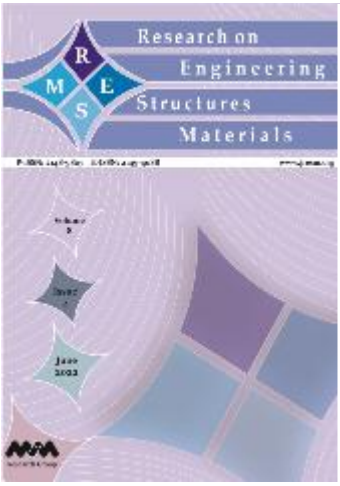
Research on Engineering Structures & Materials

journal homepage: http://www.jresm.org

Research Group



Evaluation of cement-treated ferrochrome slag and quarry dust composites for base and sub-base layers of flexible pavement

CH Ajay, K Durga Rani

Online Publication Date: 20 May 2023

URL: http://www.jresm.org/archive/resm2023.559.ma1010.html
DOI: http://dx.doi.org/10.17515/resm2023.559.ma1010

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Ajay CH, Rani D. Evaluation of cement-treated ferrochrome slag and quarry dust composites for base and sub-base layers of flexible pavement. *Res. Eng. Struct. Mater.*, 2023; 9(3): 1061-1080.

Research on Engineering Structures & Materials
journal homepage: http://www.jresm.org
MIM Research Group

Research Article

Evaluation of cement-treated ferrochrome slag and quarry dust composites for base and sub-base layers of flexible pavement

CH Ajay[1*,a], K Durga Rani[2,b]

[1]*Research Scholar, Civil Engineering Department, Andhra University, Visakhapatnam, Andhra Pradesh, India*
[2]*Professor, Civil Engineering Department, Andhra University, Visakhapatnam, Andhra Pradesh, India*

Article Info

Article history:

Received 10 Oct 2022
Accepted 15 May 2023

Keywords:

Ferrochrome slag; Quarry dust; gradation; Cement stabilization; Ultrasonic pulse velocity; Unconfined compressive strength;

Abstract

This study explores the use of ferrochrome slag as cement-bound granular layers of flexible pavement. To meet MoRTH design criteria, ferrochrome slag (FS) gradation was improved by incorporating quarry dust (Q) in proportions of 10%, 20%, 30%, 40%, and 50% (by weight). Only FS70Q30 and FS60Q40 composites have satisfied the gradation requirements of cementitious sub-base and base courses of flexible pavement. Unconfined compressive strength (UCS) and ultrasonic pulse velocity (UPV) tests were performed under OMC and MDD conditions on ferrochrome slag and quarry dust composites stabilized with cement in proportions of 2% to 10% (by weight of the aggregate mix) and curing periods of 3, 7, 14 and 28 days. FS70Q30 and FS60Q40 mixes exhibited a significant increase in strength and wave velocities with increasing cement content and curing periods. The UCS of FS60Q40 mixes was 1.03 to 1.62 times that of FS70Q30 mixes, and no significant variation in UPV was observed. An equation with a high regression factor (R-square >0.98) was formulated to correlate UCS and UPV values with cement content. Based on the developed statistical equation, the predicted minimum cement content for FS60Q40 mixes was found to be 12-16% lower than FS70Q30 mixes.

1. Introduction

Traditionally, aggregates for road construction were deployed through extensive mining activities. Uncontrolled mining has led to the depletion of natural aggregates and increased demand for alternative pavement construction materials. Industrial byproducts have driven a special interest in launching a new era in construction activities in place of conventional materials. Industrial byproducts such as waste foundry sand, blast furnace slag, steel slag, bottom ash, copper slag, and fly ash are used in large quantities in concrete applications for producing better strength, durability, and environmentally friendly concrete [1, 2]. Owing to its environmental concerns, there was a minimal analysis of the functionality of ferrochrome slag in transportation engineering applications. Every metallurgical processing industry has massive deposits piled over huge areas, which result in the leaching of toxic elements into the ground in events of saturation. In this case, ferrochrome slag occupies the available land and contains toxic metals that can cause leaching. Residual chromium in ferrochrome slag is liable for leaching and results in environmental contamination [3]. Magnetic separation and crushing followed by the jigging process produce about 59% of the residual chromium from the slag [4]. Presently,

---

[*] Corresponding author: ajay.chappa91@gmail.com

[a] orcid.org/0009-0001-0728-1461; [b] orcid.org/0009-0004-1847-6012
DOI: http://dx.doi.org/10.17515/resm2023.559.ma1010

two challenges have to be addressed 1) preventive measures to reduce chromium leaching from slag and 2) to characterize it as pavement material for its maximum utility. So adequate research on its use in view of its environmental concern may maximize the benefit of ferrochrome slag as pavement construction material and reduce several environmental issues.

To meet the design standards of MoRTH, ferrochrome slag gradation has to be improved to use in granular sub-base and base course of flexible pavement. So there was a need to explore cost-effective alternative materials. Quarry dust was a primary byproduct of the rock processing industry, accounting for 20-25% of output. Around 175 million tons of dust was generated from various sources like mining, crusher units, and quarry units [5]. These non-biodegradable wastes were deposited, blown, and entrapped as particulate matter in the air creating an environmental problem. Humans and animals can also easily inhale this dust at a quarry site [6, 7]. So its emissions should be controlled to reduce the problem. This study used quarry dust from 10% to 50% (with 10% intervals) to improve the gradation of ferrochrome slag. The use of ferrochrome slag and quarry dust materials in flexible pavement layers is an economical and sustainable solution to renew natural resources.

2. Background Studies

Sanghamitra et al. reported that ferrochrome slag aggregate had good mechanical properties, and its use in granular layers can lessen the demand for conventional aggregate [2,8]. The unconfined compressive strength, California bearing ratio (CBR), and shear strength of red soil was found to be improved by stabilizing it with ferrochrome slag and ferrochrome ash in proportions of 10%-50% (with 10% intervals) [9]. It can also be used as a subbase material through improvement in gradation of ferrochrome slag by proportioning with soil (i.e., slag: soil, 80:20) [10]. According to the marshall stability test, the slag-based mixtures were better in confrontation with the water effect than the conventional bituminous concrete mixture [11].

However, concerns have been outstretched due to residual chromium (Cr) in slag, which can leach and create ecological issues. Lind et al. constructed a ferrochrome slag road base and found minimal migration of chromium to the surrounding soil and groundwater [12]. Even at ambient temperature, ferrochrome slag remained in stable condition and was under regulatory terms of the United States Environmental Protection Agency (USEPA)[13] Though it was stable at ambient temperature, to ensure safe disposal and to prevent heavy metal leaching, solid waste has to be solidified using the right stabilization technology [14]. Complex calcium chromate was created on stabilization with Portland cement, reducing the solubility of Cr(VI) [15]. It was influential in stabilizing ferrochrome dust using cement mixtures and revealed that the leaching behavior of immobilized ferrochrome was within acceptable limits [16]. This remarkable effect of solidification was also proven to be effective in the immobilization of chromium in concrete applications reported by Panda CR et al [17]. Due to the good mechanical properties of the ferrochrome slag aggregate, it also exhibits high performance than conventional aggregates [18-24]. In this context, it is advantageous to use ferrochrome slag in cement-treated granular bases to immobilize chromium (VI) in CSH phases and to address the environmental issue.

Cement-treated or cement-bound layers include granular materials and measured quantities of cement and water, compacted to reach maximum density. Granular materials can be a combination of locally available materials and waste materials. Cement stabilization of weak subgrade helps in the economical design of pavement due to increased modulus and reduced vertical strain [25]. A granular subbase and base course with 2% cement stabilization were found to be suitable for low-traffic roads [26]. In recent studies, reclaimed asphalt pavement materials, recycled concrete aggregate, and industrial wastes were also cement treated to reduce dumping and environmental issues. Cement-treated recycled asphalt aggregates can be economically used as a replacement for virgin aggregate up to 30% in bounded layers of pavement [27-29]. So, cement-stabilized ferrochrome mixtures as road bases could be a better solution to keep heavy metal leaching within allowable limits without posing environmental issues [30, 31].

Here are some studies that focused on the use of quarry dust. The CBR of laterite soil can be considerably improved with 30% quarry dust addition, and further stabilizing it with 6% cement satisfies the criteria for a base course [32]. Fly ash and quarry dust mixed in a ratio of 1:2 up to 45% proportion in expansive soil can strengthen the subgrade soil [33]. Even its performance effectively decreases the swelling index of expansive clay soils [34]. When high plasticity silty soil was proportioned with quarry dust, the CBR value of the subgrade increased significantly [35]. The rutting resistance was also improved with the inclusion of quarry byproducts and RAP as coarse aggregate in the cement-treated granular layers of flexible pavement [36].

In this study, an attempt was made to check the suitability of ferrochrome slag and quarry dust as cement-bound pavement layers. Ferrochrome slag and quarry dust were blended in different proportions (90/10, 80/20, 70/30, 60/40, 50/50 of FS/Q) to check suitability as cement-bound subbase and base course in flexible pavements. Depending on the specifications stipulated by the MoRTH, 70/30 and 60/40 gradations were finalized to stabilize with cement content ranging from 2% to 10% (by dry weight of the mixture). The cement-treated ferrochrome slag-quarry dust samples were prepared and tested for unconfined compressive strength and ultrasonic pulse velocity test at different moist curing durations. Based on the desired UCS strength specified by the MoRTH, arrived at optimum levels of cement contents for use as cement-bound pavement layers.

3. Research Significance

Globally ferrochrome slag has been widely investigated for concrete applications due to its ability to encapsulate in calcium silicate hydrate (CSH) phases and increase Cr (VI) volatilization. Although environmental impact assessment studies have asserted that chromium leaching was within permissible limits, its use in pavement layers is minimal. Thus framework was developed to study the strength properties of cementitious ferrochrome slag and quarry dust composites through the UCS and UPV tests. This study helps practicing engineers enhance the utility of ferrochrome slag in cement-bound pavement layers.

4. Materials and Methods

4.1. Materials

Ferrochrome slag was collected from Jindal Stainless Steel Industry, Vizianagaram, Andhra Pradesh (AP). Quarry dust was collected from a nearby quarry in Vizianagaram, AP. As per IS 2386 [37], sieve analysis was performed to analyze the grain size distribution. Ferrochrome slag and quarry dust were classified as poorly graded gravel and poorly graded silty sand. The gradation curves and their corresponding IS soil classification are presented in Fig.2 and Table 3. It can be observed from the sieve analysis, ferrochrome slag has a maximum size of 10mm and a minimum size of 1.18mm, indicating that there was a deficiency of fines less than 1.18mm. Since ferrochrome has no fines, it was less sensitive to water and also there was in need to improve its gradation. Hence, mechanical stabilization of ferrochrome slag was done by mixing it with quarry dust in proportions of 90/10, 80/20, 70/30, 60/40, and 50/50 so as to improve its gradation for use as sub-base and base course material [38]. The attributes of ferrochrome slag and quarry dust are depicted in Tables 1 and 2. Ferrochrome slag and quarry dust used in this study are presented in Fig.1

The sieve analysis of the different gradations and their respective Indian soil classification systems are presented in Fig.2 and Table 3. Based on the sieve analysis from Table 3, FS90Q10 was classified as a well-graded aggregate but failed to satisfy the gradation limits specified by MoRTH as shown in Fig.2 [39]. Whereas, FS80Q20 and FS50Q50 mixtures were within the gradation limits but classified as poorly graded material as shown in Table 3. FS70Q30 and FS60Q40 composites satisfied the MoRTH gradation limits and were classified as well-graded materials. So in this study, cement stabilization was carried out by considering two gradations, i.e., FS70Q30 and FS60Q40.

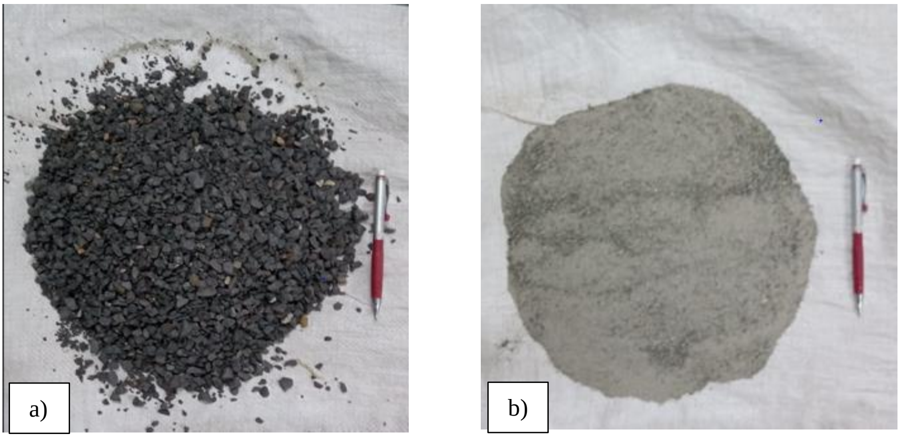


Fig.1. Materials used in this study a) Ferrochrome slag and b) Quarry dust

Table 1. Physical properties of the ferrochrome slag [40]

Physical Property	Test Value	Maximum allowable limits specified by MoRTH (2013)
Specific gravity	3.16	NA
Water absorption, %	0.37	2.0
Aggregate impact value, %	9.63	30
Angularity number	8	0-11
Flakiness and elongation Index, %	20.37	35
Los angeles abrasion Value, %	22.39	40
Soundness (based on MgSO4) %	2.83	18

Table 2. Physical properties of quarry dust

Property	value
Specific gravity	2.55
Liquid limit	NP
Plastic limit	NP
Optimum moisture content (OMC), %	10.36
Maximum dry density (MDD), g/cc	2.047
California bearing ratio (CBR), %	24.3

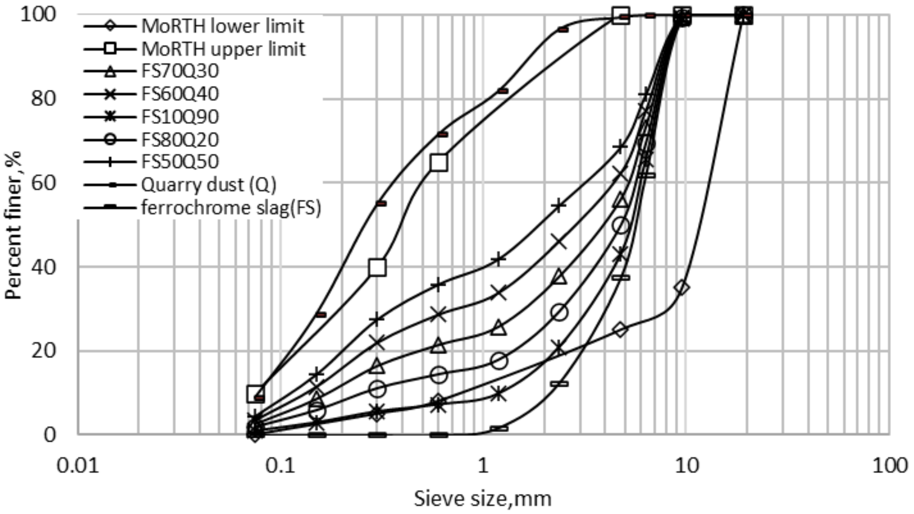


Fig. 2. Grain size distribution curves of ferrochrome slag, quarry dust and their combinations

Table 3. IS soil classifications of ferrochrome slag, quarry dust and their combinations

Mix	Coefficient of Uniformity (C_u)	Coefficient of Curvature (C_c)	IS Soil Classification
Ferrochrome slag (FS)	3	1.33	GP
Quarry dust(Q)	4.5	9	SP-SM
FS90Q10	4.83	1.38	GW
FS80Q20	20	4	GP
FS70Q30	29	2.64	SW
FS60Q40	32.3	1.05	SW
FS50Q50	30	0.44	SP

4.2 Preparation of samples

Initially, air-dried ferrochrome slag and quarry dust samples were mixed in the required proportions (FS70Q30 and FS60Q40). Cement content of 2 to 10% (by dry weight of the aggregate mix) was then added to the FS70Q30 and FS60Q40 mixtures. Ferrochrome slag, quarry dust, and cement are mixed thoroughly to ensure homogeneity before mixing with water. Care was taken to complete mixing and compaction within 30 minutes after the addition of water, as initial hydration would occur. A heavy compaction rammer weighing 4.89 kg was used to compact cement-treated mixtures in 5 layers to determine compaction properties as per IS 4332 part III [41]. Optimum moisture content (OMC) and maximum dry density (MDD) were ascertained for each cement content of FS70Q30 and FS60Q40 mixes. Cement-treated ferrochrome slag and quarry dust mixes of cylindrical size (100 mm dia. X 200 mm height) were prepared at OMC and MDD for conducting unconfined and ultrasonic pulse velocity tests. The experimental program resulted in 10 mixtures, and their details are depicted in Table 4.

Table 4. Experimental matrix

Mix proportion	Ferrochrome slag (FS), %	Quarry dust (Q), %	Cement content (C), %	Number of replicates	Type of test
FS70Q30	70	30	2	03	• Compaction characteristics • UCS test* • UPV test*
			4		
			6		
			8		
			10		
FS60Q40	60	40	2	03	
			4		
			6		
			8		
			10		

*Note; Tests conducted at 3, 7, 14, and 28 days of moist curing

4.3. Tests

4.3.1. Unconfined Compressive Strength (UCS)

UCS test was carried out as per IS4332 part V [42] on cement-treated ferrochrome slag mixtures. This test was conducted to evaluate the interfacial contact of ferrochrome slag with cement dust matrix in terms of strength. The samples were prepared with heavy compaction effort and compacted in 5 layers in steel cylindrical split molds (100 mm X 200 mm). All UCS samples were demolded after 24 hours of casting for sample retention.

Polyethylene plastic covers were wrapped around the specimens (Fig.3) to prevent moisture loss into the atmosphere after demolding and to allow cement hydration to occur with OMC. The compressive load was applied to the specimens up to failure, and the corresponding failure load was recorded. The average of the three samples was taken as the test value.

Fig.3 Cylindrical test specimens wrapped in polyethylene sheet

4.3.2 Ultrasonic Pulse velocity test (UPV)

The UPV was performed as per IS 516 [43] on cement-treated ferrochrome slag and quarry dust composites. A longitudinal wave was transmitted through the specimen through transducers fixed at one surface and another at the point of defined length. The second transducer, located at a distance of "L," converts the created pulse into electrical energy. The amount of time (t) required for a wave to traverse a predetermined distance, "L," was determined electronically. The velocity of the longitudinal wave through the test specimen was determined by dividing the predetermined length "L" with the corresponding transmission time "t". The quality of cement-stabilized ferrochrome slag and quarry dust composites was evaluated by measuring their wave velocity.

5. Results and Discussion

5.1. Compaction Characteristics

The OMC and MDD of cement-stabilized FS70Q30 and FS60Q40 composites at different cement contents were determined and their compaction curves are presented in Fig.4. From Table 5, the OMC and MDD of FS70Q30 are found to be 6.68% to 7.38% and 2.43g/cc to 2.46g/cc, respectively, for cement contents of 2% - 10%. The OMC and MDD of FS60Q40, for 2-10% cement contents, ranged from 6.33% to 6.81% and 2.387g/cc to 2.424g/cc, respectively. It was observed that the MDD of FS70Q30 mixes was higher than FS60Q40 mixes due to a higher proportion of ferrochrome slag in the FS70Q30 mixes. The overall change in OMC ranged from 6.33 to 7.38%, which shows an insignificant change with an increase in cement content, and these findings agree with previous studies [44,27]. MDD of FS70Q30 and FS60Q40 mixes were found to increase up to 6% cement content due to reduced void ratio, as shown in Table 5. This may also be due to the difference in specific gravities of quarry dust(2.55) and cement(3.11) [45]. As a result, cement being finer than the quarry dust fills the available voids in the mix, thereby increasing the dry density and reducing the void ratio. Cement content above 6% leads to flocculation of mixtures, which causes a slight change in MDD and increased void ratios of cement-treated mixtures [46].

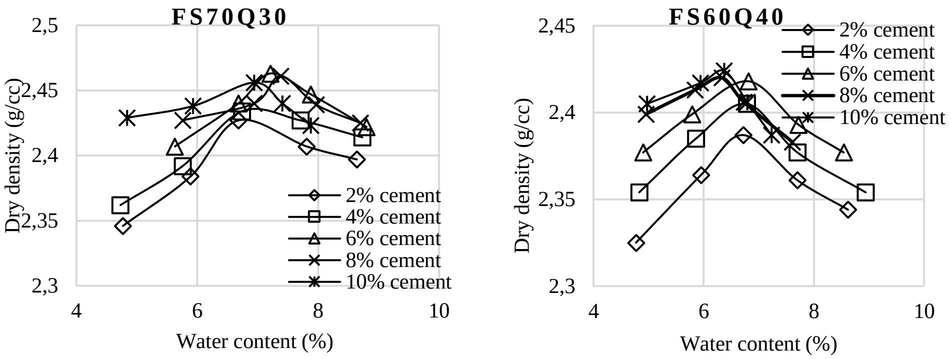


Fig.4 Compaction curves of cement stabilized FS70Q30 and FS60Q40 mixes corresponding to various cement contents

Table 5. Compaction characteristics of FS70Q30 and FS60Q40

Cement content (%)	FS70Q30			FS60Q40		
	OMC (%)	MDD (g/cc)	Void ratio (e)	OMC (%)	MDD (g/cc)	Void ratio (e)
0	6.17	2.392	0.208	6.43	2.368	0.193
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
8	7.38	2.461	0.181	6.33	2.420	0.175
10	6.94	2.456	0.184	6.37	2.424	0.175

5.2. Physical Examination

From visual inspection, it was found that FS60Q40 mixtures has a well–finished surface texture covering all the voids, as shown in Fig.5. The FS60Q40, with sufficient fines, provides good bonding and requires less cement than FS70Q30, with a deficiency of fines [47]. It was seen from Fig.6 that when FS60Q40 mix (with 2% cement content) was held together in our hands, it formed a lump indicating inter-granular bonding of quarry dust with cement, whereas FS70Q30 mix failed to form a lump in the absence of fines.

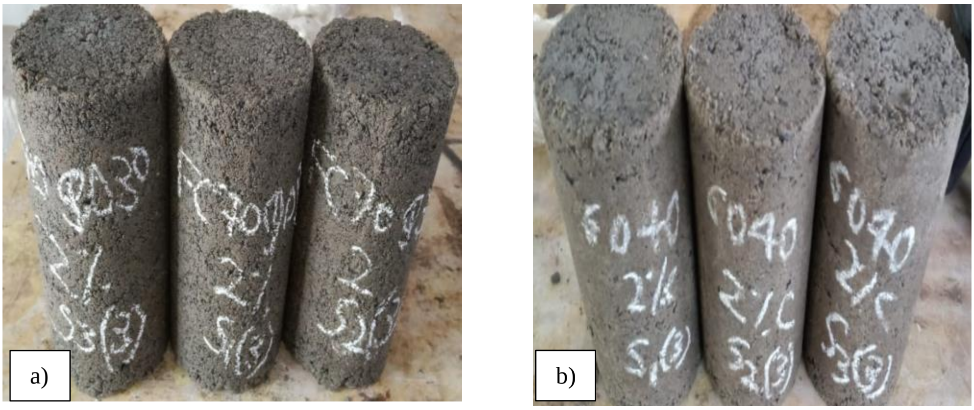


Fig.5 Variation of surface texture a) FS70Q30+2% b) FS60Q40+2%

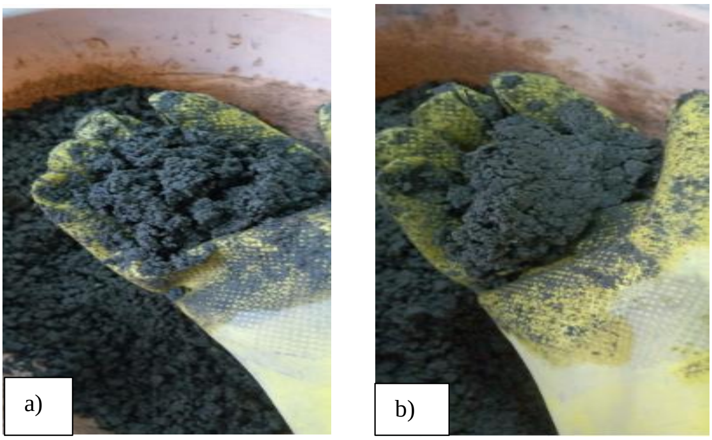


Fig.6 Variation of clump formation a) FS70Q30+2% b) FS60Q40+2%

5.3. Unconfined Compressive Strength (UCS)

The UCS of cement stabilized FS70QD30 and FS60QD40 mixtures corresponding to moist curing periods of 3, 7, 14, and 28 days for various percentages of cement (2-10%) are presented in the form of a bar graph in Fig.7. 3 samples were prepared for each cement content and curing duration (120 specimens). The standard deviations (SD) of the strengths for each cement content were calculated, and their deviation bars are depicted in Fig.7. The overall SD of the mixtures was in the range of 0.03 MPa to 1.47 MPa.

5.3.1 Effect of cement on UCS of the FS70Q30 and FS60Q40 mixes

Experimental results indicated an increase in UCS values with cement content as shown in Fig. 8. An increase in cement content resulted in the densification of the mix due to the gradual filling of pores with cement and more cementitious action[45]. The ferrochrome slag could hardly influence the hydration process as it was less sensitive to water. The high angularity of ferrochrome slag contributed to good interlocking and increased shear strength of the cement-bound mixtures. Therefore, the inclusion of quarry dust in the mixtures provided the necessary fines for the cement hydration to occur effectively. [48,49].

The UCS values at three days of moist curing ranged from 0.859 MPa to 9.904 MPa for the FS70Q30 mix and 1.090 MPa to 10.980 MPa for the FS60Q40 mix. UCS values at seven days of moist curing ranged from 0.946 MPa to 11.178 MPa for the FS70Q30 mix and 1.128 MPa to 12.630 MPa for FS60Q40. UCS values at 14 days of moist curing ranged from 1.689 MPa to 17.480 MPa for the FS70Q30 mix and 1.916 MPa to 20.540 MPa for FS60Q40. UCS values at 28 days of moist curing ranged from 1.989 MPa to 23.850 MPa for the FS70Q30 mix and 2.814 MPa to 24.995 MPa for FS60Q40, indicating a significant increase in strength with the cement content increment. The maximum UCS of 24.995 MPa was reported at 10 % cement content of the FS60Q40 and a minimum UCS of 0.946 MPa at 2% cement content of FS70Q30. The major increase in strength was recorded at 4% cement content of all the mixtures with respect to 2%. Further, it was noticed that the UCS strength of FS60Q40 was between 1.03 to 1.62 times the UCS of FS70Q30 at all cement contents and curing durations. The percentage of voids in the FS60Q40 mix was found to be 3.1 to 4.9% lower than FS70Q30 mix. This reduced void ratio was due to more quarry fines in FS60Q40 providing more significant contact points with cement than in FS70Q30 [50]. This allows for an efficient hydration process due to increased cement contact points, a more solid matrix, and increased strength in FS60Q40. Therefore, for a given cement content, FS60Q40 provided higher compressive strength when compared to FS70Q30.

5.3.2 Effect of curing period on UCS

Fig.7 indicates that the UCS values improve notably with longer curing periods for all mixtures [51, 26] Hydration time plays a crucial role in filling the pores with calcium hydroxide. As the curing period increases, the water available in the pores (OMC) reacts with the cement to form CSH (hardened paste).

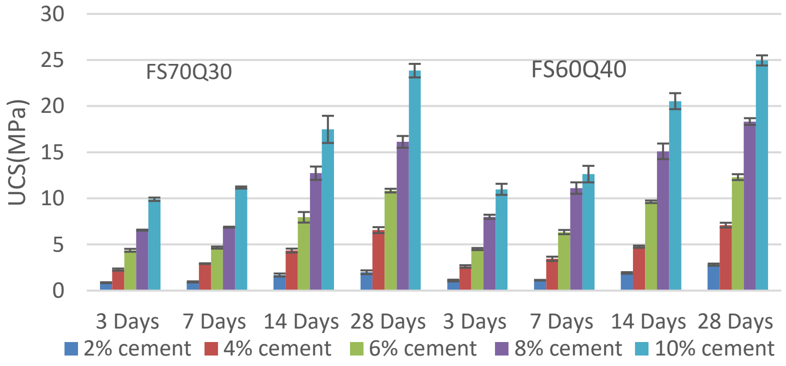


Fig.7 Variation of UCS with curing period

Initially, during compaction, the voids were filled with water (OMC) and un-hydrated cement dust particles. After obtaining the final strength, the voids were filled with hardened paste (CSH). These phenomena can be well noted through the attainment of strength with the curing period. Cement-treated mixtures gained only 34% to 44% of their

28-day UCS strength at 3 days of moist curing. About 42% to 60% of their 28-day UCS strength was achieved in 7 days. During the first 14 days of moist curing, strength was achieved between 66% and 85% of their 28-day UCS strength. IRC-37[52] recommends UCS strength of 7 days as a quick assessment for minimum cement requirement for the sub-base and base course of flexible pavement.

5.3.3. Minimum cement requirement based on UCS

According to IRC 37 [52], the recommended UCS values range from 1.5 to 3.0 MPa for cementitious sub-base and 4.5 to 7 MPa for cementitious base course at 7 days of moist curing. The percentage of cement content requirements for stabilizing ferrochrome slag and quarry dust composites is depicted in Table 3 based on the correlation developed between cement content (C) and UCS. Regression analysis was done to correlate UCS values against different cement contents. It can be observed in Fig.7 that a power function can be set up to assess the relationship between UCS and cement content for FS70Q30 and FS60Q40 mixes. In one of the studies, it was stated that a logarithmic relationship could be developed to correlate cement content and UCS (eq.1) at 28 days of curing [30]. Regression curves, their respective power function equation, and correlation factors are presented in Fig.8.

$$UCS = 6.27 Ln(PC) - 1.898;\ R^2 = 0.965 \qquad (1)\ [30]$$

Where PC is Portland cement and UCS is the unconfined compressive strength of cement-bound ferrochrome slag.

Table 6. Cement requirement for FS70Q30 and FS60Q40 mixes

Moist curing days	**FS70Q30 mix**		**FS60Q40 mix**	
	Cement requirement (%)		Cement requirement (%)	
	Sub-base	Base course	Sub-base	Base course
3	2.95 - 4.67	6.11 - 8.19	2.64 - 4.21	5.58 – 7.58
7	2.69 - 4.30	5.66 – 7.64	2.36 – 3.69	4.80 – 6.39
14	1.88 – 3.02	3.98 – 5.39	1.75 – 2.77	3.64 – 4.88
28	1.60 - 2.54	3.33 – 4.46	1.26 - 2.11	2.84 – 3.94

As seen from the predicted curves, their regression coefficients for cement-treated FS70Q30 and FS60Q40 composites are found to be greater than 0.99. Since the value of the regression coefficient was nearly equal to one, the relationship between UCS and cement content developed from experimental data was significant in evaluating the UCS of cement-treated composites. The mean standard errors of the predicted values for the FS70Q30 mixes at 3, 7, 14, and 28 days were found to be 0.22MPa, 0.461MPa, 0.218MPa, and 0.46MPa. For FS60Q40 mixes, the standard errors were found to be 0.387MPa, 0.821MPa, 0.287 MPa, and 0.094MPa at 3, 7, 14, and 28 days, respectively. The observed standard errors were minimal for all the composites, indicating that the predicted values were close to the experimental observations.

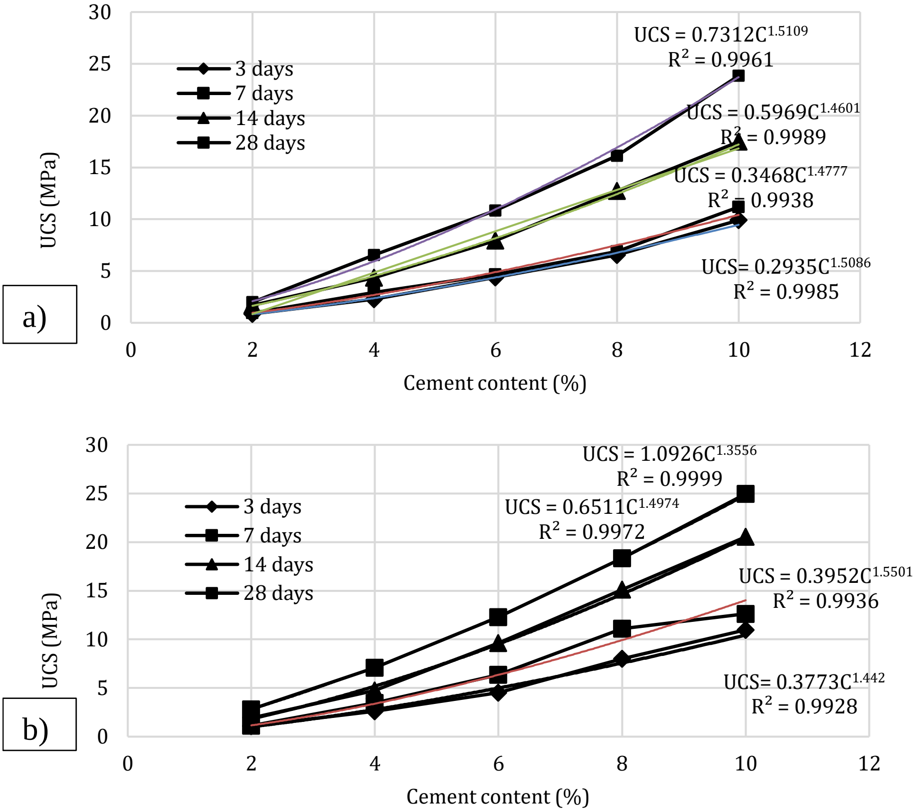


Fig.8 Variation of UCS with cement content a) FS70Q30 b) FS60Q40

Table 3 shows that due to the increased compressive strength of FS60Q40 over FS70Q30, the minimum cement requirement for FS70Q30 was higher than the FS60Q40. The minimum cement requirement for FS70Q30 is 2.7% and 5.7% for use as a sub-base and base course to attain the desired UCS values of 1.5 MPa and 4.5 MPa respectively. Similarly, 2.4% and 4.8% for FS60Q40 to use as sub-base and base courses. The minimum cement requirement for FS60Q40 was about 12-16% lower than that of FS70Q30. Based on seven days of compressive strength, MoRTH recommends a minimum of 2% cement content for the stabilization of sub-base and base courses in flexible pavements. However, from the analysis, the minimum cement content for 7-day UCS was found to be more than 2% as shown in Table 3.

5.4 Ultrasonic Pulse Velocity (UPV)mixes

UPV tests were conducted on cylindrical specimens of 100mm diameter and 200mm height moist cured for 3, 7, 14, and 28 days. The ultrasonic pulse was made to propagate through the cylindrical specimen along the 200mm length of the specimen using transducers positioned at each end of the specimen. 3 samples were prepared for each cement content and curing duration (120 specimens). The standard deviations (SD) of UPV values for each cement content were calculated, and their deviation bars are depicted in

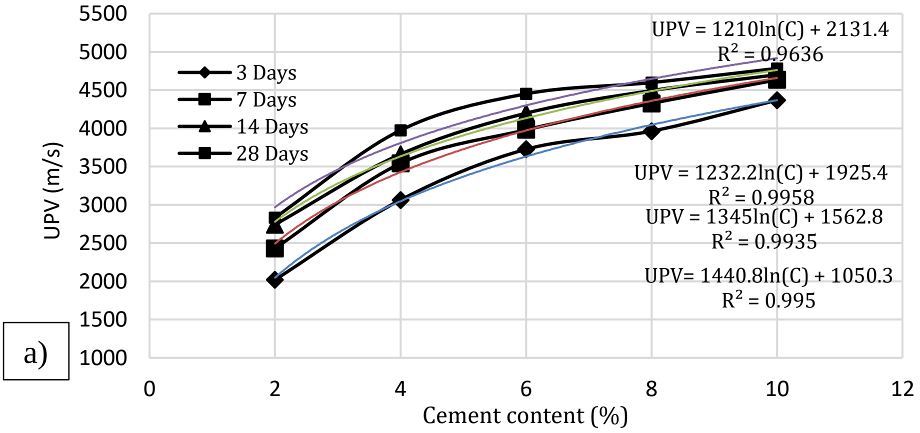
Fig.10. The overall SD of the cement-treated mixtures was found to be between 20.74m/s and 94.32m/s.

5.4.1. Effect of Cement on UPV

UPV values are plotted against the cement contents, as shown in Fig.9. In both FS70Q30 and FS60Q40 mixtures, an increase in UPV value was observed with cement content increment. It can be attributed to the fact that the filling of voids with an increase in cement content and the binding effect of cement [45]. Due to the reduced void ratio up to 6% cement content in both composites, a noticeable increase in UPV is observed. At higher cement contents (8% and 10%), a slight increase in UPV was observed as the cement to be filled exceeded the voids to be filled in the mix. A maximum increase in velocity was observed for 4% cement content with respect to 2% of all mixtures. The logarithmic variation can be set up to assess the relationship between UPV and cement content for FS70Q30 and FS60Q40 mixes, as shown in Fig.9. This relationship was in good agreement with one of the studies eq. 2 at 28 days of curing [30]. There is no noticeable difference between UPV values for the FS70Q30 and FS60Q40 mixes. The UPV values of FS70Q30 are almost identical to those of the FS60Q40 mix.

$$UPV = 1.171Ln(PC) + 1.388;\ R^2 = 0.993 \quad \text{UPV in Km/s} \qquad (2)[30]$$

The UPV values at three days of moist curing ranged from 2021 to 4367 m/s for the FS70Q30 mix and 2136 to 4272 m/s for FS60Q40. For seven days of moist curing, ranged from 2432 to 4634 m/s for the FS70Q30 mix and 2430 to 4412 m/s for FS60Q40. UPV values at 14 days of moist curing ranged from 2742 to 4701 m/s for the FS70Q30 mix and 2889 to 4564 m/s for FS60Q40. UPV values at 28 days of moist curing ranged from 2834 to 4784 m/s for the FS70Q30 mix and 3084 to 4691 m/s for FS60Q40.



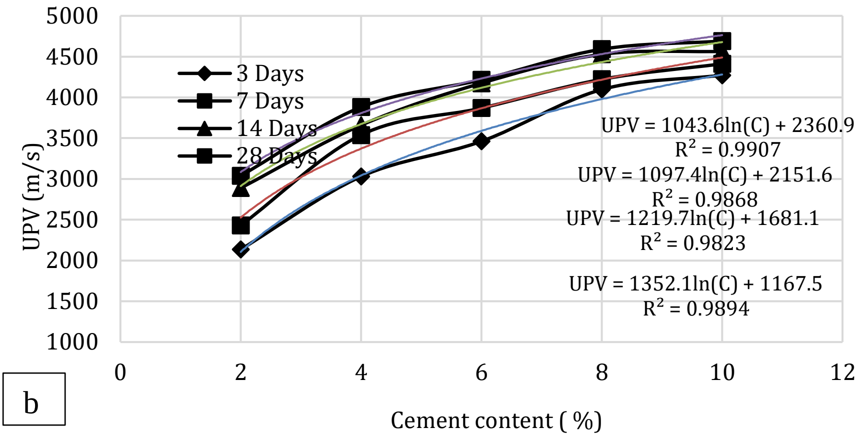


Fig. 9 Variation of UPV with the cement content a) FS70Q30 b) FS60Q4

As seen from the predicted curves, their regression coefficients for cement-treated FS70Q30 and FS60Q40 composites are found to be greater than 0.98. Since the value of the regression coefficient was near to one, the relationship between UPV and cement content developed from experimental data was significant in evaluating the UPV of cement-treated composites. The mean standard errors of predicted values for the FS70Q30 mix were found to be between 45.28m/s and 135.45m/s, and for the FS60Q40 mix, it was between 57.55m/s and 93.01m/s. The observed standard errors were minimal for all the cement composites, indicating that the predicted values were close experimental observations. The UPV values for FS70Q30 for minimum cement contents of 2.7% and 5.7% were found to be 2899 m/s and 3904 m/s, respectively. For FS60Q40, the UPV values corresponding to 2.4% and 4.8% are 2749 m/s and 3595 m/s, respectively.

5.4.2. Effect of Curing Period on UPV

It can be observed (Fig. 10) that the UPV value increased as the curing time of both FS70Q30 and FS60Q40 mixtures increased This could be another sign that the hydration process has occurred, resulting in the densification of the composites with the increase in curing duration. In the early curing periods, relatively low values of UPV were observed due to the entrapped air and water in the voids of the mix. The influence of the entrapped air and undissolved water attenuates the pulse velocity. In the later stages of curing period, the entrapped air and water reduce, solid percolation path occurs due to the development of hydration products. As the hydration process progresses bridging between the particles takes place with a more connected path. This accelerates the UPV in the mixes with increase in curing period. At higher curing periods, the UPV slowly increases and remains stable as the maximum hydration products formed covering most of the voids in the mix. All cement-treated mixes achieved 70.29% to 91.30% of their 28-day curing velocities at 3-day moist curing. For 7-day curing, the velocities achieved ranged from 79.96% to 96.86% of their 28-day curing speeds. Similarly, for 14-day moisture curing, velocities ranging from 92.13% to 99.01% of their 28-day velocities were obtained. A significant improvement in velocities with an increasing curing period was observed for 2% cement-treated mixes when compared to all mixtures.

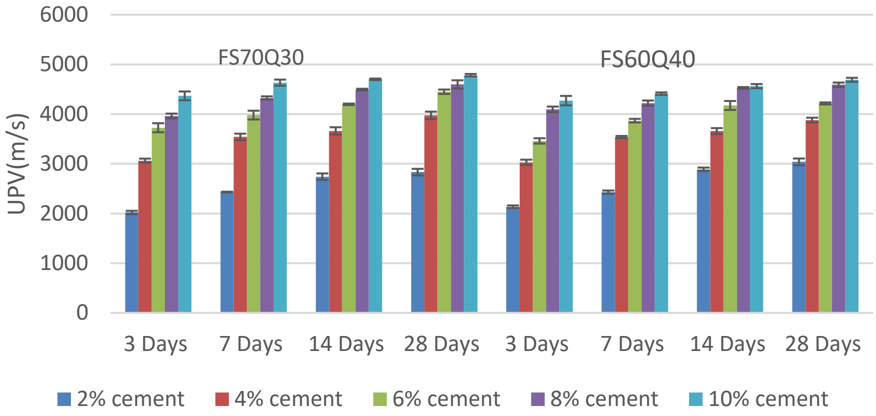
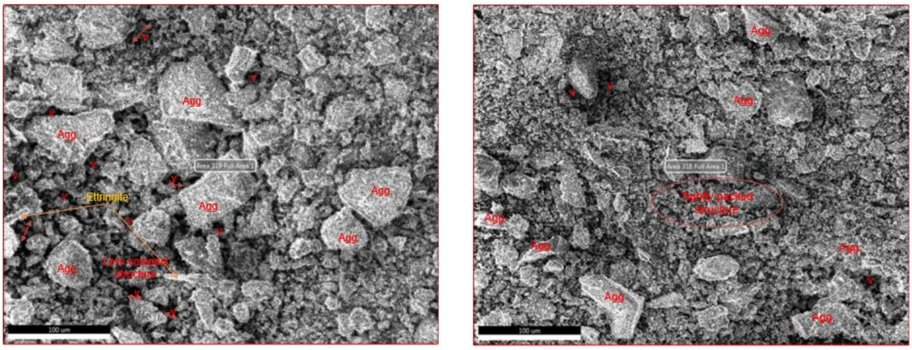


Fig.10 Variation of UPV with curing period

6. Microstructure Analysis

To analyze the behavior of the material at the microscopic level, a scanning electronic microscope (SEM) was conducted on the FS70Q30 and FS60Q40 composites. SEM images are obtained to evaluate pores and hydration products as depicted in Fig. 11. The FS70Q30 has a large number of voids and rod-like crystals (Ettringite) when compared to the FS60Q40. The cement hydration product CSH gel formed around the aggregate (Agg.) can be evident from the two images. FS70Q30 was also observed to be less compact, while the FS60Q40 structure was more closely packed. This can be attributed to the higher strength of the FS60Q40 mix than FS70Q30 for a given cement content.



FS70Q30

FS60Q40

Fig. 11 SEM images at 4% cement contents for both the composites

7. Conclusions

The present study attempts to explore and comprehend the behavior of ferrochrome slag and quarry dust composites upon cement stabilization for sustainable development. The following conclusions are drawn from the study.

- From the particle size analysis, ferrochrome slag(FS) was classified as poorly graded material and has a deficiency of fines below 1.18mm. Hence, quarry dust(Q) was incorporated in different proportions to enhance the gradation of ferrochrome slag to make it suitable as cement-bound layers of flexible pavements. Only FS70Q30 and FS60Q40 mixes were classified as well-graded materials and satisfied the gradation limits specified by the MoRTH.
- The OMC and MDD of the cement-treated mixes were found to be in the range of 6.33 to 7.38% and 2.387 to 2.456g/cc respectively. No appreciable variation in OMC with increasing cement content was found. While MDD increased up to a cement content of 6% due to the filling of voids with cement resulting in a reduced void ratio. However, the addition of cement beyond 6% resulted in flocculation of the mixes thereby increasing the void ratio and subsequent decrease in MDD.
- The high angularity of the ferrochrome slag contributed to the overall strength of the composites, while quarry dust inclusion provided sufficient fines for the cement hydration to occur.
- The unconfined compressive strength (UCS)and ultrasonic pulse velocities (UPV) of the cement-treated composites increased with an increase in cement content. This can be attributed to the gradual filling of voids and the densification of the mixes with increasing cement.
- The UCS of FS60Q40 mixes was found to be 1.03 to 1.62 times higher than the UCS of FS70Q30 mixes. The higher proportion of quarry dust in FS60Q40 mixes over FS70Q30 resulted in a reduced void ratio and enhanced contact area with cement particles. A greater inter-contact surface with cement helps in the effective hydration process, thereby increasing the strength of FS60Q40 mixes.
- The statistical equations developed in the study can be useful in predicting UCS and UPV values for a given cement content. The high correlation factors of the developed equations indicate that the dependency of UCS and UPV on cement content was well established. These equations were also useful for estimating the corresponding cement content for desired UCS values specified by the MoRTH.
- The minimum cement required for use as a cementitious sub-base and base courses was found to be in the range of 2.4% to 2.7% and 4.8% to 5.7% respectively. Due to higher compressive strengths of FS60Q40 mixes, the minimum cement contents required for stabilization was found to be 12-16% lower than FS70Q30 mixes.
- The UCS increased significantly with increasing curing time. The 7-day strengths of the cement-treated mixtures were found to be between 40% and 60% of the 28-day strengths. Longer curing periods were essential for effective cement hydration to attain maximum strength. Even with lower cement contents with prolonged curing periods can help in achieving minimum strength.

- Cement-stabilized ferrochrome slag and quarry dust composites (FS70Q30 and FS60Q40) may be used as cementitious sub-base and base courses in flexible pavements. However, further investigations through durability and field testing need to be carried.

Competing interests

The authors have no relevant financial or non-financial interests to disclose. The corresponding author declares that no funding, grants or any other support was received during the progress of the work and preparation of the manuscript.

References

[1] Dash MK, Patro SK, Rath AK. Sustainable use of industrial-waste as partial replacement of fine aggregate for preparation of concrete–A review. International Journal of Sustainable Built Environment. 2016 Dec 1;5(2):484-516. https://doi.org/10.1016/j.ijsbe.2016.04.006

[2] Ojha PN, Singh A, Singh B, Trivedi A, Kaura P. Recent Research On Iron, Steel, Copper and Ferrochrome Slag For Utilization In Construction Industry.2022 Dec.

[3] Shen H, Forssberg E. An overview of recovery of metals from slags. Waste management. 2003 Jan 1;23(10):933-49. https://doi.org/10.1016/S0956-053X(02)00164-2

[4] Ramachandra Rao S Chapter 8 – Metallurgical Slags, Dust and Fumes.” Waste Management Series 7 2007 Sep: 269-327.

[5] Sairanen M, Rinne M, Selonen O. A review of dust emission dispersions in rock aggregate and natural stone quarries. International Journal of Mining, reclamation and environment. 2018 Apr 3;32(3):196-220. https://doi.org/10.1080/17480930.2016.1271385

[6] Bluvshtein N, Mahrer Y, Sandler A, Rytwo G. Evaluating the impact of a limestone quarry on suspended and accumulated dust. Atmospheric Environment. 2011 Mar 1;45(9):1732-9. 5 https://doi.org/10.1016/j.atmosenv.2010.12.055

[7] Olusegun O, Adeniyi A, Adeola GT. Impact of granite quarrying on the health of workers and nearby residents in Abeokuta Ogun State, Nigeria. Ethiopian journal of environmental studies and management. 2009;2(1).

[8] Sanghamitra B, Reddy CN. Potential of Ferro chrome slag as construction material. Indian Highway. 2017 Jun;45(6):11-7.

[9] Das BB. Characterization of ferrochrome slag as an embankment and pavement material (Doctoral dissertation).

[10] Sinha AK, Havanagi VG, Kanaujia VK. Chrome slag in embankment and pavement construction. Highw. Res. J. 2017:45-54.

[11] Yilmaz M, Kok BV. Effects of ferrochromium slag with neat and polymer modified binders in hot bituminous mix. Indian J Eng Mater Sci. 2009;16(5):310–8. http://hdl.handle.net/11508/8772

[12] Lind BB, Fällman AM, Larsson LB. Environmental impact of ferrochrome slag in road construction. Waste Management. 2001 Jun 1;21(3):255-64. https://doi.org/10.1016/S0956-053X(00)00098-2

[13] Panda CR, Mishra KK, Nayak BD, Rao DS, Nayak BB. Release behaviour of chromium from ferrochrome slag. International Journal of Environmental Technology and Management. 2012 Jan 1;15(3-6):261-74. https://doi.org/10.1504/IJETM.2012.049227

[14] Risk Reduction Engineering Laboratory (US), Center for Environmental Research Information (US). Stabilization/solidification of CERCLA and RCRA wastes: Physical tests, chemical testing procedures, technology screening, and field activities. Center for Environmental Research Information; 1989.

[15] Wang S, Vipulanandan C. Solidification/stabilization of Cr (VI) with cement: Leachability and XRD analyses. Cement and concrete research. 2000 Mar 1;30(3):385-9. https://doi.org/10.1016/S0008-8846(99)00265

[16] Bulut U, Ozverdi A, Erdem M. Leaching behavior of pollutants in ferrochrome arc furnace dust and its stabilization/solidification using ferrous sulphate and Portland cement. Journal of hazardous materials. 2009 Mar 15;162(2-3):893-8. https://doi.org/10.1016/j.jhazmat.2008.05.114

[17] Panda CR, Mishra KK, Panda KC, Nayak BD, Nayak BB. Environmental and technical assessment of ferrochrome slag as concrete aggregate material. Construction and Building Materials. 2013 Dec 1;49:262-71. https://doi.org/10.1016/j.conbuildmat.2013.08.002

[18] Hang M, Wang J, Zhou X, Sun M. Design and Study of Physical and Mechanical Properties of Concrete Based on Ferrochrome Slag and Its Mechanism Analysis. Buildings. 2023 Jan;13(1):54. https://doi.org/10.3390/buildings13010054

[19] Gericke WA. Environmental solutions to waste products from ferrochrome production. Proceedings of the 8th International Ferroalloys. 1998 Jun 7:51-8.

[20] Acharya PK, Patro SK. Utilization of ferrochrome wastes such as ferrochrome ash and ferrochrome slag in concrete manufacturing. Waste Management & Research. 2016 Aug;34(8):764-74. https://doi.org/10.1177/0734242X1665

[21] Zelić J. Properties of concrete pavements prepared with ferrochromium slag as concrete aggregate. Cement and Concrete Research. 2005 Dec 1;35(12):2340-9. https://doi.org/10.1016/j.cemconres.2004.11.019

[22] Rajashekar K, Reddy CS. An experimental study on use of ferrochrome slag aggregate in concrete making. ICI Journal. 2015 Jan;15(4):25-9.

[23] Mallick T, Mishra SP, Nayak Sipalin SM. Part substitute of river sand by Ferrochrome slag in cement concrete: Industrial waste disposal. Journal of Xidian University. 2020;14(4).

[24] Sheen YN, Huang LJ, Sun TH, Le DH. Engineering properties of self-compacting concrete containing stainless steel slags. Procedia engineering. 2016 Jan 1;142:79-86. https://doi.org/10.1016/j.proeng.2016.02.016

[25] Sargand SM, Khoury I, Gray J, Al-Jhayyish A. Incorporating chemical stabilization of the subgrade in pavement design and construction practices. ORITE; 2014 Oct.

[26] Hossain AS, Hoque AM, Zaniewski JP. Stabilization of alluvial soils with cement and cement-rice husk ash blend for low-volume road construction in Bangladesh. Transportation Research Record. 1991(1291). http://onlinepubs.trb.org/Onlinepubs/trr/1991/1291vol1/1291-071.pdf

[27] Kasu SR, Manupati K, Muppireddy AR. Investigations on design and durability characteristics of cement treated reclaimed asphalt for base and subbase layers. Construction and building materials. 2020 Aug 20;252:119102. https://doi.org/10.1016/j.conbuildmat.2020.119102

[28] Chakravarthi S, Boyina A, Singh AK, Shankar S. Evaluation of cement treated reclaimed asphalt pavement and recycled concrete pavement bases. International Journal of Pavement Research and Technology. 2019 Nov;12:581-8. https://doi.org/10.1016/j.conbuildmat.2020.119102

[29] Xuan DX, Molenaar AA, Houben LJ. Evaluation of cement treatment of reclaimed construction and demolition waste as road bases. Journal of Cleaner Production. 2015 Aug 1;100:77-83. https://doi.org/10.1016/j.jclepro.2015.03.033

[30] Yilmaz A, KARAŞAHİN M. Compressive strength of cement-bound base layers containing ferrochromium slag. Turkish Journal of Engineering and Environmental Sciences. 2013 Oct 1;37(3):247-58.

[31] Kambole C, Paige-Green P, Kupolati WK, Ndambuki JM. Ferrochrome slag aggregate: physical-chemical characteristics and potential use in lightly cemented road bases. World Journal of Engineering. 2023 Jan 11;20(1):93-102. https://doi.org/10.1108/WJE-12-2020-0666

[32] Eze-Uzomaka OJ, Agbo D. Suitability of quarry dust as improvement to cement stabilized-laterite for road bases. Electronic Journal of Geotechnical Engineering. 2010;15:1053-66.

[33] Sabat AK, Bose B. Improvement in geotechnical properties of an expansive soil using fly ash -quarry dust mixes. Electron J Geotech Eng. 2013;18 Q(January 2013):3487–500.

[34] Sudhakar S, Duraisekaran E, Dilli Vignesh G, Kanna GD. Performance evaluation of quarry dust treated expansive clay for road foundations. Iranian Journal of Science and Technology, Transactions of Civil Engineering. 2021 Dec;45:2637-49. https://doi.org/10.1007/s40996-021-00645-4

[35] Priyankara NH, Wijesooriya RM, Jayasinghe SN, Wickramasinghe WR, Yapa ST. Suitability of quarry dust in geotechnical applications to improve engineering properties. Engineer: Journal of the Institution of Engineers, Sri Lanka. 2009 Jul 27;42(3).

[36] Qamhia II, Tutumluer E, Ozer H, Shoup H, Beshears S, Trepanier J. Evaluation of chemically stabilized quarry byproduct applications in base and subbase layers through accelerated pavement testing. Transportation Research Record. 2019 Mar;2673(3):259-70. https://doi.org/10.1177/0361198118821099

[37] IS:2386- Part I. Method of test for aggregate for concrete. Part I - Particle size and shape. Indian Stand. 1963;(Reaffirmed 2002).

[38] IRC SP 89 part-I. Guidelines for Soil and Granular Material Stabilization Using Cement, Lime & Fly Ash. Indian Roads Congr. 2010;

[39] MoRTH. Specifications for Road and Bridge Work. Indian Roads Congress. 2013. p. 1–883.

[40] Ajay CH, Rani KD. Ferrochrome Slag characterization and its compatibility with Quarry dust in Flexible pavement. InIOP Conference Series: Earth and Environmental Science 2022 Mar 1 (Vol. 982, No. 1, p. 012008). IOP Publishing.

[41] IS: 4332 (Part-3). Test for Determination of Moisture Content–Dry Density Relation for Stabilized Soils Mixtures. Bur Indian Stand. 2010;

[42] IS: 4332 (Part-V) 1970 (Reaffirmed 1995). Method for Determination of Unconfined Compressive Strength Of Stabilized Soils. Bur Indian Stand New Delhi, India. 2010.

[43] IS 516 (part5/Sec 1). Method for Determination of Non-destructive testing of concrete. Bur Indian Stand New Delhi, India 2018.

[44] Prasad AC, Reddy CS. The Potential of Cement Stabilized Gravelly Soils as Construction Material. InProc. of Indian Geotechnical Conference-2011, Kochi, India 2011 Dec 15 (pp. 493-496).

[45] Guotang Z, Wei S, Guotao Y, Li P, Degou C, Jinyang J, Hao H. Mechanism of cement on the performance of cement stabilized aggregate for high speed railway roadbed. Construction and Building Materials. 2017 Jul 30;144:347-56. https://doi.org/10.1016/j.conbuildmat.2017.03.194

[46] Mustaque Hossain AS. Cement and cement-rice husk ash stabilization of selected local alluvial soils (1986).

[47] Portland Cement Association. Soil-cement construction handbook. Portland Cement Assn; 1979.

[48] Ashtiani RS, Little DN. Acceptability criteria for high fines content aggregate pavement layers. 2007 Dec 31.

[49] Puppala AJ, Saride S, Sirigiripet SK, Williammee R, Dronamraju VS. Evaluation of cemented quarry fines as a pavement base material. InGeoCongress 2008: Geotechnics of waste management and remediation 2008 (pp. 312-319).

[50] Huddleston IJ. Cement stabilization of poor quality national forest bedrock materials for road construction. dessertation Work. 1978;(June):1–191

[51] Fedrigo W, Núñez WP, López MA, Kleinert TR, Ceratti JA. A study on the resilient modulus of cement-treated mixtures of RAP and aggregates using indirect tensile, triaxial and flexural tests. Construction and Building Materials. 2018 May 20;171:161-9. https://doi.org/10.1016/j.conbuildmat.2018.03.119

[52] IRC 37. Guidelines for the Design of Flexible Pavements. Indian Roads Congr 53. Delhi, India 2018.