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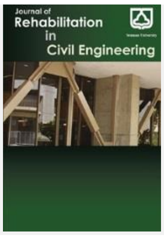

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Performance Evaluation of Bio-Medical Waste Incinerated Ash and Cement Blend as Stabilizing Agent for Low Volume Road Bases

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ABSTRACT

Incineration is the most commonly employed alternate disposal strategy of biomedical waste across the globe, which produces Biomedical Waste Incinerated Fly Ash (BMWIFA). BMWIFA is often disposed of in landfills to prevent environmental contamination. Due to limited space and the high cost of land disposal, recycling methods and ash reuse in various systems have been developed. Therefore, the present study evaluates the performance of BMWIFA and Ordinary Portland Cement (OPC) blends as stabilizing agents for the base layers of low-volume roads (LVRs). Different trial mixes of crushed aggregate (CA), BMWIFA, and OPC were tested to find the optimum mix. The stabilizer content was considered to be 3.0%, 5.0%, and 7.0% of the total dry weight of the mix, in which the BMWIFA (a)/OPC (c) ratio is taken as 100/0, 80/20, 60/40, 40/60, 20/80, and 0/100 in each percentage of stabilizer. Optimum values of compaction characteristics were used for strength evaluations of mixes in terms of unconfined compressive strength (UCS) and indirect tensile strength (ITS) at 7, 14, and 28 days of air curing. The mix proportions 97% CA, 95% CA, and 93% CA stabilized with 3% (a/c = 20/80), 5% (a/c = 40/60), 7% (a/c = 60/40) binders respectively, satisfied the 7-day UCS requirements (3MPa) according to the Ministry of Rural Development (MoRD) for LVR cement-treated bases and were found durable. Furthermore, the Toxicity Characteristics Leaching Procedure (TCLP) analysis for various heavy metals reveals that the CA, BMWIFA, and OPC compositions were non-hazardous materials. Finally, this study's findings recommend the use of BMWIFA and OPC blends as stabilizers in low-volume road construction.

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1. Introduction

Solid waste management is a sensitive topic that India and the rest of the world have to deal with. Neglecting it and being unaware of its effects causes many environmental problems, including air, water, and land pollution. The generated solid waste across the globe is broadly categorized into (i) household waste (ii) industrial waste and (iii) biomedical waste [1]. Biomedical waste generation has greatly increased due to the global COVID-19 pandemic. Hence, it must be disposed of quickly to minimize the consequences. BMW causes risks to people connected with the handling, treating, and disposing processes [2]. Currently, India generates about 968 metric tons of biomedical waste every day [3]. Biomedical waste accounts for 1 to 1.5 % of total waste generated in India [4]. From the total quantity of biomedical waste generated, 85% was considered non-hazardous, with the remaining 15% classified as hazardous material that could be infectious, poisonous, or radioactive [5]. Due to an increase in the quantity of BMW, there is a greater demand for removal transportation, a scarcity of dumping areas, and increased dumping costs. As a result, there is a pressing need to efficiently use of toxic and hazardous BMW in various construction fields, like roads and buildings. Over the last few decades, there has been a significant increase in the global generation of medical waste [6]. Different methods have been used to treat hazardous biomedical waste, such as carbon adsorption, incineration, chemical precipitation, chemical disinfection, biological oxidation, and membrane separation. Among these techniques, treating by incineration is ranked first [7]. The great advantage of this method is that it destroys pathogens and reduces the volume of waste by up to 90%, with 75% of the weight being reduced at the end of the incineration process [8]. Produced ash from the incineration process consists of toxic substances and heavy metals such as silver (Ag), zinc (Zn), mercury (Hg), iron (Fe), and arsenic (As) in significant quantities [9,10]. When ash is dumped in a landfill, toxic metals and inorganic compounds are released into the environment [11,12]. Improper treatment causes leaching from dumping ashes in landfills, which causes groundwater and environmental pollution [13,14]. Toxins leaching from BMWIFA into groundwater are also a serious issue that must be considered when assessing the risk of biomedical waste to human health and the environment [15]. To address these issues, the production of BMWIFA should be redirected in a beneficial and environmentally friendly manner. The construction industry, which uses these materials to build infrastructure, may be ready to adopt them after carefully examining their characteristics. Many researchers have evaluated the physical and chemical characteristics of BMWIFA. The major chemical oxide compounds found in BMWIFA were Fe_2O_3 (0.39–52.71%), Al_2O_3 (5.16–14.34%), Na_2O (2.5–9.13%), CaO (1.64–89.2%), and SiO_2 (39.74%) [16–21]. Various physical characteristics like moisture content range from 2.38% to 7.53%, specific gravity varies from 1.82 to 2.72, particle sizes range from 6.3µm to 103µm, and the material looks dark grey [17–19,22–26]. Various researchers have done their studies on concrete applications. Al-Mutairi et al. (2004) [16] compared the compressive strength of ash mixes to that of micro silica and normal concrete in order to assess their effectiveness. In general, replacing 5% of the cement with micro silica, or BMWIFA, improves concrete compressive strength up to 800 °C. According to Prasanth and Ranga Rao (2019), utilizing 20% biomedical waste incinerated bottom ash (BMWIBA) and 20% metakaolin boosted the compressive and split tensile strengths of M30-grade concrete at 28 days when compared to control concrete [27]. According to Kaur et al. (2019), BMWIBA comes in a wide range of particle sizes, making it perfect for use as a filler in concrete. They investigate the effects of BMWIBA as a replacement for fine aggregate on concrete strength and permeability. Concrete can have up to 10% of its fine aggregate (sand) replaced with BMWIBA without losing any of its strength [25]. Concrete loses workability when BMWIBA is further added, necessitating the use of a superplasticizer to restore it. Furthermore, cement was able to stop heavy metal leaching, according to the results of the solidified matrix. Compression, flexural strength, setting time, water absorption, density, temperature development, and leaching results were investigated. The results showed that the supplementary cementitious materials system could use BMWIFA [22,28]. In 3D printing concrete, according to Rehman et al. (2020) [29], MWFA is used as a substitute for ordinary Portland cement to create a rapid method of building without the use of formwork. The findings revealed that the MWFA's effect on setting time and initial yield stress enhancement enabled rapid construction. Meanwhile, the pozzolanic interaction between MSWFA and cement, which was investigated by Yan et al. (2019) [30], improved the mechanical properties of cement-stabilized macadam (CSM), which contained 25% MSWFA. Additionally, after 7 days of curing, CSM, including MSWFA, had a lower concentration of heavy metals than the Chinese Standard. In a study by Azni et al. (2005) [23], the BMW was incinerated and melted at 1200°C to produce slag. Spectra electron microscopy (SEM) analysis reveals that the slag generated after melting contained more than 53% SiO_2, 9% CaO, and 16% Al_2O_3. The slag leaching provided strong heavy metal stabilization via the melting process, and the slag could be used as a replacement for traditional road construction aggregates. Many researchers have reported that chemical stabilization by cement, lime, and flyash is popular to increase the strength of recycled aggregate as pavement layers [31–34]. Stabilization by cement is predominant compared to all others. However, cement production is an energy-intensive process that consumes non-renewable resources and emits large quantities of CO_2 gases into the atmosphere [35,36]. Therefore, low-carbon cementitious agents like BMWIFA may partially replace cement as a sustainable pavement stabilizing agent. The use of BMWIFA in the pavement stabilization process not only addresses the issue of reducing the emission of CO_2 gases into the atmosphere and the energy required for the production of cement but also the disposal of hazardous of BMWIFA in sustainable way. The present study aims to promote the BMWIFA as a stabilizer for the base layers of low-volume roads. The main objective of the study is to present the results (UCS, ITS, durability, and leachate analysis) of laboratory evaluation of granular bases of low volume roads stabilized with different ratios of BMWIFA to OPC: 100/0, 80/20, 60/40, 40/60, 20/80, and 0/100. In addition, recommendations on the potential use of BMWIFA as a stabilizer for low-volume road bases should be made. The objective is also to design low-volume roads as per IRC: SP: 72-2015 with optimum mixes [37].

2. Materials and properties

2.1. Biomedical waste incinerated fly ash

Biomedical waste incinerated fly ash (BMWIFA) for this investigation was collected from a biomedical waste incinerator plant in Warangal, Telangana, India. The physical properties of BMWIFA are shown in Table 1. Figure 1 depicts the SEM image of the BMWIFA, while Table 2 illustrates the chemical oxide compositions obtained from the X-ray fluorescence (XRF) investigation. BMWIFA's major chemical oxide composition sum ($SiO_2 + Al_2O_3 + Fe_2O_3$) exceeds 70%, showing that it is a pozzolanic material [38].

2.2. Ordinary portland cement (opc)

Ordinary Portland Cement (OPC) of Grade 43 was used as a source of calcium, procured from a local vendor. The chemical oxide compositions are given in Table 2. The physical properties of OPC were determined in the laboratory and presented in Table 3.

2.3. Crushed aggregates (ca)

In the present study, CA was used as flexible pavement base course materials collected from a nearby quarry in the required sizes. The physical properties of CA are determined and presented in

Table 4. From the results, it was observed that the aggregates obtained from the quarry meet the MORTH (Ministry of Road Transport and Highway Officials) and MoRD (Ministry of Rural Development) specifications [39,40].

Table 1. Physical characteristics of BMWIFA.

Property	Obtained Value	Specifications
Specific gravity	2.17	IS:2720 (part-3-1980) [41]
Water absorption by mass (%)	5.28	NA
Color	Grey	NA
Fineness modulus	3.98	IS 4031 (Part 1- 1996) [42]
Maximum Dry Density (g/cc)	1.25	IS 2720 (Part 8 -1985) [43]
Optimum water content (%)	31	

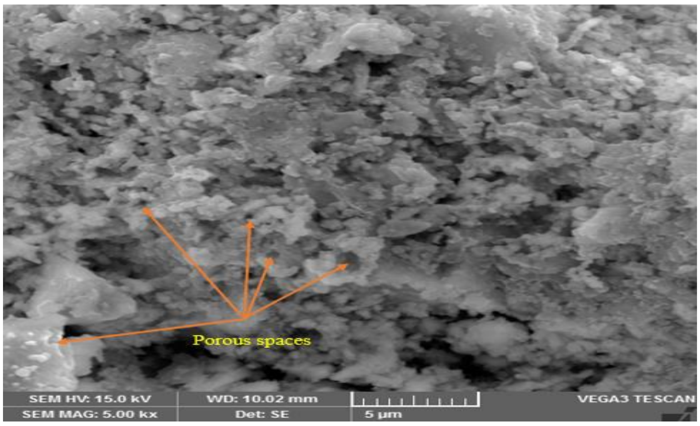

Fig. 1. SEM image of BMWIFA.

Table 2. Major chemical oxides composition of BMWIFA and OPC.

Materials	Oxides composition (% Wt.)				
	SiO2	Al2O3	Fe2O3	MgO	CaO
BMWIFA	36.86	25.92	7.5	2.78	23.43
OPC	26.95	4.01	2.85	2.2	58.7

Table 3. Physical properties OPC.

Physical property	Obtained value	As per IS: 8112–1989 [44]
Initialsetting time(Minute)	35	30
Final setting time (Minute)	254	600
Specific gravity	3.1	-
Soundness(mm)	3	10

Table 4. Engineering properties of CA.

Property	CA	MoRD(2014) Requirements	Code of practice
Flakiness Index (%)	12.35	Subbase < 30 %, base < 25%	IS 2386 (Part I) [45]
Elongation Index (%)	15.62	NA	IS 2386 (Part I) [45]
Combined Flakiness and Elongation (%)	27.97	Maximum 35% (MoRTH 2013)	IS 2386 (Part I) [45]
Abrasion Value (%)	30.1	Maximum 40% (MoRTH 2013)	IS 2386 (Part IV) [46]
Aggregate Impact Value (%)	15.2	subbase< 50 %, base < 40%	IS 2386 (Part IV) [46]
Specific Gravity	3.22	NA	IS 2386 (Part III) [47]
Water Absorption (%)	1.58	< 2%	IS 2386 (Part III) [47]

3. Experimental methods

The physical characteristics and chemical oxide compositions of the materials under consideration for this study were determined, and the proportion of CA and stabilizers like BMWIFA and OPC were chosen in accordance with the dry weight of the final mixture. The stabilizer content considered for this study was 3.0%, 5.0%, and 7.0%, in which OPC replaces BMWIFA by 0%, 20%, 40%, 60%, 80%, and 100% by weight of cement. The mix compositions and nomenclature are given in Table 5. The gradation limits of material for stabilization with cement were followed as per MoRTH (fifth revision, 2013) throughout the study [39]. The targeted gradation of mixes in this study is shown in Fig. 2. The modified proctor compaction test performed on the mixes presented in Table 5 as per the AASHTO T180 protocol [48]. For which compaction characteristics like optimum water content (OWC) and maximum dry density (MDD) were determined. Unconfined Compressive Strength (UCS) test specimens were prepared in a cylindrical mold of aspect ratio 2 (100 mm dia. x 200 mm height) at the obtained OWC and MDD according to ASTM D 1632 [49]. After 24 hours of curing, the sample was dismantled from the mold and wrapped in plastic bags to prevent moisture escaping from the sample. Samples are air-cured for 7, 14, and 28 days at room temperature. Indirect Tensile Strength (ITS) test samples were cast at the required MDD in a mold with dimensions of 100mm internal diameter and 63 mm height according to ASTM D 6931 [50]. Then it was extracted from the mold after 24 hours, followed by curing for 7 and 28 days.ITS tests were conducted on specimens as per ASTM D6931 at a loading rate of 50.8 mm/minute [50]. The durability test was performed to check the performance of the stabilized material against weathering action. After satisfying UCS criteria, stabilized material should meet durability criteria for acceptance as a stabilizer. The wet and dry cycle method following IS 4332 (Part IV) is adopted for durability, and the specimens are subjected to 12 wet and dry cycles. One cycle consists of 5 hours of submergence in water at room temperature, followed by oven drying at 70°C for 42 hours. The specimen's weight was measured after each wet-dry cycle [51]. In order to determine the strength variation, specimens were also tested for UCS and ITS values after each cycle. This study performed the Toxicity Characteristics of Leaching Procedure (TCLP) test on mix compositions M5, M10, and M15 for different heavy metal concentrations. 7-day-cured samples were crushed to obtain a particle size of < 9.5mm. The crushed material was first mixed with distilled water, and after 24 hours, the pH of the samples was measured. The samples were extracted in closed vessels with the leaching solution at pH 2.88 ± 0.05 as per the TCLP protocol at 30 ± 2 rpm for 18 ± 2 hours at ambient temperature (23 ± 2°C). The leachate was filtered using filter paper to remove the suspended solids. TheMicrowave Plasma-Atomic Emission Spectrometer (MP-AES) uses a filtered liquid to determine heavy metals in leachate. The average values for each extraction were obtained by testing in triplicate to ensure data consistency. Further, for the cementitious base layer, the laboratory-based elastic modulus (E) value is calculated from the following Eq. (1).

$$E = 1000 \times UCS \tag{1}$$

Where E = elastic modulus of cementitious granular base layer in MPa and UCS = 28-day cured sample strength of cementitious granular base layer in MPa.

The elastic modulus value calculated from Eq. 1 was used in the design of a low-volume road (LVR). The Indian LVR design is based on million-standard axle (msa) and subgrade CBR values [37]. LVR design was carried out under traffic conditions of T9 (T9 > 1.5 msa–2 msa) using optimum mixes [37]. The IITPAV software program was used to analyse stresses and strains within the pavement layers [52]. Finally, the conventional LVR pavement design thickness was compared to the a-c blend stabilized pavement thickness. Fig. 3 illustrates the material used and testing methods in this research.

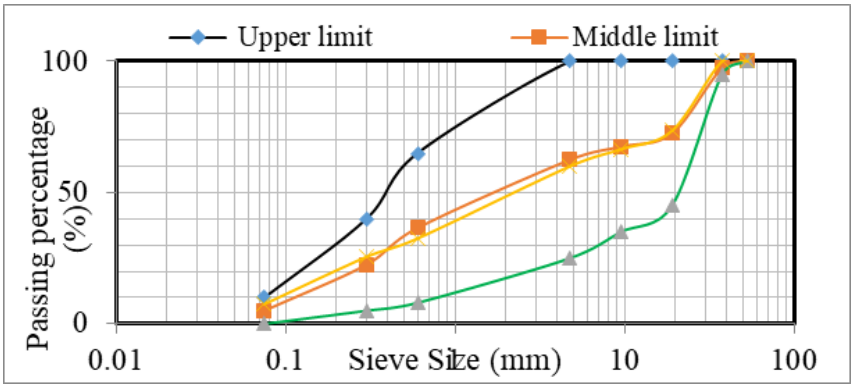

Fig. 2. MoRTH gradation for CTB.

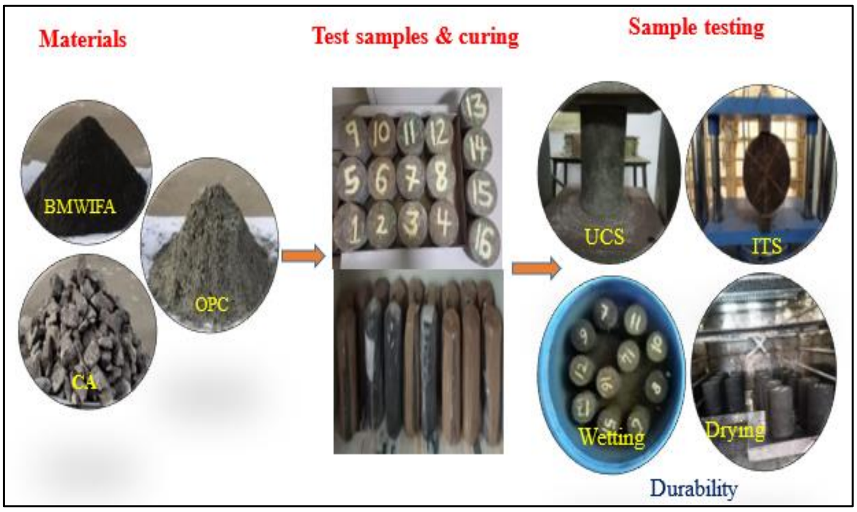

Fig. 3. Materials, samples and testing method.

Table 5. Mix composition and Nomenclature.

CA (%)	Stabilizer (%)	BMWIFA (%) in stabilizer (a)	OPC (%) in stabilizer (c)	Mix- Nomenclature
97	3	100	0	97CA+3B: a/c = 100/0(M1)
		80	20	97CA+3B: a/c = 80/20 (M2)
		60	40	97CA+3B: a/c = 60/40(M3)
		40	60	97CA+3B: a/c = 40/60(M4)
		20	80	97CA+3B: a/c = 20/80(M5)
		0	100	97CA+3B: a/c = 0/100(M6)
95	5	100	0	95CA+5B: a/c = 100/0(M7)
		80	20	95CA+5B: a/c = 80/20(M8)
		60	40	95CA+5B: a/c = 60/40(M9)
		40	60	95CA+5B: a/c = 40/60(M10)
		20	80	95CA+5B: a/c = 20/80(M11)
		0	100	95CA+5B: a/c = 0/100(M12)
93	7	100	0	93CA+7B: a/c = 100/0(M13)
		80	20	93CA+7B: a/c = 80/20(M14)
		60	40	93CA+7B: a/c = 60/40(M15)
		40	60	93CA+7B: a/c = 40/60(M16)
		20	80	93CA+7B: a/c = 20/80(M17)
		0	100	93CA+7B: a/c = 0/100(M18)

4. Results and discussions

4.1. Compaction characteristics

The variation in OWC and MDD with different ratios of a/c is shown in Table 6. The results enlisted in this table state that, when the a/c ratio is 100/0 in all percentages of stabilizer, the OWC and MDD of the compacted sample are the highest and lowest, respectively. The high OWC and low MDD are due to the porous characteristics of BMWIFA. The low specific gravity of BMWIFA is also attributed to the low MDD. As the a/c ratio decreased, OWC decreased, and MDD values increased. Decrease and increase of OWC and MDD because of the high specific gravity of OPC compared to that of BMWIFA, which agrees with previous studies [53]. Moreover, smaller cement particles could occupy the pores in BMWIFA, resulting in increased MDD [54]. Compaction test results reveal that the MDD values for all mixes at selected stabilizer and CA percentages and at different a/c ratios are 100/0 < 80/20 < 60/40 < 40/60 < 20/80 < 0/100.

Table 6. OWC and MDD of all mixes.

a/c ratio in stabilizer	3% Stabilizer + 97% CA		5% Stabilizer + 95% CA		7% Stabilizer + 93% CA	
	MDD (g/cc)	OWC (%)	MDD (g/cc)	OWC (%)	MDD (g/cc)	OWC (%)
100/0	1.946	10.2	1.936	10.32	1.932	11.20
80/20	1.956	9.48	1.956	10.0	1.948	10.45
60/40	1.974	8.64	2.054	9.54	2.105	9.75
40/60	2.189	7.6	2.195	8.34	2.169	8.50
20/80	2.194	7.0	2.210	8.0	2.189	7.65
0/100	2.254	6.85	2.225	7.58	2.212	7.23

4.2. Unconfined compressive strength (UCS)

The UCS of a-c stabilized CA samples at various a/c ratios (100/0, 80/20, 60/40, 40/60, 20/80,0/100), stabilizer percentage (3.0%, 5.0%, 7.0%), and curing time (7, 14, 28 days) are presented in Figs. 4, 5, and 6. It was found that the CA stabilized with 3%, 5%, and 7% of BMWIFA (a/c = 100/0) had lower UCS values for all the curing periods. It could be due to the porous nature of BMWIFA and insufficient cementitious compounds. To impart strength to the mix, the calcium-rich OPC was partially replaced by BMWIFA at a rate of a 20% increment in the a/c ratio of the selected stabilizer percentages. Due to this, the UCS of BMWIFA-stabilized CA increases with a decrease in the a/c ratio and increases with curing periods. It is due to high content of CaO in the mix was attributed to better bonding and increased strength. Gonawala et al. (2019) [55] stated that as cement content increases in the mix, a continuous increase in UCS is observed. It is caused by the pozzolanic reactions of BMWIFA and OPC. CaO from

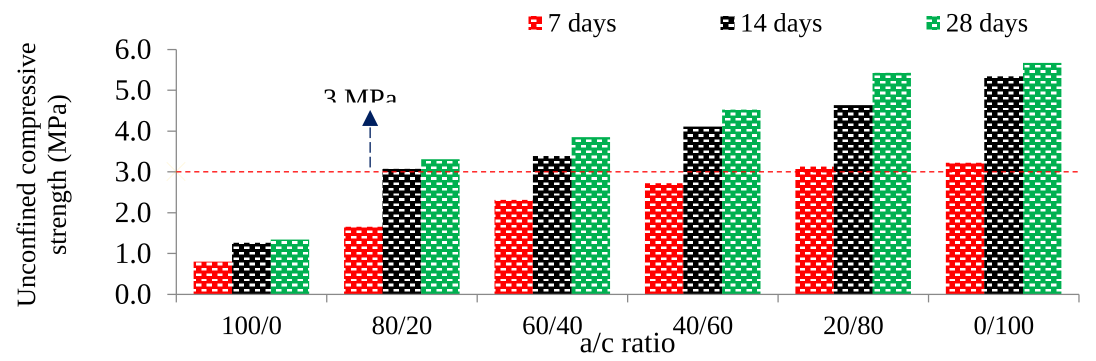

Fig. 4. Variation of UCS with different curing periods (for 3% stabilizer).

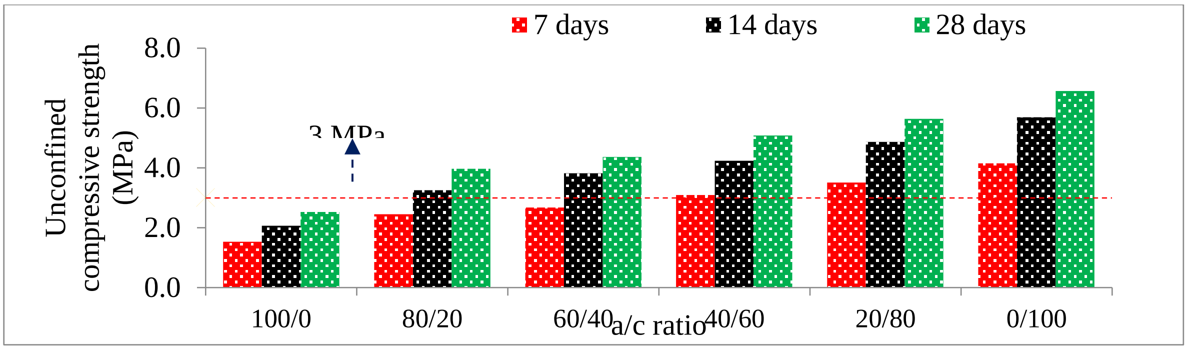

Fig. 5. Variation of UCS with different curing periods (for 5% stabilizer).

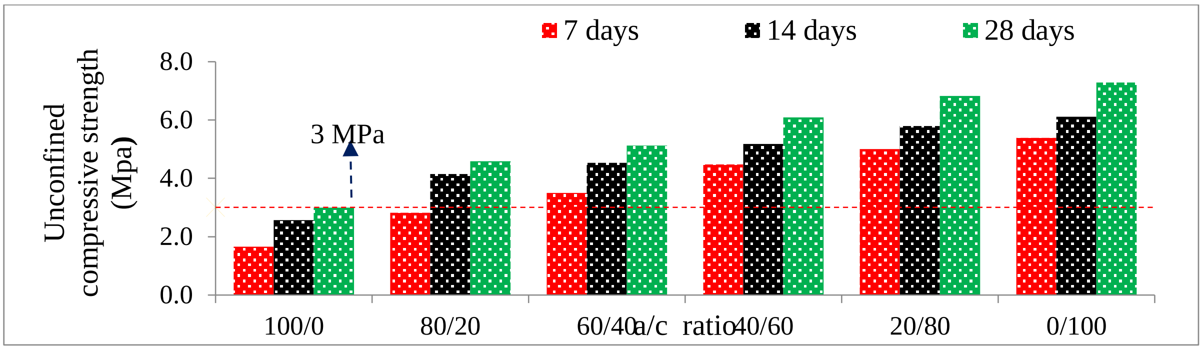

Fig. 6. Variation of UCS with different curing periods (for 7% stabilizer).

OPC undergoes hydration as soon as it comes into contact with the adsorbed moisture during the stabilization process, as a result calcium hydroxide ($Ca(OH)_2$) is formed. In the presence of alumina (Al_2O_3) and silica (SiO_3) from BMWIFA, this compound undergoes carbonation to produce the pozzolanic reaction. CaO is further hydrated, resulting in the formation of calcium aluminosilicate hydrated (C-A-S-H) gel [56]. Therefore, forming C-A-S-H gel improves the bonding performance of the mix, resulting in strength enhancement [57]. The Eq. 2 illustrates the pozzolanic reaction between BMWIFA and OPC.

$$CaO \xrightarrow{H_2O} Ca(OH)_2 \xrightarrow{Al_2O_3 + SiO_3 + H_2O} C-A-S-H\ (gel) \tag{2}$$

The maximum value of UCS was observed at an a/c ratio of 0/100 for all binder percentages and curing times. Furthermore, the UCS value increases with the curing period at a specific a/c ratio, indicating that the pozzolanic reaction between BMWIFA and OPC with $Ca(OH)_2$ continues over time, resulting in more dense colloid substances and thus increased UCS [58]. The UCS results are compared with the LVRs for cement-treated bases or subbases of local specifications. It was found that the compositions M5, M6, M10, M11, M12, M15, M16, and M18 satisfied the seven-day UCS requirements as per MoRD, 3 MPa for LVRs with cement-treated bases. Except for the compositions M1, M2, M7, and M13, all other compositions satisfied the seven-day UCS requirements of 1.7 MPa for LVR cement-treated subbase as per MoRD. However, in accordance with IRC 37-2018, the mixes M17 and M18 are qualified for high-volume road cement-treated bases with a minimum strength requirement of 4.5 MPa.

4.3. Indirect tensile strength (ITS)

To determine the tensile strength of mixes presented in Table 5, the ITS test was performed on a/c stabilized CA samples at various a/c ratios (100/0, 80/20, 60/40, 40/60, 20/80, 0/100) with stabilizer contents of 3%, 5%, and 7%. The results of the ITS test are shown in Figs. 7, 8, and 9. From the figures, it was observed that, similar to UCS, for all curing periods, CA stabilized with 3%, 5%, and 7% of BMWIFA having lowered ITS values. It might be because BMWIFA is porous and does not contain enough contentious compounds. In a similar vein to UCS, ITS also increased with a decrease in the a/c ratio. The a-c content in the mix forms a stronger bond with CA by forming the C-A- S- H gel. From the results, it is also observed that the ratio between average UCS and average ITS at 28 days of age was found to be 10.2. The UCS to ITS ratio for conventional cement-bound mixtures is usually between 10 and 12, and the results obtained in the present study are consistent with previous studies [59,60]. Figure 10 shows a consistent linear relation between UCS and ITS values after 28 days of curing, as stated in the literature for cement-bounded materials [61].

4.4. Resilient modulus of material (MR)

The resilient modulus value is derived from the UCS value using equation (1). According to IRC:37-2018, 20% of the MR value obtained from Eq. (1) must be used in the flexible pavement design. However, the MR is restricted to 1700 MPa when it results from the UCS test. IRC:37-2018 specifies that after 28 days of curing, the cementitious base or subbase of LVR must have a minimum MR of 450 MPa. Table 7 illustrates the design MR values for the mixes under consideration. It is permissible to utilize M5, M6, M10, M11, M12, M15, M16, M17, and M18 mixes for LVR road bases according to MoRD (2015) and IRC: SP:72-2015 requirements.

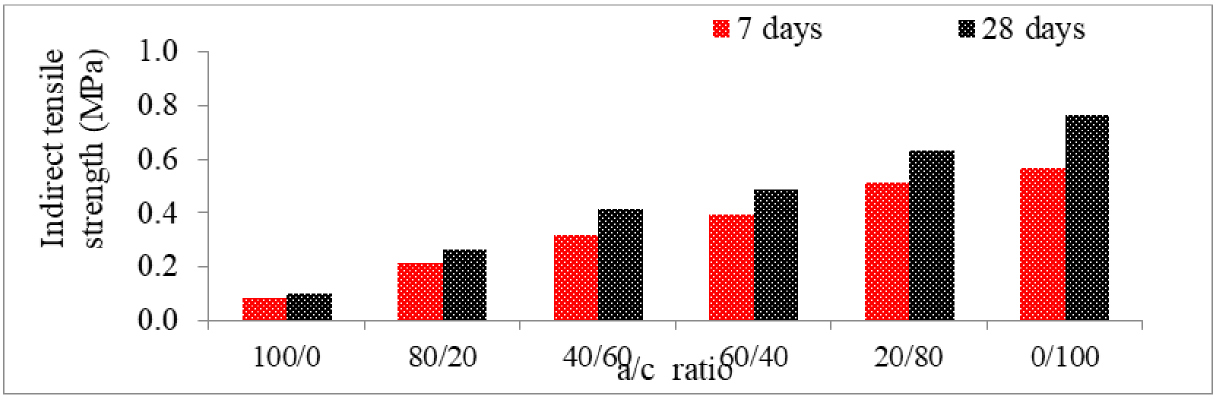

Fig. 7. Variation of ITS with different curing periods (for 3% stabilizer).

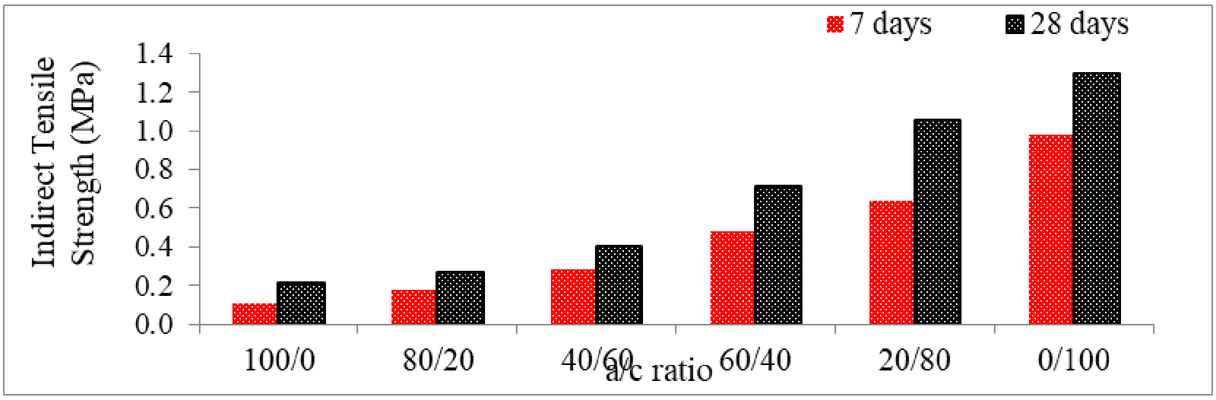

Fig. 8. Variation of ITS with different curing periods (for 5% stabilizer).

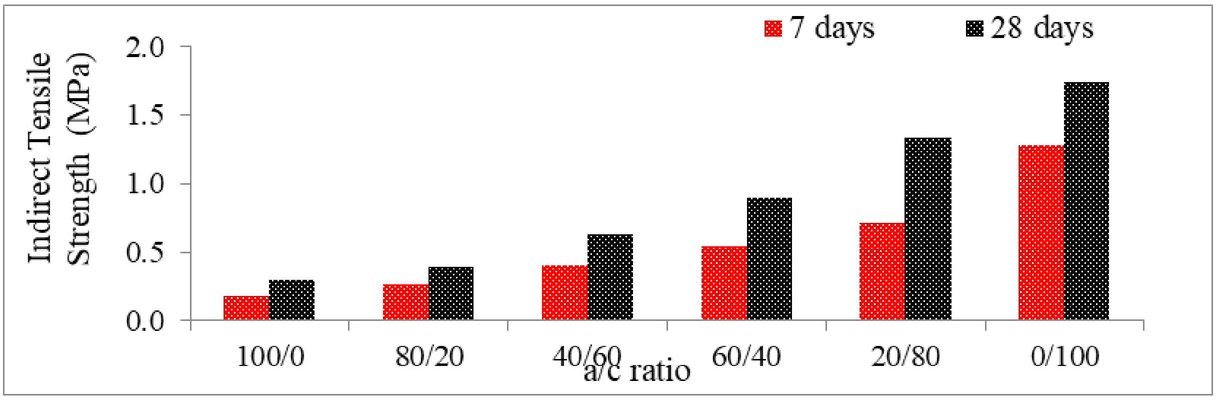

Fig. 9. Variation of ITS with different curing periods (for 7% stabilizer).

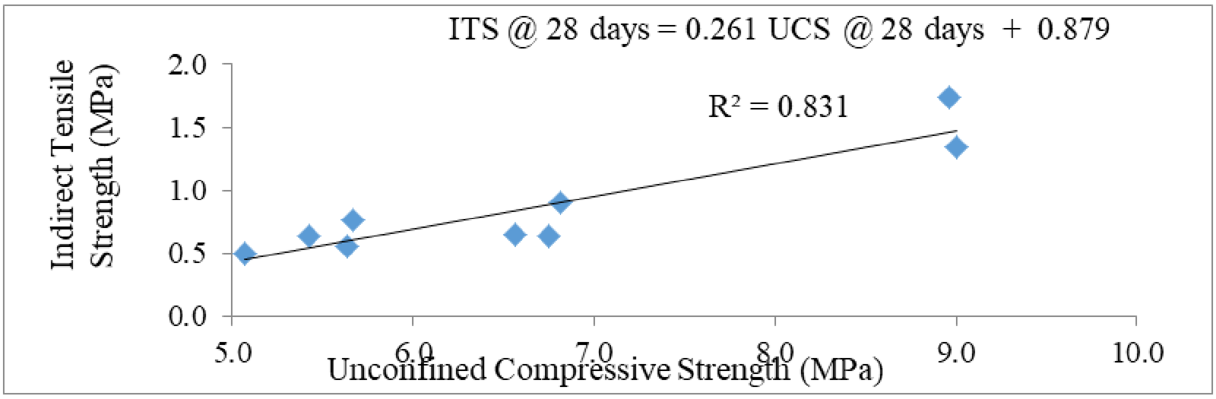

Fig. 10. Relation between UCS and ITS at 28 days of curing.

Table 7. Resilient Modulus (MR) values for mixes.

Mix designation	UCS(MPa) 28 days	MR from UCS (MPa)	Design MR value (MPa)
M1	1.337	1336.902	267.380
M2	3.310	3310.424	662.085
M3	3.850	3850.277	770.055
M4	4.520	4520.001	904.000
M5	5.424	5424.002	1084.800
M6	5.666	5665.917	1133.183
M7	2.527	2527.381	505.476
M8	3.973	3972.508	794.502
M9	4.361	4360.846	872.169
M10	5.074	5073.861	1014.772
M11	5.639	5639.179	1127.836
M12	6.562	6562.278	1312.456
M13	2.998	2998.480	599.696
M14	4.584	4583.663	916.733
M15	5.122	5122.244	1024.449
M16	6.084	6083.540	1216.708
M17	6.819	6819.472	1363.894
M18	7.284	7284.205	1456.841

4.5. Durability analysis

For the durability test, compositions M5, M10, and M15 are considered, as they have a high content of BMWIFA. The variation in UCS and ITS values with respect to each W-D cycle is presented in Fig. 11. From Figure 11, it is clear that, for the selected three mixes, strength values increase with increasing W-D cycles up to 7. It is due to the formation of cementitious compoundsduring the W-D process [62]. After 7 cycles, the rate of increase in strength decreased. The relationship between the weight losses of mixes M5, M10, and M15 versus the number of cycles W-D is illustrated in Fig. 12. Weight loss for three selected mixes sharply increases up to two cycles; thereafter, it gradually increases with an increase in cycles. It is notedthat the weight lossof mixes M5 < M10 < M15. It is the high percentage of cement in the mixes that leads to a stronger bond; hence, the loss of weight will be less. The percentage weight loss of UCS samples after 12 W-D cycles prepared with compositions M5, M10, and M15 was found to be 2.25%, 2.6%, and 3.3%, respectively. ITS samples casted with the same mixes werefound to be 2.35%, 2.50%, and 3.25%. The maximum percentage loss of volume of samples prepared with mixes M5, M10, and M15 is 1.2%, 1.43%, and 1.7%, respectively. The total weight loss of the sample after 12 w-d cycles was well within the limit of IRC: SP: 89-2018, i.e., not more than 14%. Hence, the selected mixes satisfied the durability criteria.

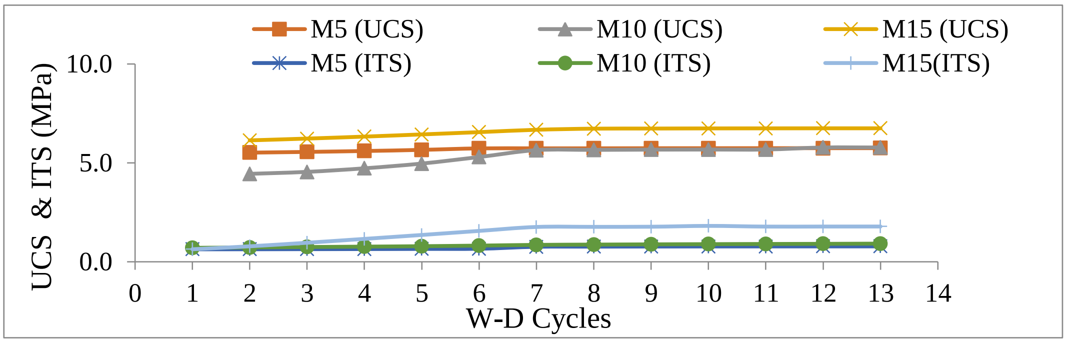

Fig. 11. Variation of UCS & ITS values with W-D cycles.

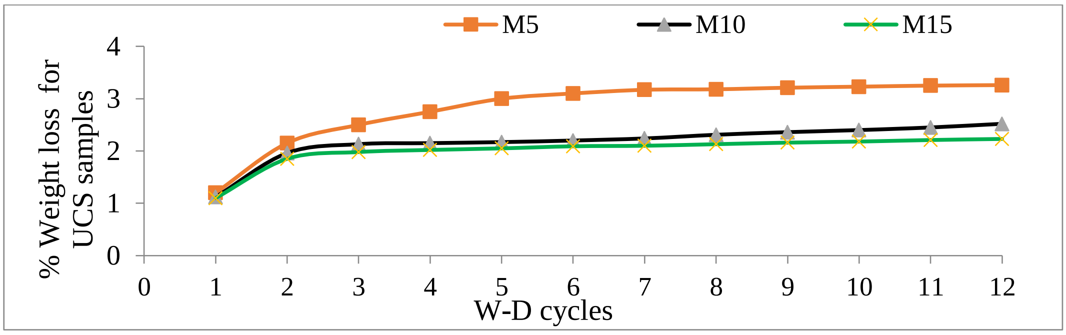

Fig. 12. W-D cycles Vs. Weight loss (%).

4.6. Heavy metal analysis

Stabilized samples were tested for heavy metals such as Ni, Pb, Cr, and Cu using the USEPA's Toxicity Characteristics Leaching Procedure (TCLP) (1311 of July 1992), according to IRC: SP: 89 (Part-II)-2018 [63]. Heavy metal leaching from specific mixtures (M5, M10, and M15) was investigated using the MP-AES. Because the rapid hardening stabilizer (a-c blend) was used in this study, early 7-day UCS samples were crushed to particles smaller than 9.5 mm for the leachate test. According to the leachate test results shown in Table 8, all heavy metals were detected at levels well below the US EPA limits for the tested samples. Cement - hydration products effectively immobilize heavy metals through a combination of physical encapsulation and chemical solidification. As a result, the mix compositions M5, M10, and M15 were determined to be non-hazardous to the environment. The pH values of the leachate produced by the M5, M10, and M15 mix compositions are 8, 8.25, and 9, respectively. These findings indicate that the pH levels of all mixtures are within the EPA's (Environment Protection Agency) 2005 permissible limits for storm water sampling, namely 6 to 9.

Table 8. Heavy Metal Analysis of CA Stabilized with a-c Blends by MP-AES Analysis.

Metal	Mix composition			USEPA Limits (ppm)
	M5	M10	M15	
	pH = 8	pH=8.25	pH = 9	
Nickel	<0.001	<0.001	<0.001	1.2
Lead	0.21	0.24	0.25	5
Chromium	<0.005	<0.005	<0.005	5
Copper	0.6	0.75	0.8	15

5. Design of low volume roads as per IRC- SP: 72-2015

A typical LVR pavement structure having a bituminous surface course with an a-c stabilized base and subgrade was considered. The pavement structure was considered in IRC SP 72-2015 and was designed for traffic category T9 (T9 > 1.5 msa–2 msa) and subgrade conditions S3 (CBR = 5%), S4 (CBR = 7%), and S5 (CBR = 10%). The LVR pavement structure is designed for a 10-year design period with a traffic growth rate of 5%. The standard wheel load of 80 kN, which imparts a 0.56 MPa tire pressure on the pavement system, is considered. The thickness of eachlayer is obtained from IRC SP 72-2015. Subgrade strength is evaluated by CBR, and after that, the corresponding subgrade CBR plate is used to select the pavement thickness of each layer of pavement for the given traffic category. The performance of pavement is then assessed by fatigue and rutting strains, measured at the bottom of the bituminous layer and above the subgrade under standard axle loads, respectively. The pavement analysis software IITPAV was used to calculate these strains. where the thickness of pavement layers, material properties, and loading conditions are input parameters. In pavement design work, M5, M10, and M15 mixes were considered. LVR comprises a bituminous surface, a crack relief aggregate layer (CRAL), a stabilized base, and a natural subgrade. The surface, subgrade, and CRAL properties were kept constant in the IITPAVE analysis, and base properties were varied as mentioned in Table 9. The final thickness of the pavement is obtained by a trial-and-error process with different thicknesses to get fatigue and rutting strains within the allowable limits. The final designed thickness and computed strains are presented in Table 10. Further, a comparison of pavement thickness with conventional pavement at the same traffic condition (T9) and CBR categories (S3, S4, and S5) is illustrated in figure 13. It was observed that there is a significant reduction in thickness when the pavement base is treated with a-c blend. Therefore, the present research work illustrates the application of a-c blend stabilized CA as pavement material for the construction of LVR’s. Further, the present work provides an appropriate approach to effectively utilizing hazardous BMWIFA in pavements and contributes to hazardous waste management by diverting the ashinto an alternative to cement in the pavement stabilization process, particularly in LVR’s.

Table 9. Material properties used in IITPAV analysis.

Properties	Bituminous layer (BL)	CRAL	Subgrade	Stabilized Base Layer (SBL)		
				M5	M10	M15
Poisson's ratio	0.35	0.25	0.35	0.25	0.25	0.25
Resilience Modulus (MPa)	3000	450	49.3, 61 and 77	1085	1015	1024

Table 10. The designed values of Low volume flexible pavement stabilized with a-c blend for T9 traffic category.

Mix	CBR (category)	Thickness of layers(mm)			Horizontal tensile strain in bituminous layer (micro strains)		Vertical compressive strain on subgrade layer (micro strains)		Horizontal tensile strain in stabilized layer (micro strains)	
		BL	CRAL	SBL	computed	allowable	computed	allowable	computed	allowable
M5	S3	50	75	200	150.7	160	99.7	120.2	121	132
	S4	50	75	190	153.4	160	101	120.2	118.4	132
	S5	50	75	175	156.6	160	104.3	120.2	115.8	132
M10	S3	50	75	200	151.5	158.45	104.4	124	126.1	141.5
	S4	50	75	190	154.2	158.45	106.2	124	123.2	141.5
	S5	50	75	175	157.5	158.45	109.8	124	120.4	141.5
M15	S3	50	75	200	151.4	157.5	103.7	122.8	125.4	138
	S4	50	75	190	154.1	157.5	105.5	122.8	122.5	138
	S5	50	75	175	157.3	157.5	109	122.8	119.7	138

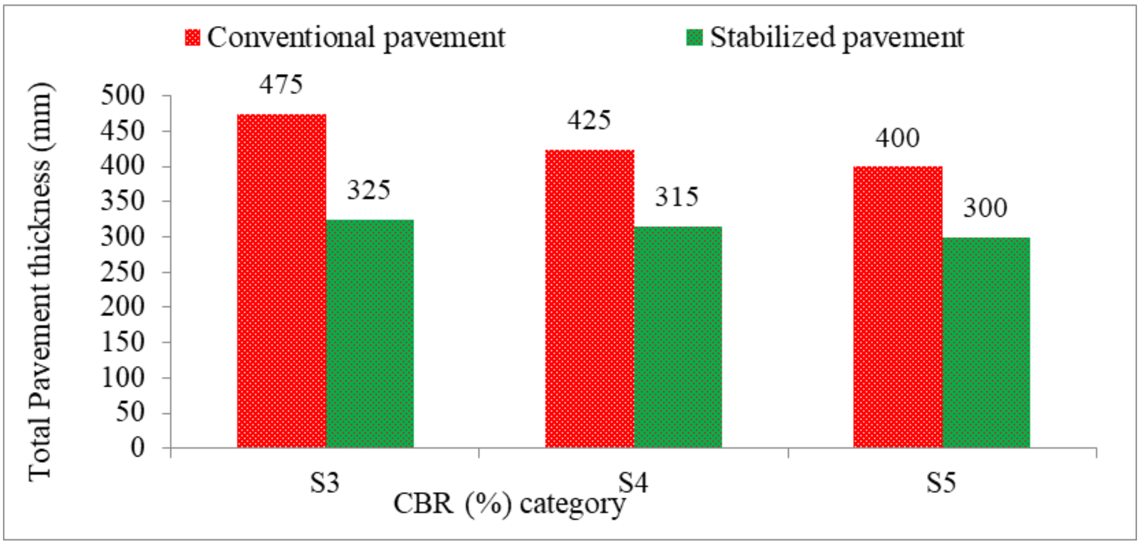

Fig. 13. Pavement thickness comparison between a-c blend stabilized pavement and conventional pavement.

6. Summary and conclusions

The experimental studies were conducted to determine the appropriateness of the a-c blend as a stabilizer in the subbase or base layer of LVR's flexible pavement. The stabilizer content considered for this study was 3.0%, 5.0%, and 7.0% of the total weight of dry mix, in which a/c ratios of 100/0, 80/20, 60/40, 40/60, 20/80, and 0/100 were considered in each percentage of the stabilizer. Strength, durability, and leaching analyses of heavy metals were carried out. Thefollowing conclusions were drawn, as presented below:

- The maximum dry density of a-c blend stabilized CA mixtures increased as the a/c ratio decreased. It is because BMWIFA has a lower specific gravity than OPC and CA.

- The results of this investigation show that as the a/c ratio decreases and curing time increases, the UCS and ITS of BMWIFA-stabilized CA increase. Higher cement dosages in the mix may improve bonding performance by forming a C-A-S-H gel.
- It is concluded from the durability studies that the selected mixes, M5, M10, and M15, can withstand the 12 W-D cycles. Weight loss for three selected mixes sharply increases up to two cycles and gradually increases within an increase in cycles. It is also noted that the weight loss of mixes M5, M10, and M15 is less than 14.0%; hence, mixes are durable as per IRC: SP: 89–2015.
- It is concluded from the TCLP test results that heavy metals like Cr, Ni, Pb, and Zn were found to be within acceptable limits. Therefore, using BMWIFA in the construction of roads would not present any possible hazards.
- At the same traffic circumstances as conventional materials for LVRs, the use of a-c blend stabilized CA materials resulted in a considerable reduction in pavement thickness ranging from 25 to 31.57%, as per IRC SP:72-2015.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Ramulu Gugulothu: Conceptualization; Data curation; Formal analysis; Investigation; Methodology;Writing – original draft.

Shankar Sabavath: Conceptualization; Project administration; Resources; Supervision; Writing – review & editing

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