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Performance evaluation of asphalt concrete mixes having copper industry waste as filler

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Abstract

Increase in demand of copper and copper allied products have led to unavoidable generation of billions of tons of copper tailings throughout the globe. This study investigated the possibility of utilizing copper tailings (CT) of Indian origin in place of conventional stone dust as filler in asphalt concrete mixes. Detailed physical, morphological and mineralogical characterization of both fillers was done through specific gravity, plasticity index, methylene blue value (MBV), particle size distribution, German filler values, Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), hydrophilic coefficient and pH value tests. Thereafter, asphalt concrete mixes containing both fillers were designed using Marshall mix design procedure and their optimum asphalt contents were determined. At their respective OAC's, both mixes were compared on the basis of their stabilities, volumetric properties as well as their performance against various distresses (rutting, cracking, ravelling and moisture susceptibility) using relevant testing procedures. Copper tailing mixes delivered satisfactory Marshall and volumetric properties at relatively lower OAC than conventional mixes, which was attributed to the relatively lower porosity of copper tailings. Also, copper tailings mixes were found to have superior rutting and cracking resistances due to their lower VMA and fineness of copper tailings respectively. However, copper tailing mixes displayed relatively inferior (yet satisfactory) performance than conventional mixes in terms of moisture sensitivity, ravelling resistance, active and passive adhesion. This was due predominance of silica as well as absence of calcium based water insoluble minerals like dolomite in the composition of copper tailings.

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Keywords: Asphalt concrete; filler; copper tailings, sustainability; waste utilization

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1. Introduction

Flexible pavements are the major part of global road network which primarily composed of flexible pavements, which comprises of asphalt concrete mixes as their wearing course. Asphalt concrete mixes majorly consist of aggregates (coarse and fine), filler and asphalt as binder. Aggregates of various sizes provide stability by forming a skeleton to resist traffic load whereas asphalt provides the binding action as well as provide durability to asphalt mixes.

Filler is an integral part of asphalt mixes and influences their performances against various distresses. Filler can be termed as the finest portion of aggregate which passes through a particular sieve (0.075 mm in United State, India and 0.063 mm in Europe) and occupies up to 12% by weight in asphalt mixes (EN 13043; MORTH, 2013). Filler should also be free from organic impurities and should not have plasticity index greater than four (except for cement and hydrated lime) (MORTH, 2013).

Unlike the other components, filler plays a dual role in asphalt mixes. Coarser filler particles not only primarily act as inert material which fill interstices between larger aggregates in mixes, but also finer filler particles which have size smaller than asphalt film thickness (AFT) have an active role in modification of viscosity and consistency of asphalt-filler mastic (Huang et al., 2007). Presence of fillers is associated with better internal stability and reduced optimum asphalt content due to their good packing behaviour (Kandhal et al., 1998). Numerous studies have observed significant influence of filler's physical (specific gravity, particle shape, size, texture, size distribution, porosity) and chemical (mineralogy, active clay content) properties over primary pavement distresses (rutting, fatigue, low-temperature cracking, ravelling, aging and moisture susceptibility) (Huang et al., 2007; Kuity et al., 2014; Pasandin et al., 2016; Wang et al., 2011). Hence, choice of appropriate filler and its concentration in the asphalt mix is crucial since it influences cost as well as performance of pavements from construction stage to throughout their entire service life (Cardone et al., 2015).

Recently due to increase in environmental concerns and inflation in cost of pavement materials, there is a growing interest in the scientific community in replacing conventional fillers (hydrated lime, stone dust and cement) with alternative environmentally friendly materials. Numerous researchers have studied the performance of asphalt mixes incorporated with wastes fillers like: bauxite residue (Choudhary et al., 2018c); borogypsum (KutukSert and Kutuk, 2012); brick dust (Arabani et al., 2017; Kuity et al., 2013); coal fly ash (Chandra and Choudhary, 2013); dimensional limestone dust (Choudhary et al., 2018b); rice husk ash (Al-Hdabi, 2016; Arabani et al., 2017); glass powder (Choudhary et al., 2016) etc. All these wastes had numerous positive influences on the performance of asphalt mixes against various distresses. Hence this thought is becoming outstanding to introduce new wastes which have physical and chemical composition similar to the conventional fillers to successfully produce economical and sustainable asphalt mixes.

Copper tailing is one of the major wastes generated from copper industries during concentration stage of copper extraction process. It is the waste rock remaining after ore has been processed to remove the copper and ultimately disposed in the form of fine sand after being pulverized. Each ton of copper production generates 128 tons of copper tailings (Gordan, 2002). It must be noted that the increase in world population and exponential growth in demand of copper for various telecommunications, electrical and construction applications will intensify the generation of copper tailings. Hence systematic disposal of copper tailings as a pavement material is an option worth investigating. However, studies concerning the utilization of copper tailing as filler for asphalt mixes are very limited and this area is open for wide speculation. There is only one recent study existed which has suggested that asphalt mixes produced with copper tailings has marginally lower yet satisfactory Marshall stability and rutting resistance (Choudhary et al., 2018a).

This study investigated the potential of copper tailing of Indian origin as filler in asphalt concrete mix. The performance characteristics of mixes containing both fillers were evaluated by examining their fundamental characteristics and by performing various laboratory investigations, involving minimum of three specimens in each test to meet the reproducibility criteria in standard testing. This work will be instrumentally useful for next steps in field of copper tailing utilization in asphalt research.

2. Materials

2.1. Aggregates

The crushed aggregates of dolomite origin were collected from Dalla quary of Sonbhadra district (24.22°N, 83.04°E) in Uttar Pradesh, India and used in this investigation. Aggregates were sieved and washed over their respective sieve sizes to remove fines attached to them. The physical properties of aggregates were stated in Table 1. Asphalt concrete (Grading II) mix which is one of the most popular wearing course was designed as per Indian specifications (MORTH, 2013). The chosen gradation was specified in Table 2.

Table 1. Properties of aggregates and asphalt

Material	Characteristic	Testing Specification	Results
Aggregate	Bulk specific gravity of coarse aggregate (g/cm³)	ASTM C127	2.795
	Apparent specific gravity of coarse aggregate (g/cm³)	ASTM C127	2.820
	Bulk specific gravity of coarse aggregate (g/cm³)	ASTM C128	2.720
	Apparent specific gravity of coarse aggregate (g/cm³)	ASTM C128	2.747
	Water absorption of coarse aggregates (%)	ASTM C127	0.374
	Aggregate impact value (%)	IS 2386 (Part IV)	11.1
	Los Angeles abrasion value (%)	IS 2386 (Part IV)	13.4
	Combined flakiness and elongation index (%)	IS 2386 (Part I)	21.3
Asphalt	Absolute viscosity at 60ºC, (poise)	IS: 73	2692
	Penetration at 25ºC, 100g, 5s, (0.1mm)		62
	Softening Point,(Ring & Ball Apparatus) (ºC)		51.5
	Ductility at 27°C (pull of 5 cm/ minute),(cm)		>100
	Specific gravity		0.999

Table 2. Adopted gradation of asphalt concrete mix.

Sieve Size	Lower-Upper Limit (%)	Adopted Gradation (%)
19	100	100
13.2	79-100	91
9.5	70-88	78
4.75	53-71	67
2.36	42-58	52
1.18	34-48	45
0.6	26-38	35
0.3	18-28	23
0.15	12-20	13
0.075	4-10	7

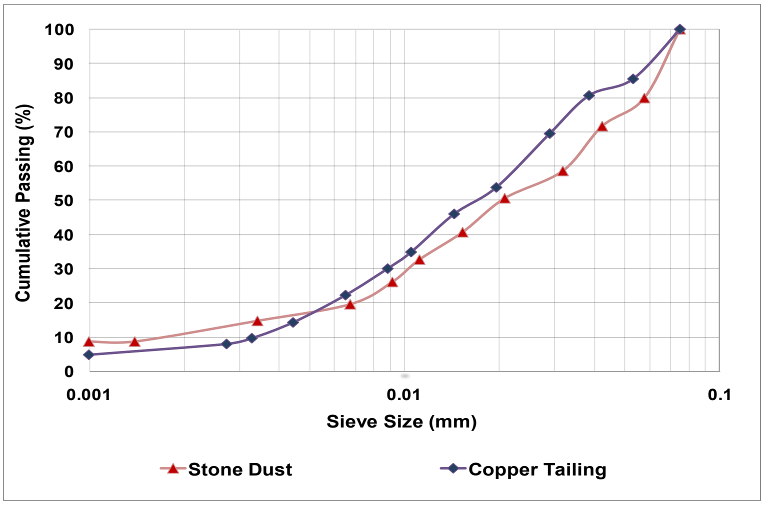


Fig. 1. Particle size distribution of fillers

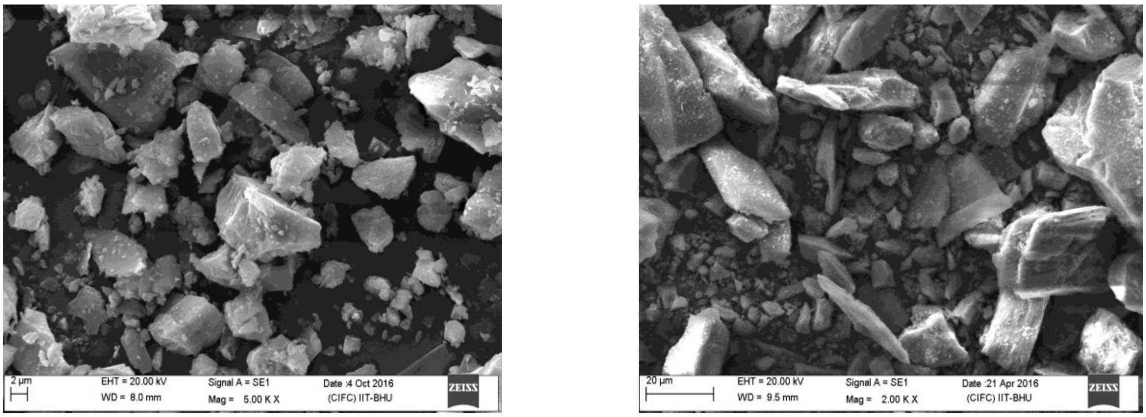


Fig. 2. (a) SEM image of copper tailing (b) SEM image of stone dust

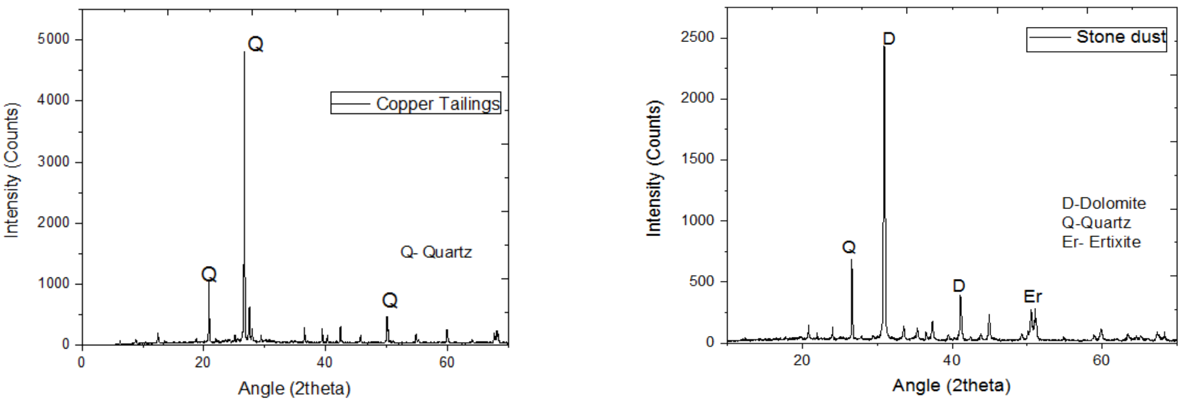


Fig. 3. (a) XRD of copper tailing (b) XRD of stone dust

2.2. Fillers

Conventional stone dust of dolomite origin was utilized as control filler in this study and was collected from the Dalla quary in Sonbhadra district (24.22°N, 83.04°E). While, copper tailing used in this study was collected from dumping ground of Hindustan Copper Limited (HCL) plant of Malanjkhand city (22.02°N, 80.71°E) of Madhya Pradesh, India. In this analysis, oven dried filler with only the fraction that passes through 0.075 mm sieve was used. Physical characterization parameters such as specific gravity, plasticity index, particle size distribution and fractional void content were assessed using specific gravity test (ASTM D854), particle size analysis (ASTM D 422), and German filler test value respectively. Harmful clay content was determined as per methylene blue value test (EN 933-9). Morphological and mineralogical analyses were performed using Scanning electron microscope (SEM) (ASTM E 986) and X-Ray Diffraction (XRD) techniques. Apart from these, affinity of materials towards asphalt was assessed using pH value and hydrophilic coefficient (MTPRC, 2004) tests. Various results are stated in Table 3, and in Figures 1-3.

Table 3. Characterization properties of fillers

Characteristics	Copper Tailings	Stone Dust	Inferences
Specific gravity	2.721	2.698	Copper tailing has a relatively higher specific gravity due to which it occupies lower volume in the asphalt mix for same weight.
Plasticity index	Non Plastic	Non Plastic	Both fillers have PI<4 and both satisfied requirement of filler as per Indian specifications.
Methylene Blue Value (mg/g)	1.5	3.25	Copper tailing has lower harmful clay content per unit weight of material.
German filler value (g)	100	85	Stone dust has higher porosity/fractional voids per unit weight which may influence OAC of mixes.
Fineness modulus	4.28	5.38	Copper tailing is the finer filler than stone dust.
Coefficient of Uniformity (Cu)	7.19	17.89	Stone dust has relatively well graded particles.
Particle shape and texture (SEM)	Sub angular particles with rough texture	Angular particles with smooth to rough texture	Small particles and rough texture of copper tailing may lead to higher asphalt absorption.
Primary Mineralogical Composition (XRD)	Quartz (SiO_2)	Dolomite ($CaMg(CO_3)_2$); Quartz (SiO_2); Ertixite ($Na_2Si_4O_9$)	Stone dust constituted dolomite in its composition which is calcium based insoluble mineral having good bitumen adhesion. No expansive clay mineral was found in both materials. Thus satisfactory stripping resistance is expected from both.
Hydrophilic coefficient	0.85	0.77	Both material displayed hydrophobic nature.
pH	8.94	12.57	Both materials are alkaline in nature and displayed good affinity towards asphalt.

3. Experimental Investigation

3.1. Design of asphalt concrete mixes

Marshall method of asphalt mix design is recommended in Indian condition to determine optimum asphalt content (OAC) of the mix (MORTH, 2013). Mix design procedure as specified in MS-2 was used to determine OAC of the mix (Asphalt Institute, 1997). As per this procedure, samples of asphalt concrete mixes were prepared at specified gradation (Table 1) and at five different asphalt contents (4.5%, 5%, 5.5%, 6.0%, and 6.5%). The aggregates were heated to 160º-170ºC for 24 hours before mix preparation. Then, asphalt was heated to 135º-140ºC before mixing with aggregates. The mixes were compacted using standard Marshall hammer with 75 blows each side. For each filler, total of 15 samples (3 for each asphalt content), were tested to determine Marshall stability, flow, percentage air voids (VA), voids in mineral aggregates (VMA) and voids filled with asphalt (VFA). OAC is considered as asphalt content corresponds to 4% VA of prepared samples (Asphalt Institute, 1997; MORTH, 2013). For each filler type, three more samples were prepared at OAC, and average values of Marshall stability, flow, VA, VMA, and VFB were compared (Table 4). At OAC, apparent film thickness (AFT) of was also calculated as per procedure devised in NCHRP Report 567 (Christenson and Bonaquist, 2006). AFT can be calculated using Equation 1.

$$AFT = \frac{1000VFE}{G_{mb}P_sS_s} \tag{1}$$

Where, AFT=Apparent film thickness (microns); VBE= Effective binder content (% by total mix volume); S_s= Aggregate specific surface (m^2/kg); P_s= Aggregate content, (% by total mix weight); G_{mb}= bulk specific gravity of mix

3.2. Rutting resistance

Marshall Quotient (MQ) is the ratio of Marshall stability (kN) to flow (mm) at OAC, and can act as an indicator to estimate the permanent deformation (rutting) of asphalt mixes. Higher MQ displays material's higher resistance to permanent deformation, shear stresses and hence rutting.

3.3. Cracking resistance

The indirect tensile strength (ITS) of compacted asphalt mix is associated with its resistance against cracking and was determined as per ASTM D 6931. This test is carried out at 25°C in which, a Marshall specimen was loaded diametrically in compression using steel strips at a constant rate of 50.8 mm/min. Six samples (three per filler) was prepared and mean ITS values were compared. The maximum tensile strength generated was calculated as

$$ITS = \frac{2000P}{\pi DT} \tag{2}$$

where, ITS is indirect tensile strength in kPa; P is peak load (N); D is diameter of sample (mm); and T is thickness of sample (mm).

3.4. Moisture Susceptibility

The moisture susceptibility of both mixes was determined as per modified Lottman test as per AASHTO T283 specification. For each filler, six Marshall specimen were casted at their respective OAC and were divided in two groups. The first group of specimens (conditioned specimen) were partially vacuum saturated with water as per specifications, and then were wrapped tightly with plastic film. The conditioned specimens were then packed into a plastic bag containing approximately 10 ml of distilled water and were subjected to one freezing cycle for 16 hours at -18ºC, followed by placement in 60ºC water bath for 24 hours. At the end of cycle, specimens were placed in water bath for 2 hrs at 25ºC and then their ITS were calculated. The second group of specimens (unconditioned specimens) was immersed in water bath for 2 hrs at 25ºC before being tested. The TSR was determined as per equation below

$$TSR = \frac{ITS_{cond}}{ITS_{uncond}} \times 100 \quad (3)$$

where , $ITS_{uncond.}$ is the average Indirect tensile strength for unconditioned specimens (kN); and ITS_{cond} is average Indirect tensile strength for conditioned specimens (kN).

3.5. Ravelling resistance

Cantabro durability test in dry state is employed for relative assessment of mix's resistance to disintegration (raveling). It is a relatively simple test which is widely used for a assessing durability of open and gap graded mixes, however recent studies found the viability of test in cases of dense graded mixes as well (Doyle and Howard, 2016). This test measures the breakdown of compacted Marshall specimen using the Los Angeles abrasion testing machine. The percent of loss in weight (Cantabro loss) act as an indicator of durability and is related to the cohesion and adhesivity of mixes. In this test, a Marshall specimen is placed into the Los Angeles drum operating without steel balls, and then given 300 rotations at a speed of 30 to 33 rotation per minute. The specimens were weighed before and after the test and the Cantabro loss value is calculated. The percentage weight loss with respect to original weight of specimen is measured and reported. Cantabro Loss was calculated as per Equation 4.

$$AFT = \frac{1000VFE}{G_{mb} P_s S_s} \quad (4)$$

Where, CL= Cantabro loss (%); A= Initial weight of specimen; B= Final weight of specimen.

3.6. Adhesion analysis

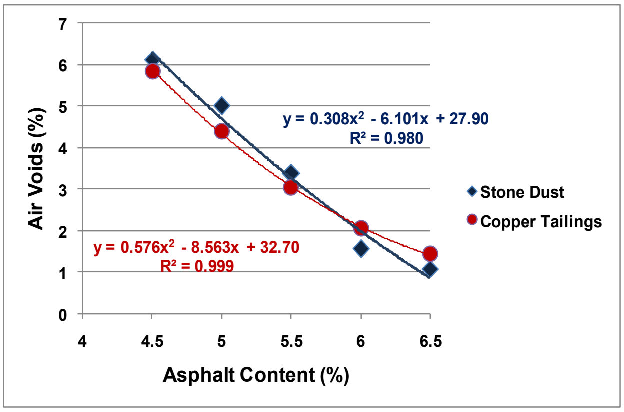
Loss of adhesion between aggregate-asphalt interfaces is the responsible mechanism for moisture damage of asphalt mixes and could be divided into active and passive adhesion. Active adhesion is the asphalt's ability to completely coat the aggregate during mixing operation of manufacturing of asphalt mixes. The mixing times of both stone dust and red mud modified mixes were measured to study the influence of various fillers over active adhesion. Aggregates, fillers, and bitumen were heated at 170ºC and then manually mixed. The measurement of total time (in seconds) elapsed was measured between the moment of addition of bitumen and the moment at which 100% coating is achieved (Pasandin & Parez, 2015). Passive adhesion is the ability of bitumen to stick on the aggregate surface under the influence of external factors such as water and traffic (Tarrer & Wagh, 1991). Passive adhesion analysis was done as per ASTM D 3625 specification. In this test bitumen coating retained over a loose mix is estimated when the mix is placed in boiling water for 10 minutes. Mix with higher retained coating has higher passive adhesion.

4. Results and Discussions

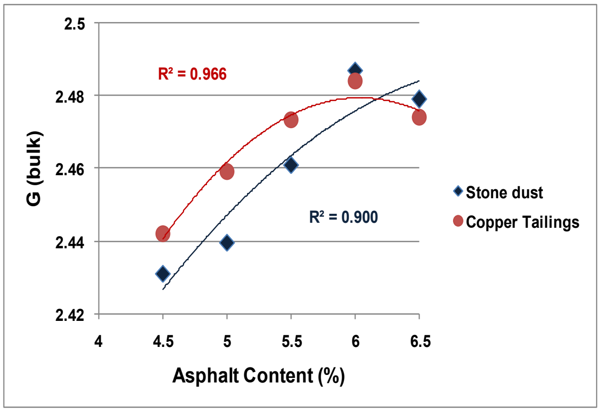
4.1. Marshall and volumetric properties

The Marshall and volumetric test properties are stated Fig. 4. From the Figure 4(a), OAC of copper tailing mix (5.10%) was found to be lower than stone dust mix (5.38%). This might be due to the lower porosity of copper tailings, as determined from its higher German filler value (100 g) than stone dust (85 g). Because of its lower porosity, copper tailing mixes also displayed lower air void content and lower VMA at same asphalt levels (Figure

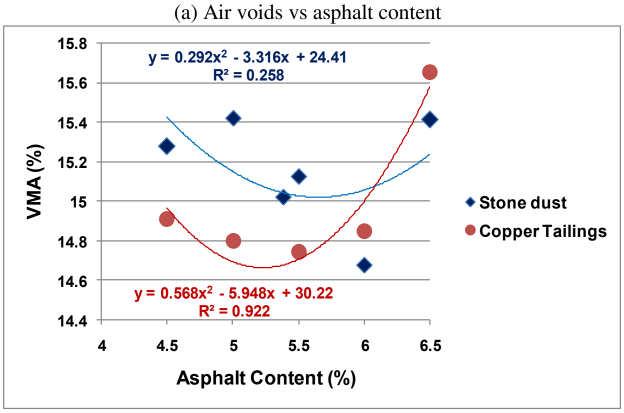
4(a) and 4(c)). This justified their need for lower asphalt to achieve 4% air voids, which led to lower OAC of copper tailing mixes.



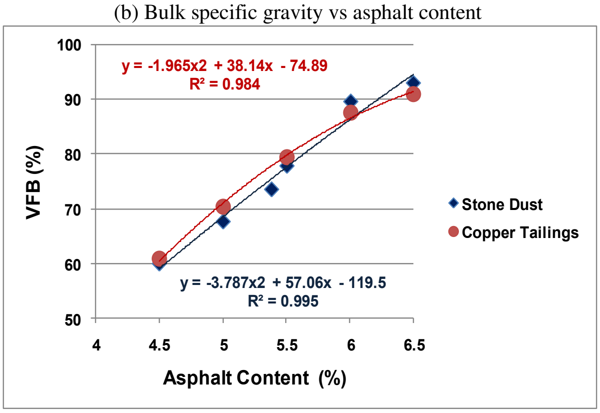
(a) Air voids vs asphalt content



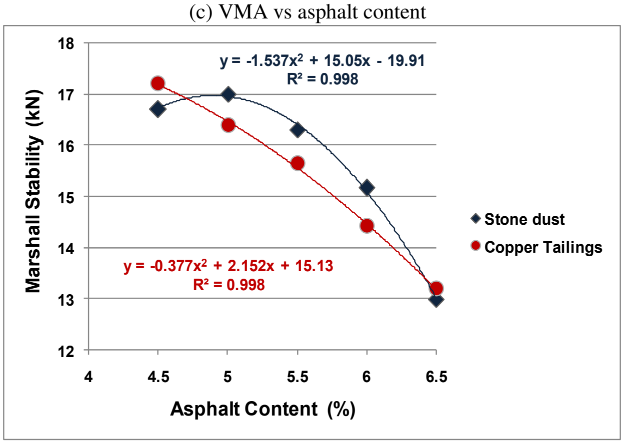
(b) Bulk specific gravity vs asphalt content



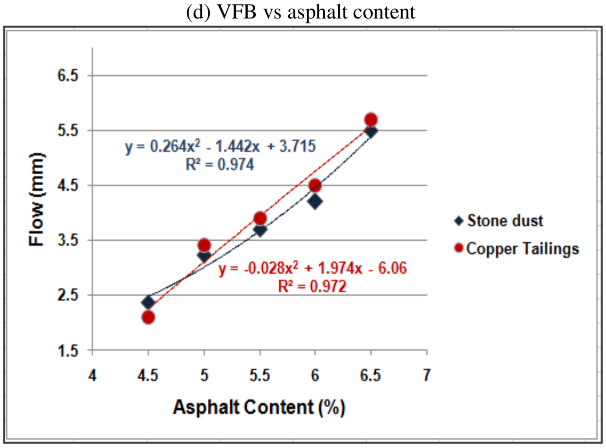
(c) VMA vs asphalt content



(d) VFB vs asphalt content



(e) Marshall stability vs asphalt content



(f) Flow vs asphalt content

Fig 4. Marshall and volumetric properties of both mixes

Higher specific gravity of copper tailing and lower air voids of copper tailing mixes resulted in higher bulk specific gravity of their mixes (BSG) as seen from Figure 4 (b). Marshall stability (MS) is load bearing capacity of mix which partly dependent on interaction between the asphalt and filler. Amongst the two fillers, stone dust seemed to improve cohesion and adhesion amongst matrix due to its greater affinity towards asphalt which lead to higher stability of stone dust mixes (Table 4). VFA values at OAC were found to be 74.61% and 71.96% for stone dust and copper tailing mixes respectively (Table 4). Since VFA value of copper tailings mixes were lower than stone dust mixes, hence copper tailings mixes may be preferred in regions having hot climates (Kutuk-Sert and Kutuk, 2012). Average AFT of copper tailing mix (5.31μ) was found to be slightly lower than stone dust mix (5.78μ). This may be due to lower OAC and lower VMA of copper tailing mixes.

Table 4. Average Marshall and volumetric properties of mixes at OAC

Type of Mix	OAC (%)	Marshall stability (kN)	Flow (mm)	Bulk specific gravity (g/cm^3)	VMA (%)	VFA (%)	AFT (μ)
Stone dust	5.38	15.96	3.45	2.453	15.31	74.61	5.78
Copper Tailings	5.10	15.25	3.10	2.461	14.51	71.96	5.31
Requirements	-	9.00	2-4	-	14 (min)	65-75	-

4.2. Rutting resistance

Average Marshall quotient (MQ) value of copper tailing mixes (4.93 kN/mm) was higher than stone dust mix (4.66 kN/mm). Previous studies have suggested that mixes having lower VMA and AFT may lead to higher rutting resistance (Christenson and Bonaquist, 2006; Jenks et al., 2011). Since copper tailing mixes have lower AFT and VMA than stone dust mix, this explains why they have higher MQ value than conventional mix.

4.3. Cracking resistance

Copper tailing mixes (1222 kPa) had superior ITS than conventional mixes (1085 kPa). Finer fillers have great potential for uniform distribution which lead to the formation of integrated structure in the asphalt mix, which subsequently improves stiffness and ITS of mixes (Choudhary et al., 2018a; Modarres and Bengar, 2017). Hence, superior ITS of copper tailing mixes may be attributed to its relatively finer nature as evident from their lower fineness modulus than stone dust.

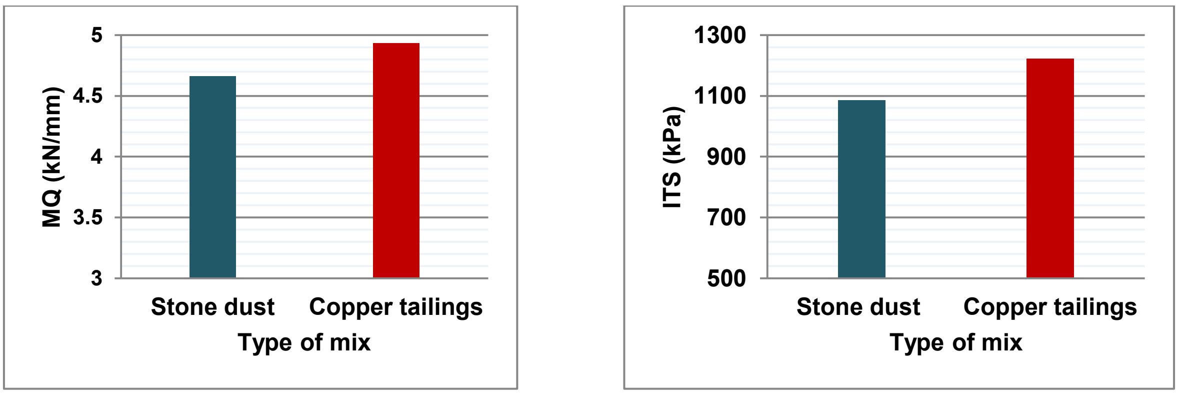


Fig 5. Marshall quotient (left) and Indirect tensile strengths (right) of both mixes

4.4. Moisture susceptibility

Stone dust mixes (89.26%) were found to have slightly higher TSR values than that of copper tailing mixes (84.24%). Stone dust has high proportion of calcium based water insoluble dolomite in its composition which promotes asphalt-filler adhesion (Pasandin et al., 2016). Stone dust mixes also have thicker AFT than copper tailing mixes which provide higher durability in terms of moisture resistance. Copper tailing also has higher proportion of silica content, which may also be responsible for its lower tensile strength ratio (Bagampadde, 2004). However, it still showed satisfactory moisture resistant behavior as it fulfill the minimum requirement of TSR (80%) by a good margin.

4.5. Ravelling resistance

The influence of both fillers against ravelling resistance of mixes is shown in Figure 6. However, both wastes displayed significantly good resistance against raveling. Both copper tailing and stone dust mixes displayed almost similar cantabro loss of 4.7% and 4.3% respectively. Hence it can be said that, both fillers can provide similar adhesion in absence of moisture and can be used interchangeably in the regions having low moisture exposure. Unlike the moisture resistance of the mixes, ravelling of asphalt mixes were not found to be significantly affected by the mineralogical composition of it's constitute filler.

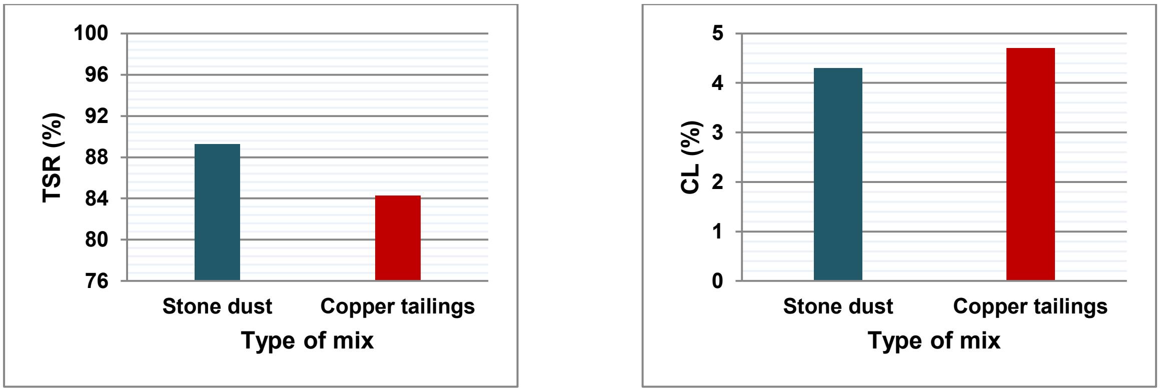


Fig 6. Tensile strength ratio (left) and cantabro loss (right) of both mixes

4.6. Adhesion analysis

Results of active and passive adhesion analysis are stated in Table 5. Similar to the results of moisture sensitivity of mixes, stone dust mixes displayed superior active and passive adhesion than copper tailing mixes. Stone dust mix had lower mixing time as well as higher asphalt coverage. This may be due to alkaline nature of stone dust as evident from it higher pH, which ensures good adhesion with asphalt. Copper tailing mixes have relatively inferior active and passive adhesion, which may be due to predominance of silica in the composition of copper tailing. This result is in agreement with a previous studies which suggested that high silica content in aggregates and filler have a negative influence on adhesion in asphalt mixes (Bagampadde, 2004; Choudhary et al., 2018a; Wu et al., 2007).

Table 5. Average active and passive adhesion of both mixes at OAC

Mix type	Active adhesion (mixing time in seconds)	Passive adhesion (asphalt coverage in %)
Stone dust	94	97
Copper tailing	115	95

5. Conclusions

This study evaluated the suitability of copper tailing from copper industry as filler (in lieu of stone dust) in asphalt concrete mixtures. Characterization of both fillers was done initially and their influence over performances of asphalt concrete mixes was investigated using relevant test standards. Copper tailing can be utilized as mineral filler since not only it fulfills all requirements demanded by Indian specifications but also it also displayed positive characterization traits of good filler. Physical characterization suggested that, copper tailing is a fine grained material have at relatively lower porosity and marginally higher specific gravity than conventional stone dust. It primarily consists of quartz and doesn't possess harmful expansive clay minerals also has low harmful clay content as interpreted by its low MBV value. It also displayed good affinity towards asphalt than with water due to its alkaline and hydrophobic nature.

Copper tailing asphalt mixes has fulfilled all Marshall and volumetric criteria specified by Indian paving specifications. These mixes were also found to be economical due to their relatively lower OAC. Although, they have 4.45% lower Marshall stability than conventional mixes, they displayed superior resistance against rutting due to finer nature of copper tailings. Similarly copper tailings mixes also had 12.63% higher indirect tensile strength values which signified their superior performance in terms of cracking resistance. Copper tailings mixes also displayed resistance against ravelling equivalent to conventional mixes. In terms of moisture sensitivity, copper tailings mixes fulfilled the minimum TSR requirements i.e. 80% with a higher margin. Prepared mixes have also displayed reasonably good passive adhesions. This indicated satisfactory performance of its mixes against moisture permeation. However, moisture resistance as well as active adhesion of copper tailing mixes is relatively inferior to stone dust mixes due to higher silica content as well as absence of asphalt adhesion promoters like dolomite in its composition. In conclusion, copper tailing can be satisfactorily used as mineral filler in asphalt concrete mixtures especially in the regions of their extensive generation.

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