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Sustainable use of ferrochrome slag and quarry dust composite as cement-bound layers of flexible pavement

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Graphical abstract

Abstract

In this study, an attempt was made to characterize ferrochrome slag as cement-bound layers of flexible pavement in view of its leaching behavior. Toxicity Characteristic Leaching Procedure (TCLP) test was conducted to assess the mobility of toxic elements in ferrochrome slag. Ferrochrome slag aggregate was classified as a non-hazardous material that has good physical and mechanical properties. The standards for cement stabilization set forth by the MoRTH can be met by two gradations, ferrochrome slag(F) and quarry dust(Q) in the ratios of 70/30 and 60/40(F/Q) respectively. Cylindrical specimens of cement contents (2%, 4%, and 6% dry weight, respectively) were cast at optimum moisture content and maximum dry density for 7 and 28 days of curing to perform unconfined compressive strength. The cylindrical specimens are subjected to a series of cycles consisting of alternative wetting and drying, and the corresponding weight loss for each cycle is recorded in order to evaluate the effect of subsequent cycles. The strength of cement-treated ferrochrome slag and quarry dust mixtures was measured before and after they were subjected to durability testing. The cement-treated F60Q40 mix showed better performance than the F70Q30 mix and it can be efficiently utilized as a replacement for granular sub-base and base courses of flexible pavement, thereby reducing leaching and environmental pollution.

Keywords: Ferrochrome slag, leaching, quarry dust, cement stabilization, durability, sustainability

1. Introduction

Ferrochrome slag is an industrial byproduct from the production of pure ferrochromium alloy, which is a key ingredient in the manufacture of stainless steel. As long as stainless steel is produced, it must rely on the manufacture of ferrochromium. The associated Ferro-slag deposits accumulate, occupying large areas and creating environmental problems. About 1.1 to 1.6 tons of slag is produced per ton of ferrochrome (Niemelä and Kauppi 2007). The possible use of ferrochrome slag deposits in structural buildings and pavements with the correct technical support can alleviate environmental issues and lead to sustainable development. Despite the fact that several studies have indicated the viability of ferrochrome slag as a construction material, its actual application is limited due to environmental concerns. The chromium content (approximately 8 to 12 percent) in ferroalloy slags is the primary environmental concern, and it may be efficiently recovered using gravity and magnetic separation (Shen and Forssberg 2003; Oxygen *et al*. 2006). Most of the chromium exists as Cr (III) which is considered to be stable and also might be possible to reach a higher oxidation state of Cr (VI) due to adverse environmental conditions (Panda *et al*. 2012). Further studies have concluded that to decrease the widespread accumulation of industrial slag and the accompanying environmental issue, an appropriate stabilization technology must be employed (Reduction and Agency 1989; Conner and Hoeffner 2010). In context to the solidification, the solubility of Cr (VI) in the cement system was reduced due to the formation of complex calcium chromate (Wang and Vipulanandan 2000). In concrete applications, ferrochrome slag can be utilized as both fine and coarse aggregate, meeting both mechanical and environmental concerns by immobilizing chromium within the matrix of the concrete (Panda *et al*. 2013; Acharya and Patro 2016). Due to the higher abrasive and crushing resistance of slag, it can be advantageously used as coarse aggregate over conventional limestone in cement concrete pavements

(Zelić 2005; Rajasekhar Konda 2016). From the aforementioned investigations, it is evident that the encapsulation of ferrochrome slag with cement generates a solid matrix structure to immobilize chromium. The use of cement stabilized ferrochrome slag aggregate can be used as road bases to control leaching, thus protecting the environment (Chewe Kambole *et al* 2021; Altan Yilmaz and Mustafa Karasahin 2014). Hence, in this study cement stabilization of ferrochrome slag was carried out keeping in view its leaching behaviour.

Although several studies have stated that ferrochrome slag aggregate has better mechanical properties than conventional aggregates (Sanghamitra and Reddy 2017; Yılmaz and Karaşahin 2010; Kumar *et al*. 2022), it has been classified as a poorly graded material (IRC SP 89 part-I 2010). To increase the gradation, coarse-grained and fine-grained ferrochrome slag has been reported to be mixed in a ratio of 40:60 to reach the required gradation for the granular subbase material. It was also noticed that the CBR, and shear strength of the red soil were enhanced when it was blended with fine grained ferrochrome slag (Das 2014; Sinha and Havanagi 2018). Hence in this study, to enhance gradation, ferrochrome slag was mixed with quarry dust to check compatibility for cement treated granular bases of flexible pavement.

Quarry dust was a waste material accumulated at a quarry site during quarrying operations. Quarry byproducts were used for the mechanical stabilization of laterite soil, thereby improving CBR. Even its performance effectively decreases the swelling index of expansive clay soils (Sudhakar *et al*. 2021). When high plasticity silty soil was proportioned with quarry dust, the CBR value of the subgrade increased significantly (Priyankara 2020) It can also be used as a sub-base when treated with 6% cement (Eze-Uzomaka and Agbo 2010). The presence of optimum fines in quarry dust reduced the cement content and also enhanced the performance of the mixture (Ashtiani and Little 2007). It was also observed that high strength was achieved due to the reaction of cement with the fines in quarry dust (Anand J. Puppala *et al*.).

The initial objective of the study was to improve the gradation of ferrochrome slag by mixing it with quarry dust in proportions of 90/10, 80/20, 70/30, 60/40, and 50/50 (F/Q). Depending upon the suitability as cement bound layer, F70Q30 and F60Q40 composites were considered for cement stabilization. In addition, the performance of composites comprised of ferrochrome slag and quarry dust treated with cement (2%, 4%, and 6% by weight of the aggregate mix) was evaluated before and after durability test.

2. Research Significance

Although ferrochrome has been extensively researched for its suitability and applicability, its practical application in laying pavement layers has not yet been elucidated due to its environmental problem. Based on past research, it is evident that the solidification of ferrochrome slag in calcium silicate hydrate (CSH) phases can reduce leaching. Consequently, the leaching phenomena can be minimized and its use can be maximized by employing an appropriate stabilization method. In this research, ferrochrome slag was stabilized with cement in proportions of 2%, 4%, and 6% to reduce leaching phenomena and its performance is evaluated by conducting the UCS before and after durability test.

3. Materials and Methodology

3.1. Material used and experimental plan

Ferrochrome slag was procured from Jindal Stainless Steel, Vizianagaram. Based on sieve analysis (IS:2386- Part I), the particle size ranges from 10 mm to 1.18 mm. According to the Indian soil classification system, ferrochrome slag was classified as poorly graded gravel (GP). The physical and mechanical properties of ferrochrome slag are summarized in Table 1. From the sieve analysis, it was found that there was particle deficiency below 1.18mm, so quarry dust was mixed with ferrochrome slag in proportions of 10% to 50% (% by weight) with 10% increment to enhance gradation. Quarry dust was procured from a quarry place in Vizianagaram. Quarry dust was classified as poorly graded silty sand(SP-SM) and non-plastic(NP) with particle sizes ranging from 4.75mm to 0.075mm. OMC and MDD of quarry dust were found to be 10.36% and 2.047g/cc respectively. The engineering properties of quarry dust are depicted in Table 2.

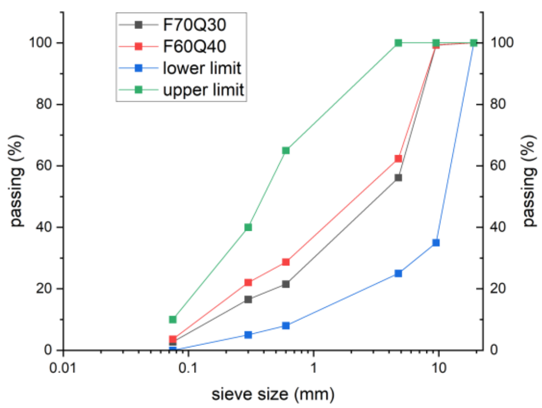

Figure 1. Grain size distribution curves of F70Q30 and F60Q40 with MoRTH gradation limits

Ferrochrome slag (F) and quarry dust (Q) were mixed in the ratio of 90/10, 80/20, 70/30, 60/40, and 50/50 (F/Q) to satisfy the gradation of cementitious subbase and base course material prescribed by the Ministry of Road Transport and Highways (MoRTH 2013). As per MoRTH, the gradation has to be well-graded and shall be in between the upper and lower limits as shown in Figure 1. F90Q10 proportion does not satisfy the required gradation limits of MoRTH, whereas F80Q20 and F50Q50 have reached the required gradation limits but are classified as poorly graded materials. Only F70Q30 and F60Q40 are well graded and satisfied the gradation limits specified by MoRTH. The mix proportions, their respective coefficient of uniformity Cu and coefficient of curvature Cc values along with IS soil classification are depicted in Table 3. The gradation curves of the F70Q30 and F60Q40 are presented in Figure 1. OPC

43 grade cement was added to F70Q30 and F60Q40 mixes in proportions of 2%, 4%, and 6% (% by weight) to determine compaction characteristics, UCS, and durability test.

Table 1. Physical and Mechanical properties of the ferrochrome slag

property	Test value	MoRTH specifications (2013)
Specific gravity	3.16	NA
Grain size distribution		-
Gravel (%)	62.43 %	
Sand (%)	37.57 %	
Fines (%)	0	
Coefficient of uniformity (C_u)	3	-
Coefficient of curvature (C_c)	1.33	-
IS classification symbol	GP	-
Aggregate Impact Value, %	9.63	Max. 30
Flakiness and Elongation Index, %	20.37	Max 35
Angularity Number	8	0-11
Water Absorption, %	0.37	Max 2.0
Soundness (based on MgSO4) %	2.83	Max 18
Abrasion value (%)	22.39	Max. 40
Crushing value (%)	22.75	Max 45

Table 2. Engineering properties of quarry dust

Property	Test value
Specific gravity	2.55
Grain size distribution	
Gravel (%)	0.5 %
Sand (%)	90.5 %
Fines (%)	9
Coefficient of uniformity (C_u)	4.5
Coefficient of curvature (C_c)	0.9
Plasticity characteristics	
liquid limit	NP
plastic limit	NP
IS classification symbol	SP-SM
Compaction characteristics	
Maximum Dry Density (g/cc)	2.047
Optimum Moisture Content (%)	10.36
California Bearing Ratio (%)	24.3

Table 3. Gradation analysis of the various combinations of ferrochrome slag and quarry dust mixes

Mix	Coefficient of Uniformity (C_u)	Coefficient of Curvature (C_c)	IS Classification
F80Q20	20	4	GP
F70Q30	29	2.64	SW
F60Q40	32.3	1.05	SW
F50Q50	30	0.44	SP

3.2. Toxicity Characteristic Leaching Procedure (TCLP)

TCLP test was performed as per U.S. Environmental protection agency (USEPA) to check the mobility of heavy metals in ferrochrome slag. The ferrochrome slag was sieved through a 9.5 mm sieve to carry out a leaching test as per the procedure. The ferrochrome slag was allowed to leach into an extraction liquid of 5.7ml glacial acetic acid. A liquid-solid ratio of 20:1 was prepared and stirred continuously for 18 hours by a vibrating shaker at a temperature of 25° C. After 18 hours of agitation, the solution was filtered through a 0.4 µm glass filter membrane to separate the leachate.

3.3. Sample preparation

Proposed ferrochrome slag and quarry dust gradations (F70Q30 and F60D40) at different cement contents (2% to 6%) mixed manually to determine OMC and MDD in accordance with IS Heavy compaction test (IS: 4332 Part-III). Based on predetermined OMC and MDD, the samples were compacted in cylindrical molds (100mm dia. and 200mm high) in 5-layers with 25 blows each layers using 4 9 kg heavy rammer (IS: 4332 Part-V). After 5th layer compaction, the top surface of the cylindrical mold was covered with polyethylene cover (Figure 2) and left undisturbed for 24 h. Later specimens were demolded and wrapped with polyethylene cover to prevent loss of moisture. All the specimens stored for a moist curing period of 7 and 28 days. After completion of curing duration, cement treated cylindrical specimens were tested for UCS and durability studies.

3.4. Unconfined compressive strength (UCS)

UCS was performed according to IS 4332 (part V). Total 6 cylindrical specimens were prepared for each cement content at Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), 3 specimens were tested for UCS before durability and the remaining three were tested after the completion of 12 cycles of durability. The compressive strength was taken as the maximum load recorded by the compressive testing machine divided by the cross-sectional area of the specimen. The mean value of the 3 specimens is taken as final compressive strength.

Figure 2. Storage of polyethylene wrapped cylindrical specimens

3.5. Durability test

After completion of a moist curing period of 7 and 28 days, the cylindrical specimens that were wrapped with polyethylene cover are removed and proceeded for durability test. The wetting and drying method was adopted to carry out durability tests on specimens as per IS 4332 (Part IV). Each cycle constitutes 5 hrs. of soaking in water followed by 42 hrs. of drying in an oven at 70^0C and 20 strokes applied uniformly on all the surfaces with a wire brush. The same procedure was executed for the 12 cycles and the weight loss for each cycle was noted. After 12 cycles, the samples were heated to a constant weight at 110^0 C and final weight loss was recorded.

4. Results and discussion

4.1. Leaching test analysis

TCLP test was conducted to classify ferrochrome slag as hazardous or non-hazardous solid waste. Heavy metal elements and their average concentrations are depicted in the Table 4. TCLP values of ferrochrome slag were compared with World Health Organization (WHO) limits for drinking water and Environmental Protection Agency (EPA) standards for solid waste disposal. This experimental study revealed that all metal ions (listed in the Table 4) were within the allowable limits specified by the EPA. In particular, the total chromium was 531.507 ppb, which is below regulatory norms and can be classified as non-hazardous solid waste. When evaluated against WHO, Cr and Ni exceeded drinking water standards as shown in the Table 4. In fact, the TCLP test was conducted in a simulated acidic environment, upon which the dissolution of metal ions occurs. This can be attributed to the fact that slag under acidic environmental condition, which accelerates the dissolution process of heavy metal resulting in the contamination of surrounding soil and ground water (Kambole *et al*. 2021a). However, encapsulating ferrochrome slag in a cement matrix creates an alkaline environment, an acidic environment that is unlikely to occur. The possibility of water seeping through the pavement layers is not possible, for which they are intended to be designed. Ferrochrome slag application in cement-bound layers of flexible pavements will be a good solution to control leaching and increase durability.

Table 4. TCLP result analysis in comparison to WHO drinking water standards and USEPA standards

Elements analysed	Heavy metal Concentration in ferrochrome slag, ppb	WHO limits for drinking water, ppb (World Health Organization:fourth edition incorporating the first and second addenda 2022)	EPA regulatory limits for solid waste, ppb (USEPA 2009)
Cr	531.507	50	5000
Fe	11542.526	NA	NA
Ni	274.942	70	NA
Cu	14.415	2000	NA
Zn	1552.041	NA	NA
As	0.893	10	5000
Cd	0.249	3	1000
Hg	0.020	6	200
Pb	7.118	10	5000

Table 5. Compaction characteristics of FS70Q30 and FS60Q40

Cement content (%)	FS70Q30			FS60Q40		
	OMC (%)	MDD (g/cc)	Void ratio	OMC (%)	MDD (g/cc)	Void ratio
2	6.68	2.427	0.192	6.72	2.387	0.186
4	6.74	2.434	0.191	6.78	2.406	0.178
6	7.21	2.463	0.178	6.81	2.418	0.174

4.2. Compaction characteristics

Moisture density relationships for F70Q30 and F60Q40 composites at various cement contents are depicted in the Figure 3. An increase in dry density was observed with increase in water content up to OMC due to lubrication of slag and dust particles. For water content beyond OMC, density decreases with increasing water content due to displacement of slag and dust particles with water. The OMC and MDD of the F70Q30 composite with cement stabilization were in the range of 6.68% to 7.21% and 2.427 g/cc to 2.463 g/cc. Similarly, for F60Q40 composite was in the range of 6.72% to 6.81% and 2.387 g/cc to 2.418g/cc. OMC of both mixes increased with an increase in cement content and its change was found to be marginal. These observations are in agreement with previous results which stated that OMC changed slightly with cement increment. (Prasad 2011; Kambole *et al*. 2021; Chakravarthi *et al*. 2019; Kasu *et al*. 2020). 2% water content above OMC was also acceptable in the field as specified by MoRTH. Hence its variation is found to be insignificant within 2% variation in the OMC. A similar trend was observed in MDD with increase in cement content. As cement was finer than quarry dust, all voids are filled with cement, resulting in a reduction in the void ratio. The void ratios were found to decrease with increase in cement content and their values are depicted in Table 5. Additionally, the increase in MDD may also be due to higher specific gravity (3.11) of cement than quarry dust fines (2.54) as mentioned in (Guotang *et al*. 2017).

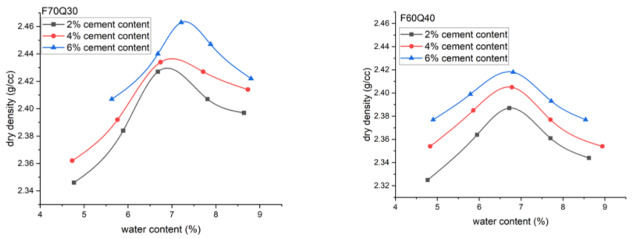

Figure 3 Compaction curves of cement stabilized FS70Q30 and FS60Q40 mixes corresponding to various cement contents

4.3. Unconfined compressive strength before the commencement of durability test

The unconfined compressive strengths of F70Q30 and F60Q30 mixes with respect to different cement contents were depicted in Figure 4 and Figure 5. An increase in UCS with an increase in cement content is observed in both the composites. The high angularity of ferrochrome slag results in good interlocking ability but may not have an active participation in cement hydration process. The increase in strength was due to the formation of cement hydration products with quarry dust fines in the composites. This observation was in agreement with the previous studies (Ashtiani and Little 2007; Anand J. Puppala *et al*. 2008)

The UCS values of the F70Q30 were found to be in the range of 0.946 MPa to 4.667 MPa and for F60Q40 were in the range of 1.128 MPa to 6.345 MPa for a 7-day moist curing period. The minimum UCS was obtained for F70Q30 at 2% cement content and maximum at 6% cement content of F60Q40 mix. UCS of stabilized F60Q40 mix was higher than F70Q30 mix. The F60Q40 mix UCS values are 1.18 – 1.36 times the UCS of the F70Q30 mix for all cement contents. The reason may be due to the presence of necessary fines in the F60Q40 better than the F70Q30 resulted in effective hydration process. A higher proportion of quarry dust in F60Q40 provides the necessary fines for cement hydration to occur. It is also shown in the Table 4. that the void ratio of F60Q40 was lower among all cement contents compared to F70Q30. Reduced void ratio gives an idea that the particles are more densely packed, have more contact area, and therefore more cementing action resulting in increased strength. Similar observations were also seen in (Huddleston 1978)(Portland Cement Association 1995). For the design of flexible pavement, the minimum UCS at 7 days of curing for the sub-base was 1.5 MPa and 4.5 MPa for the base course (IRC SP 89 part-II 2018; IRC 37 2018). The minimum cement content based on UCS for the F70Q30 mix was 2.7% and 5.7% for the subbase and base course. For F60Q40, 2.4% and 4.8% cement content for subbase and base courses of flexible pavement. It can be observed that the cement content requirement for use as a sub-base and base course for F60Q40 was less than the F70Q30. This was due to higher UCS values of F60Q40 than F70Q30 at the same cement content. In general, the minimum cement content requirement for well-graded sand was in the range of 3 -5% by weight as specified by the Portland Cement Association, and F60Q40 mix seems to be more economical than F70Q30. However, durability studies have to be carried out to finalize these minimum cement content. Further increase in the curing period has a remarkable increase in UCS strength for all cement contents of both the composites. About 40% to 52% of their 28-day strength was achieved in the 7 days curing period for all cement contents (2%, 4%, and 6%) for F70Q30 and F60Q40 composites. This may be due to the slow rate of hydration of cement to form C-S-H and CH products in the first 7 days, which were primary sources of strength. As a quick assessment, MoRTH recommends 7 days of UCS strength for minimum cement content estimation, but if we allow it to cure for 28 days we can achieve lower cement content and more strength.

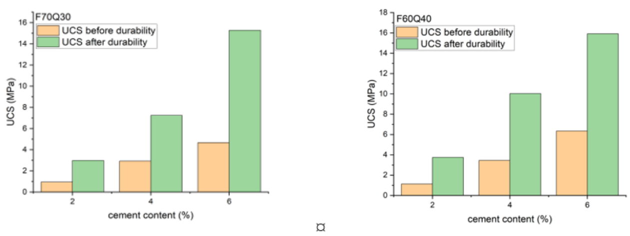

Figure 4. UCS of cement tretaed F70Q30 and F60Q40 mixtures before and after durability tests for 7 days moist curing

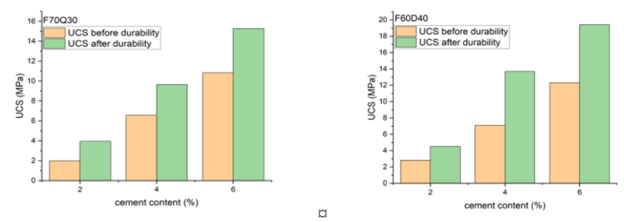

Figure 5. UCS of cement tretaed F70Q30 and F60Q40 mixtures before and after durability tests for 28 days moist curing

4.4. Durability test

Durability test is carried out to accelerate the field condition by extensive exposure to water soaking and drying in its service life (IS 4332 Part IV). All the cylindrical specimens were subjected to 12 consecutive cycles of drying and wetting as shown in Figure 6. The maximum weight loss was observed for 2% cement content when compared to all cement contents (4% and 6%) for both F70Q30 and F60Q40 composites. The minimum weight loss was observed to be at 6% cement content of F60Q40 mix. The enhanced bonding characteristics due to the presence of more cement contributed to the minimum weight loss at 6% cement content. The percentage weight loss of the F70Q30 and F60Q30 mixes at each cement content after 12 cycles is presented in Figure 7 and Figure 8. The impact of strokes, corresponding its weight loss was decreased with an increase in cement content due to greater integrity and bonding. The impact of strokes has a more pronounced effect at 2% cement content than at 4% and 6% cement content. A steeper curve can be observed for 2%, while the other curves increase initially but remain stable. This indicates that the percentage increase in weight loss was higher in the 2% cement content mix when compared to other cement contents. This can be attributed to the fact that 2% cement content mixtures were less durable than other cement contents (2% and 4%). For higher cement contents (4% and 6%), major weight loss was observed in the initial 4-5 cycles and thereafter the weight loss change was negligible. This effect may be due to fact that the pozzolanic reaction was taking place in the initial 4-5 cycles showing less restraint to strokes. After 4-5 cycles, the minimum strength achieved was sufficient to restrict the impact of strokes, thereby remained stable.

Figure 6. Durability tests on Cylindrical specimens subjected to a) wetting and b) drying

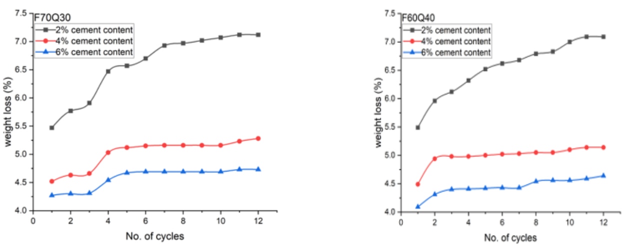

Figure 7. Weight loss % at each cycle after 7 days moist curing

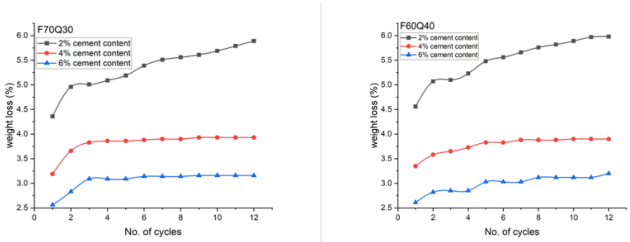

Figure 8. Weight loss % at each cycle after 28 days moist curing

The weight loss decreased with an increase in curing duration for both composites. The increase of strength with curing duration resulted in lower dust-cement losses at 28 days than at 7 days. The percentage weight loss for F70Q30 was in the range of 7.12% to 4.73% and for F60Q40 is in the range of 7.09% to 4.67% at 7-day moist curing period after 12 cycles. For the 28 days moist curing period, the weight loss for F70Q30 was between 5.96% and 3.23%. and for F60Q40 composites was between 5.98% and 3.2%. The samples before starting the durability and after exposure to 12 cycles of durability are presented in Figure 9 and Figure 10. Initial weights and final weights at 7 days and 28 days of F70Q30 and F60Q40 mixes are presented in the Table 6 and Table 7. Comparatively the 28 day weights were lower than the 7 day weights. This variation in weights was due to hydration process from 7 days to 28 days curing, which causes exothermic reactions to occur, resulting in moisture evaporation over 28 days. Weight losses at 28 days found to be lower than the losses at 7 days as their strengths corresponding to 28 days were more. On the other hand, higher strengths show greater tolerance to strokes. Weight loss for F70Q30 mixes was also found to be higher than F60Q40, but marginal variations were observed. The increased strength of F60Q40 over F70Q30 did not show a significant difference in weight loss. However, both the composites exhibit a weight loss lower than 14% at the end of 12 cycles (IRC SP 89 part-II 2018)(IRC 37 2018 2018). As both the composites satisfy the durability criteria, based on UCS the minimum cement requirement for F60Q40 was less than the F70Q30. Hence F60Q40 can be more economical than F70Q30 for the design of subbase and base course of flexible pavement.

Table 6. Percentage weight loses at 7 days and 28 days moist curing for F70Q30 mixes

Cement content, %	7 Days			28 Days		
	Initial weight , gm.	Final weight gm.	Weight loss, %	Initial weight , gm.	Final weight gm.	Weight loss, %
2	4046	3758	7.12	4017	3778	5.96
4	4072.5	3857.5	5.28	4047	3888	3.93
6	4199	4000.5	4.73	4174	4039	3.23

Table 7. Percentage weight loses at 7 days and 28 days moist curing for F60Q40 mixes

Cement content (%)	7 Days			28 Days		
	Initial weight , gm.	Final weight gm.	Weight loss, %	Initial weight , gm.	Final weight gm.	Weight loss, %
2%	4008	3724	7.09	3914.5	3680.5	5.98
4%	4066.50	3857.5	5.14	4026	3869	3.90
6%	4093.5	3902.5	4.67	4065	3934	3.22

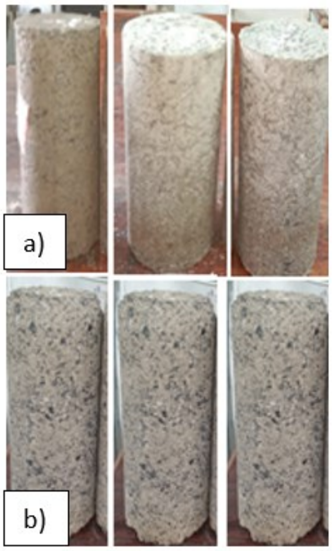

Figure 9. Durability at 7 days a) before and b) after 12 cycles

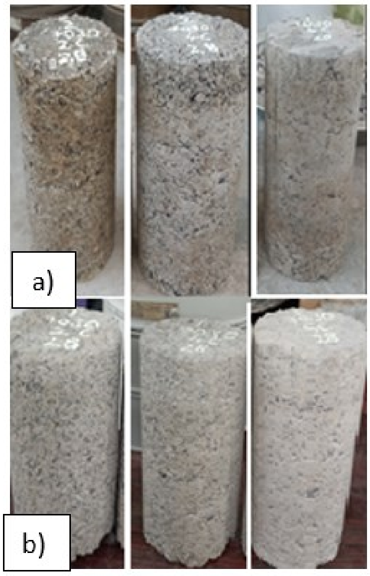

Figure 10. Durability at 28 days a) before and b) after 12 cycles

4.5. Strength assessment after durability

After 7 days of moist curing, samples are exposed to 12 cycles, after which the UCS values range between 2.984 to 15.278 MPa for F70Q30 and between 3.746 and 15.916 MPa for F60Q40. UCS values ranged from 3.934 to 15.278 MPa for F70Q30 and 4.521 to 19.416 MPa for F60Q40 in samples subjected to 12 cycles following a moist curing period of 28 days. As shown in the Figure 4 and Figure 5, the 7-day-cured specimens of both F70Q30 and F60Q40 exhibited a considerable increase in strength compared to the strength before durability. At all cement contents, the strength of F70Q30 and F60Q40 composites was increased by 147% to 232%. UCS after 28 days of moist curing increased the strength from 41 to 98% as shown in Figure 9. Similar increasing trend in UCS has been observed in previous study (Zaman *et al*. 1999). Immersion of cylindrical specimens in water supplies the water required for hydration during the wetting phase, and the increase in strength results from the accelerated hydration process during the heating stage of the durability test. After 7 days of curing, the pozzolanic reaction occurs continuously during the 12 cycles; however, for 28 days of moist curing, the maximum hydration occurred over the curing time. A potential pozzolanic reaction occurred after 7 days because the retention of anhydrite molecules was greater at 7 days than at 28 days. This can be better identified by the difference in initial weights at the beginning of the durability test as shown in the Table 6 and Table 7. A weight difference of about 0.6% to 2.3% was observed between their initial weights. Thus, a considerable improvement was reported for 7-day durability compared to 28-day durability. After 12 cycles, the cement-treated F60Q40 is between 1.04 and 1.42 times the UCS of F70Q30 mix that has been cured for 7 days and 28 days of moist curing. The F60Q40 mixture performed better than the F70Q30 at all cement contents and curing times after durability.

5. Conclusions

The physical and mechanical properties of ferrochrome slag aggregate are within the permissible limits stipulated by MoRTH and it can be used as granular materials of flexible pavement.

According to the TCLP test, heavy metal mobility in ferrochrome slag is within permissible limits when compared to USEPA standards and can be classified as a non-hazardous waste. However, when compared to the World Health Organization guidelines for drinking water, Cr and Ni exceeded the specifications.

From the compaction properties, it is apparent that the MDD and OMC for both F70Q30 and F60Q40 composites increased marginally as the cement concentration increased. For all composites, OMC ranges from 6.68% to 7.21 %, and MDD ranges from 2.38 to 2.46 g/cc. hence, the change in MDD and OMC is negligible and has no significant impact on cement content.

For 7 days of curing, the UCS of all cement-treated composites is between 0.946 MPa and 4.504 N/mm2, and between 1.980 MPa and 12.304 MPa for 28 days. All composite compositions exhibited a significant improvement in UCS with increasing cement concentration. The cement-treated F60Q40 has a UCS strength between 1.08 and 1.41 times that of F70Q30. About 40% to 52% of 28-day strength was attained in 7 days of moist curing for all composites, which was a significant effect as curing duration increased.

With the wetting and drying method, all cement-treated composites lost between 3.60 and 7.24 percent of their weight after 7 days of moist curing and between 3.22 and 5.98 percent after 28 days of moist curing. Both F70Q30 and F60Q40 composites satisfied the durability criteria as per MoRTH.

After the specimens subjected to durability test, an increase in UCS of about 147% to 233% was recorded after 7 days of moist curing, and an increase in strength of about 41% to 98% was observed after 28 days of moist curing.

On the basis of the UCS and durability test, the optimal composition was determined. The cement-treated

F60Q40 show higher performance than the cement-treated F70Q30 at all cement content. This is because the F60Q40 mix has sufficient fines more than F70Q30 resulted in effective cement hydration products.

The minimum cement content required for the F60Q40 mix is 2.4 % and 4.8% for use as cement-treated subbase and base courses of flexible pavement.

The use of cement-treated ferrochrome slag and quarry dust composite F60Q40 in flexible pavements is a promising solution for efficient management of solid waste and to reduce the leaching of toxic elements, environmental pollution.

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7. Competing interests

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8. Author Contributions

Conceptualization, Formal analysis, Investigation, Methodology, Writing, Drafting was performed by CH Ajay[1] Conceptualization, Review and Editing, Resources, Supervision was performed by K Durga Rani[2]

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