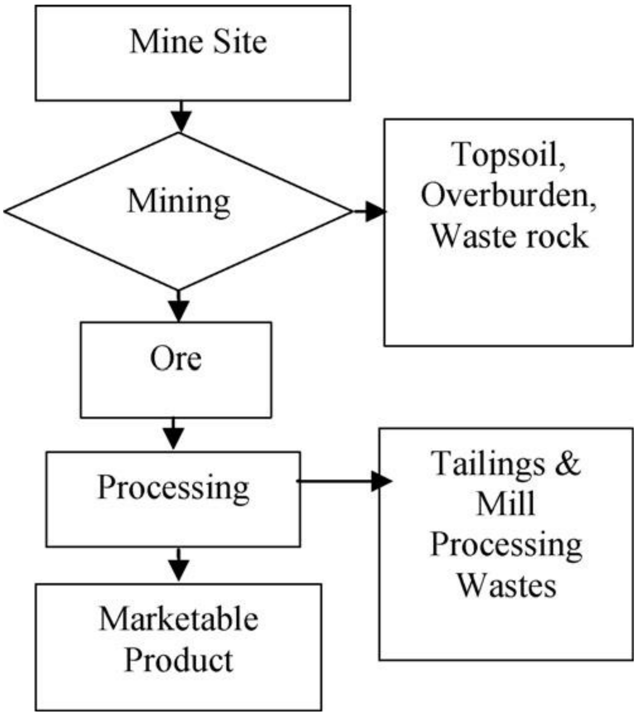

Fig-1: Waste generation during mining and processing of minerals (BRGM, 2001).

The mining industry generates millions tones of tailings from mining each year which subsists process water and fine-gossamer industrial waste engender through beneficiation of ore minerals. In many cases these by-products are discharged in the form of a slurry into ponds, impoundments, where solids and system fluids separate due to the action of gravity (Wang et al., 2014). Whenever the escapes of the mining industry is not appropriately handled there is a consequential repayment by environment of the negligence of homo-sapiens consisting of ecological imbalances such as acid mine drainage and pollution and contamination of various ecosystem (Khalil et al., 2013).

Contemporary situation faced by almost all mineral producing country is the problem of sustainable consumption of mine waste as its accumulation along with lack of appropriate storage space is affecting all surroundings. For many years the mining industry has utilized its waste in many small civil structures of which many are mainly present in close range to the establishments (Skarzynska, 1995). Maneuver of mine waste and its further utilization as a construction material for various civil operations like embankments of roadways, railways, rivers and dams has increased in the last 20 years so as to vanquish the issue of abuse of non-renewable natural resources. In the present state of affairs and with an outlook of flourishing sustainable avant-garde methods for orderly tailings management, literature studies alongside with experimental work to sustain it have been conducted to appraise the possibility of their recycling in the civil construction sector, as partial substitutes of natural sand and cement in concrete respectively.

USE OF BASE METAL TAILINGS IN CONCRETE

Due to various ecological constraints in the construction sector also some of the contemporary studies have been orchestrated to assess the mine tailings possible recycling as cementing material, and also as an accompaniment for mortars/concretes. Wong et al., (2004) studied for concrete the prospective reuse as a supplementary material of calcined oil sand tailings for the above purpose. It was shown the tailings could be suitable as replacement as they showed their suitability as a partial substitution for OPC. This replacement was found to be very beneficial in improving compressive and flexural strengths. Likewise it has been observed that for cement replacement with satisfactory properties could be inaugurated plying adequate measure of tailings from tungsten mine waste (up to 10% by mass).Besides this Onuaguluchi and Eren, (2012) demonstrated that control mixture with pre-wetted copper tailings at 5% addition level if used had more beneficial properties than CM. These tailings seemed to make mortars with significant strength, aloft abrasion and significant chloride resistance than the control mixture. For the production of M25 grade concrete, copper tailing have also been delineated to be used as partial replacement of sand (till 60% replacement) (Thomas et al., 2013). The uses of iron, tungsten, and cooper tailings have furthermore been studied and the mechanical properties of tailings-replaced materials which have been obtained show significant improved results (Argane et al., 2015). Nonetheless most the research schooled is still at laboratory scale status lacking field implementation. Further more detailed studies to assess the durability of the said tailings-based mixtures is yet to be carried out (Thomas et al., 2013).

Several studies on the recycle/reuse of variety of solid mineral wastes have been carried out to assess the possibility of making ceramic structural products out of these wastes (Fine and Heising, 1968; Kluth, 1984; Trinity-Stevens, 1995). Former office of coal research of West Virginia University has developed an innovative technique to reuse the mine tailing waste for making building bricks and other structural units under the sponsorship of Department of Interiors.

Stanford University has also reported several studies on the feasibility of using siliceous gangue from California gold mine tailing as raw materials for calcium silicate bonded bricks (Mining Journal, 2000). Colorado School of Mines also conducted similar investigations which mainly aimed at making building bricks from various mine and mill waste tailings located throughout Colorado (Boving and Herold, 1967). The use of copper mill tailings and other mine wastes have also been reported by Dean et al., (1986) for making building bricks . It is observed that reuse of the waste which is highly economically feasible, and its use in the down- stream economic activities can be very useful in the socio-economic factors of mine shut-down. The schismatic remuneration polarity could be minimized and a greater community self-sufficiency and self-reliance may be greatly emboldened. Further the use of mine tailings was also considered as part of intensive research into waste utilization in the 1970's in producing bricks and blocks (Collins and Miller, 1979) . Lead-zinc tailings from the Upper Mississippi Valley mining district have been reported to be used to produce a whole range of building products, including foamed building blocks, concrete beams and tiles, and dense silicate bricks and aerated concrete to support the above said cause (Hansen et al., 1968). The tailings and mine waste have the potential for use in manufacture of building material, glass, and ceramics have been stated in various investigations carried out in developed countries like USA, Canada and Britain . Some of the highly cost effective beneficial results from the tailings uses are the manufacture of silicate bricks from gold tailings, lightweight-building products from taconite tailings, and bricks from iron ore tailings have also been reported (Jacobi, 1975). Developing countries like India are also now leading in construction sector towards more ecological and economical natural products. Manufacture of glass by utilizing the quartz and feldspar from waste produced in mica mines; and the use of tailings with high silica content limestone to benefit agriculture as a carrier for pesticides and manure (IBM, 2002; Kumar, 2000) have been reported by many research studies.

The most recent studies reported from the Montana State University, USA revealed that concrete blocks made from gold tailings mixed with fly-ash as partial cement replacement were significantly stronger than standard OPC concrete blocks (Trinity-Stevens, 1995). Likewise Struthers, (1999) during base metal mine tailings recycling research in Melbourne, Australia stated that concrete blocks made from tailings also resulted in superior compressive strengths than conventional control blocks. It was observed that tailings are too fine to work quite successfully in a commercial high-speed production system. However it has been observed that they are suited to slow, intermediate technology methods and are ideal for the production of complex concrete form work.

Mining industry wastes are often seen as a rich resource and can be highly suitable as aggregates for road construction and building materials. Emery, (1975) and Williams, (1996) have also supported the mining and metallurgical waste utilization in construction. Kim et al., (2016) investigated the probability of considering the arsenic-rich mine tailings mined in South Korea as source material for controlled low-strength materials (CLSM). The CS of the CLSM mixtures was equivalent to what it was advocated in American Concrete Institute (ACI) Committee 229R in which amount of cement was monitored to be 10-30% by the weight of the tailings. Similarly Sancak and Çoban, (2015) conducted study for the use of forsterite mine tailings (FOT) to impart steel reinforcing bar corrosion inhibition result. The results showed that with the increasing additive amounts the CS efficacy procured for concrete specimens containing FOT leaned to decline simultaneously. But, all the specimens besides those holding 40% (5%, 10%, and 20%) had compressive strengths more than the chosen C30 grade concrete. The corrosion scale mean face value procured for specimens containing 5%-10% FOT were less than what was acquired for CM which makes the use of 5% and 10% FOT as optimal switch percentage. Several studies have shown that base metal tailings have great potential as building material such as conducted by Argane et al., (2015;2016) .The work showed the feasibility to use BMT with low sulphide content (As =30 mg/kg, Cr = 60 mg/kg, Pb = 4500 mg/kg, Zn = 250 mg/kg) as aggregates with good mechanical and durability potential, thus replacing 30% of natural sands in masonry mortars and 100% for the making of renderings. Tailings-based contents show high porosity due to their greater finer contents and which is the cause of higher water demand for their making. The elevated porosity of BMT-based renders decreases their fight to wetting/drying cycles. In the conditions of acid rain, the leaching of metals was notably decreased after including BMT in the main mix. Also Mun et al., (2007) recommended resin concrete commodity which are considerably unguarded to corrosion by H_2SO_4 by utilizing fine tailings (FT) in place of ground calcium carbonate (GC) as a filler to produce the merchandise of greater defiance to corrosion triggered by H_2SO_4.

Yellishetty et al., (2008) showed that when iron mine waste is used in construction, the results secured for uniaxial compressive strength (UCS) of concrete cubes after 28 days of curing using mine aggregate and granite aggregate were in the order of 21.93 and 19.91MPa respectively. Both Huang et al., (2013) and Zhu et al., (2015) studied the Iron ore tailing. Huang et al., (2013)

conducted study to consider the possibility of using iron ore tailings (IOTs) in place of Micro-silica sand as aggregates in standard Engineered Cementitious Composites (ECC). The ECC mixtures with IOTs- Fine or IOTs-425 showed tensile first cracking strength of 3.0–3.9 MPa, UTS of 4.7–5.8 MPa, tensile strain capacity of 2.8–4.2%, and CS of 27.9–50.1 MPa at 28 days respectively, depending on the FA/C weight ratio. Whereas Zhu et al., (2015) deliberated the practicality of plying iron ore tailings (IOT) as fine aggregate to built ultra high performance concrete (UHPC).The strength of UHPC extend to highest point when silica sands were used instead 60% by IOT. The UHPC got great result and was superior to only utilizing silica sands as aggregate.
Bakulamba et al., (2015) used Iron Ore Tailings (IOT) and finely powdered waste glass from mining industries as a partial replacement of cement and fine aggregates in concrete respectively. It was found that 30% replacement of cement by GP and 30% of fine aggregate by IOT met maximum flexural strength in comparison to that of normal control concrete. Correspondingly Sunil et al., (2015) further explored the studies in the concrete mixes for the feasibility of utilizing Tailing Material (TM) as a part replacement to fine aggregate and Fly Ash (FA) as a part replacement to cement, The strength in mixture TM35% and F20 % was found to be 4% higher than the control concrete specimen.
Zheng et al., (2015) in Portland cement further investigated the use of phosphate tailings as a filler and studied its effect on hydration, volume stability and properties of Portland cement because of possible dedolomitization . Dedolomitization is a phenomenon occurring in the presence of alkali to dolomite present in phosphate tailings, which further leads to its subtle expansion, although the impact on strength due to it is negligible. The findings indicated the viability to use phosphate tailings in Portland cement as a filling substance, thus providing a sustainable choice to predispose the solid waste produced from phosphate industry. Additionally Sibanda et al., (2013) analyzed magnesite tailings and they were catalogued as well-graded sand with Cu ≥6 and 1≥ Cc ≤3. It had 43.32% silica and thus was deduced as fairly befitting for application in various engineering projects which entails well-graded soils with medium shrink-swell embryonic future along with medium plasticity and comparatively dry strength.

CONCLUSIONS

Globally the metal ore processing activities generates huge quantity of mill tailings at mine sites which creates a serious environmental problem. As an auxiliary proxy mitigation considering directorate measure, it is delineated by number of studies that these tailings could be utilized as a concrete making material.
The reuse feasibility of the said tailings includes evident particulars that fabricate every tailing to be extremely individually distinct. In explicit location, fine content percentage, density differentiation and substantial specific area of tailings are influencing factors for flow properties, bulk density and water absorption characters of the resulting concrete. Residual metal concentrations of each tailing also affect concrete setting time. In term of strength showed by TC and SC concrete mix it can be concluded that the utilization of base metal tailings as aggregates plunged the temper of concrete resistances initially at some stages of critical proceedings of curing. The aforementioned could also be kindred to tailings high fine content along with the retarding effect of Pb-Zn fraction. Natheless, no relation has up till now been entrenched linking those patrimony to concrete length change or the predisposition to cracking.
The umbrella comprehension cessation of this study is that the base metal tailings can be used as

aggregates and cement replacements through superseding natural sand and OPC in concrete. The exercise usage of these tailings as an accompaniment in concrete will abridge environmental pollution. It will also shepherd us along to re-claim land previously usurped by tailings deposits. Prospective proffer amply pronounced benefits while fostering the material greenness along with nurturing natural resource conservation and stimulating environment protection.

REFERENCES

Argane, R., Benzaazoua, M., Hakkou, R., and Bouamrane, A.(2016). A comparative study on the practical use of low sulfide base-metal tailings as aggregates for rendering and masonry mortars. J Clean Prod., 112(1), 914–925.

Argane R., Benzaazoua M., Bouamrane A. and Hakkou R., (2015). Cement hydration and durability of low sulfide tailings-based renders:A case study in Moroccan constructions, Miner. Eng., 76, 97–108.

Aswathanarayana U., (2003). Mineral resources management and the environment. A.A. Balkema, Pub. Tokyo. pp. 1-17.

Bakulamba Devi T S, Natesh M G, Praveen kumar K S , Archana N, Ashwini sogi (2015). An Experimental Study on Utilization of Iron Ore Tailings (IOT) and Waste Glass Powder in Concrete ,Civil and Environmental Research,Vol.7, No.8, 2015. 107-109.

Collins, R.J. Miller, R.H. (1979) Utilization of mining and mineral processing wastes in the United States. Mineral. Environ. 1, 8–19.

Dean, K.C, Froisland, L.J, Shirts, M.B.(1986). Utilization and stabilization of mineral waste. Bulleting 688. United States: Department of Interior Bureau of Mines; . p.46.

Emery, J.J.(1975). Use of mining and metallurgical wastes in construction. Minerals and the environment. In: The institute of mining and metallurgy proceedings of international symposium; . p. 261–72.

Fine, M.M, Heising, L.F.(1968) Iron orewaste occurrence, beneficiation and utilization. In: The institute of mining and metallurgy proceedings of international symposium; p. 67–72.

Hansen, T.C, Richards, C.W, Mindess, S. (1968). Production of high pressure steam-cured calcium silicate building materials. From mining industry waste products. Dept. of Civil Engg., Stanford University, Tech. Rep. 86, January; p. 83.

Huang X. Ranade R., Wen Ni W , Li V.C. (2013). Development of green engineered cementitious composites using iron ore tailings as aggregates, Construction and Building Materials 44 ;757–764.

IBM. (2002). Indian Minerals Year Book, Indian Bureau of Mines, Ministry of Mines, Government of India, Issued by Controller General; p. 35: 11–16; 76: 23–24.

Jacobi, J.S.(1975). Recovery and reuse of metals. Minerals and the environment. In: The institute of mining and metallurgy proceedings of international symposium; p. 291–301.

Ji Tao, Chen Cai-Yi, Zhuang Zhou,Y.. Feng, C.J.(2013). A mix proportion design method of manufactured sand concrete based on minimum paste theory Construction and Building Materials 44 ; 422–426.

Khalil, A., Shaikh, S. N., Nudrat, Z. R. and Farzana, H. (2013). The effect of silica on the properties of marble sludge filled hybrid natural rubber composites. Journal of King Saud University - Science, 25 (4) , 331-339.

Kim B.J., Jang J.G., Park C.Y., Han O.H., Kim H.K., (2016) Recycling of arsenic-rich mine tailings in controlled low-strength materials., Journal of Cleaner Production, 118, 151-161.

Kluth, D.J.(1984). Use of mine spoil in the Selby Wistow-Cawood barrier bank. 1st international symposium, on reclamation, treatment and utilization of coal mining wastes. Durham, U.K.; 1984. p. 46.1–46.14.

Kumar, A.(2000). Conveners Report. Published in the souvenir of mines environment and mineral conservation week (Goa and parts of Karnataka); . p. 8.

Lu, X., Wang, H., (2012). Microbial oxidation of sulphide tailings and the environmental consequences. Elements 8, 119-124.

Mining Journal. Bricks from gold, Mining Journal paper, Aug 18th, 2000, vol. 335, No.8596.

Monteiro M.P., Concrete: Microstructure, Properties, and Materials, McGraw-Hill 2015.

Moustafa, A., ElGawady, M. A. (2015). Mechanical properties of high strength concrete with scrap tire rubber,Construction and Building Materials 93 ;249–256.

Mudd, G., Boger, D.V. (2013). The ever growing case for paste and thickened tailings e towards more sustainable mine waste management. Aust. Inst. Min. Metall. Bull. 2, 56-59.

Mun, K.J. , Choi, N.W. , So, S.Y. , Soh Y.S. (2007) Influence of fine tailings on polyester mortar properties.,Construction and Building Materials 21, 1335–1341.

Onuaguluchi, O., Eren, O. (2012). Recycling of copper tailings as an additive in cement mortars. Constr. Build. Mater. 37, 723-727.

Prabhu G. G., Hyun J. H. and Kim Y. Y. (2014). 'Effects of foundry sand as a fine aggregate in concrete production', Constr. Build. Mater. Vol. 70, pp.514–521,.

Rashad, A.M, (2016). Cementitious materials and agricultural wastes as natural fine aggregate replacement in conventional mortar and concrete. J. Build. Eng. 5, 119–141.

Sancak E., and Ömer, C.(2015) The Corrosion Inhibition Effect of Forsterite (Mg_2SiO_4) Mine Tailings for Steel Rebar in Reinforced Concrete, Int. J. Electrochem. Sci., 10 (2015) 5770 – 5786.

Sibanda, Z., Amponsah-Dacosta, F. and Mhlongo S. E. (2013). "Characterization And Evaluation Of agnesite Tailings For Their Potential Utilization: A Case Study Of Nyala Magnesite Mine, Limpopo Province Of South Africa." ARPN Journal of Engineering and Applied Sciences, 8(8), 606-613.

Siddique, R., Aggarwal, Y., Aggarwal, P., Kadri, E.H., Bennacer, R., (2011). Strength, durability, and micro-structural properties of concrete made with used-foundry sand (UFS). Constr. Build. Mater. 25, 1916–1925.

Skarzynska, K.M.(1995). Reuse of coal mining wastes in civil engineering. Part 1. Properties of minestone.Waste Management .15(2):3–42.

Struthers, S.(1999). Constructive recycling of mine wastes. Proceedings of fourth international conference on tailings and mines waste. Colorado, USA; p. 17–25.

Sunil B.M, Manjunatha L.S, Ravib,L.,Yaragal, S.C.(2015). Advances in Concrete Construction, Vol. 3, No. 1 55-69.

Thomas B.S., Damare A. and Gupta R.C.,(2013) 'Strength and durability characteristics of copper tailing concrete'. Constr. Build. Mater. Vol. 48, pp.894-900 .

Thomas, B.S., Damare, A., Gupta, R.C., (2013). Strength and durability characteristics of copper tailing concrete. Constr. Build. Mater. 48, 894-900.

Trinity-Stevens A. (1995). Student makes concrete cubes from mine tailings. Bozeman, MT,USA: MSU Communications Services; .

Wang, C., Harbottle, D., Liu, Q., Xu, Z., 2014. Current state of fine mineral tailings treatment: a critical review on theory and practice. Miner. Eng. 58, 113-131.

Williams, D.J.(1996). Management of solid wastes. In: Mulligan DR, editor. Environmental Management in the Australian Minerals and Energy Industry. Sydney: UNSW Press in association with Australian Minerals and Energy Environment Foundation;1996. p. 157–188 [chapter 7].

Wong, R.C.K. , Gillott, J.E., Law, S. Thomas, M.J., Poon, C.S.(2004) . Calcined oil sands fine tailings as a supplementary cementing material for concrete Cement and Concrete Research 34 1235–1242.

Yellishetty Mohan , Karpe Vanda , Reddy E.H. , Subhash K.N., Ranjith P.G. (2008). Reuse of iron ore mineral wastes in civil engineering constructions:A case study, Resources, Conservation and Recycling, 52 : 1283–1289.

Zheng, K., Zhou, J. and Gbozee, M.(2015). Influences of phosphate tailings on hydration and properties of Portland cement. Construction and Building Materials, 98:593–601.