Utilization of Quantum Electric Arc Furnace (QEAF) and Ladle Refining Furnace (LRF) slag Generated in GPH ISPAT

A Research Project Funded by GPH Ispat

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Implemented by
Materials Research Center (MRC)
Bangladesh University of Engineering and Technology (BUET)
Dhaka- 1000, Bangladesh

Preamble

The research project titled "Utilization of Quantum Electric Arc Furnace (QEAF) and Ladle Refining Furnace (LRF) slag generated in GPH Ispat," was funded by GPH Ispat, Bangladesh. This research was conducted under the provision of the "Memorandum of Agreement" signed between GPH Ispat and the Materials Research Centre (MRC), Bangladesh University of Engineering and Technology (BUET), Dhaka.

The research project proposed to study the nature of the Quantum Electric Arc Furnace (QEAF) and Ladle Refining Furnace (LRF) generated in GPH Ispat in the process of its utilization in the construction sector. Reuse of this industrial waste that is being generated in an ever-increasing volume will be financially rewarding for the industry. The utilization of this slag would also help maintain a healthy environment. The project was proposed for one years. The project was implemented by an expert team of teachers/researchers and the team members delicately performed their well-defined responsibilities with active cooperation with the Principal Investigator throughout the project implementation period.

Dr. Fahmida Gulshan, Professor, Department of Materials and Metallurgical Engineering and coordinator of Materials Research Center, BUET worked as the principal investigator (PI) of the project. Dr. Md. Muktadir Billah, Associate Professor, Department of Materials and Metallurgical Engineering of BUET and Dr. Raquib Ahsan, Professor, Department of Civil Engineering, BUET worked as co-principal investigators (Co-PIs) of this project. Four Research Assistants (graduates of metallurgical/materials and civil engineering) worked wholeheartedly for the project implementation. They conducted necessary tests and prepared the final report according the suggestions of the PI and Co-PIs.

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EXECUTIVE SUMMARY

Introduction

Slag is the main by-product generated during iron and crude steel production. The nature and composition of slag depend on the type of steel made and the raw materials used for steel making. Over the past decades, both the types of steel and the quantity of steel produced have increased. Consequently, slag is more diversified in composition and nature generating higher volumes. Investigations have been directed to reduce the quantity of slag generation, recover value materials contained in it and find suitable applications for this slag. Slag can be used for many valuable applications. When it is electric arc furnace slag, the composition is different than that of the induction furnace slag. In this case application of this slag can be different and especially treating the slag is quite different due to having different chemical composition. In densely populated countries like Bangladesh, the sustainable use of slag can contribute to natural resource savings, reduction of energy consumption and CO_2 emissions. Bangladesh consumes more than 7 million tons of steel per annum and per capita steel consumption is 45 kilograms. More than 400 steel mills of different categories and sizes currently produce steel in Bangladesh. With the progress of economy, the per capita consumption of steel and hence the production of steel in Bangladesh will increase leading to the generation of higher volumes of slag. About 900000 metric tons of steelmaking slag is generated in Bangladesh. The current utilization rate of steel slag in Bangladesh is far behind the developed countries like USA, Japan, German and France, of which the rates have been close to 100%. In these developed countries, 50% of slag has been used for the road project directly, with the remaining part for sintering and iron-making recycling in plant.

In Bangladesh most of the steel making plants dump these solid wastes only for landfill purpose. Due to land scarcity, landfill will no longer be the major methods for solid waste management. Only in recent years there has been some concern in the steel sector regarding the management of the ever-increasing amount of slag. Less scientific utilization of such slag in concrete structures are being attempted.

GPH ISPAT is one of the leading steel industries in Bangladesh which currently produce steel using latest Quantum Electric Arc Furnace (QEAF) technology followed by ladle refining. So GPH Ispat is producing huge amount of slag annually. Proper study is essential to make best use of this slags produced in GPH Ispat. This is not only to find some application, but most importantly it will be harder and harder to manage the large amount of slag anywhere else. The ingredients of these slags are similar to those of natural aggregates, the exact composition is however different and varied. There is enough indication that such slag can be converted into or incorporated in building materials and thus help manage the slag generated in GPH Ispat at the same time this will help reduce CO_2 emission while producing large quantity of steel from a leading steel industry GPH Ispat.

This study examined the possible utilization of QEAF and LRF slags produced in GPH Ispat, in some useful products primarily used in the construction sector. The utilization can be summarized into four segments. Utilization in cement, concrete, flexural pavement, and concrete block. Chemical characterization of slags was conducted before using them as an additive in cement production, and the mechanical properties of slag were determined before using them as aggregates in concrete and flexible pavement. The objectives are as follows:

1. Study the physical, chemical and mechanical properties of QEAF and LRF slags produced in GPH Ispat.
2. Investigate possible utilization of QEAF and LRF slags in the production of Cement
3. Determine optimum percentages of replacement by volume of coarse and fine aggregate in concrete by QEAF and LRF slag.
4. Observe the performance of QEAF slag in partial replacement of coarse aggregate in Flexible Pavement
5. Investigate possible utilization of QEAF and LRF slag in the production of Concrete Block

Figure F-1 is the methodology followed in this project. Steelmaking slag, both QEAF and LRF slags, were collected from GPH steel plants. Experiments were carried out to evaluate the effects of replacing natural aggregates (coarse and fine) by slag (QEAF and LRF) on concrete, cement, flexible pavement, and concrete blocks and observing their strength and other required properties.

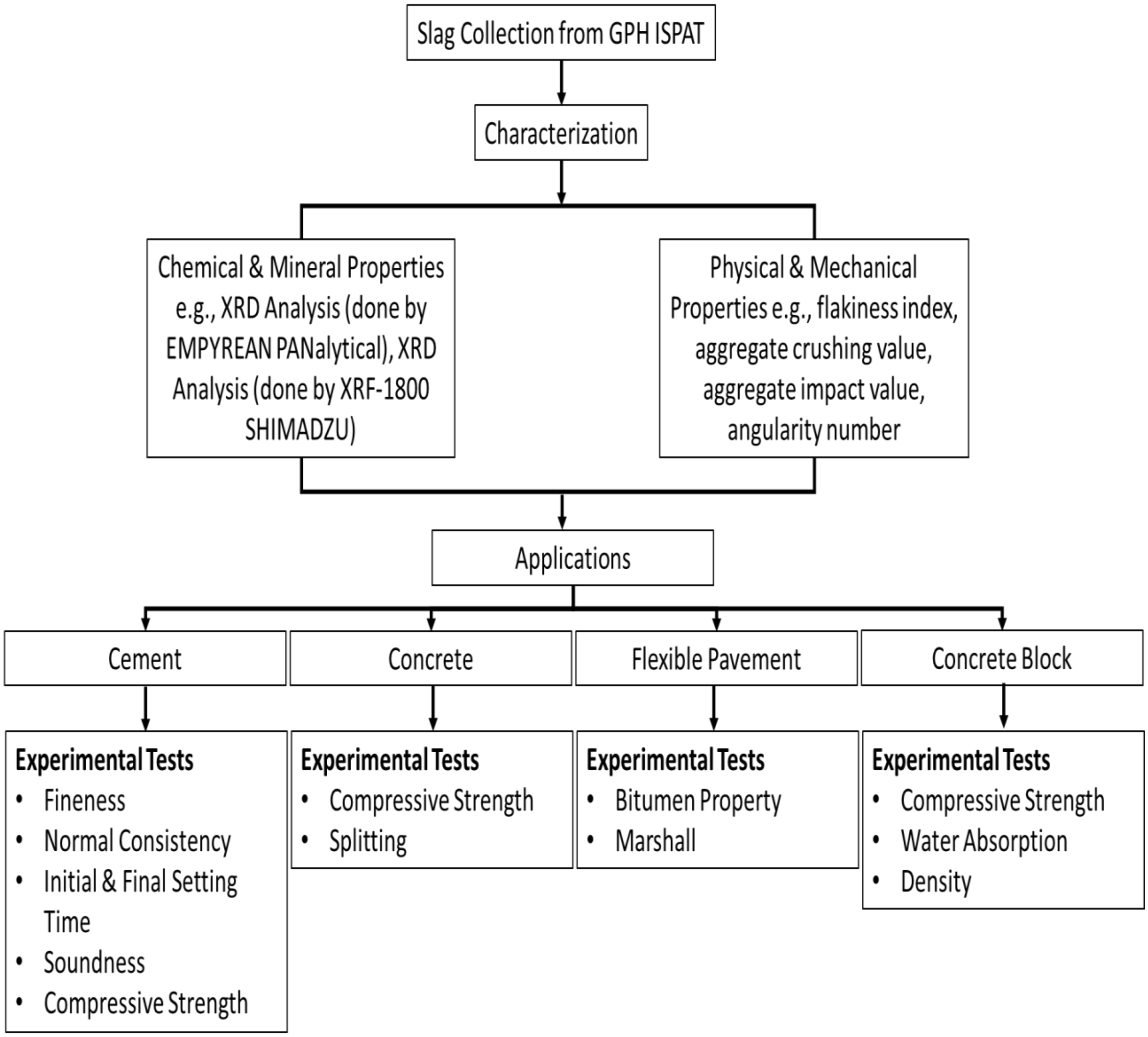


Figure F-1: Flowchart of the methodology

Characterization of Slag

The QEAF Samples were received from GPH Ispat in two sizes; namely, 3/4-inch downgrade and 1/5-inch downgrade. QEAF slag is a stable and hard form of slag and can be investigated both as coarse aggregates and fine aggregates. But LRF slag is like a fine powder form and cannot be investigated as coarse aggregate replacement.

X-Ray Diffractometric (XRD) analysis was performed for both slags. Wustite (FeO) and magnettite (Fe_3O_4) phases are predominant in the x-ray diffraction pattern of QEAF slag. Sodium aluminosilicate ($NaAlSiO_4$), Quartz (SiO_2), Larnite (Ca_2SiO_4) and Hematite (Fe_2O_3) are other minor mineral phases present. For LRF slag, Belite (C_2S), Alite (C_3S) are major phases while Tricalcium aluminate (C_3A), Calcite ($CCaO_3$), Periclase (MgO), Portlandite ($Ca(OH)_2$), Ferrite (C_4AF), Gehlenite (C_2AS), and Calcium sulfoaluminate (CSA) are minor phases present in the slag.

X-Ray Fluorescence (XRF) test of the raw QEAF and LRF slags were also performed (Table T-1). It is found that the major components of QEAF slag are: Fe_2O_3, CaO and SiO_2. Significant amounts of Al_2O_3, MnO and MgO are also present. The major components of LRF slag are: CaO and SiO_2. Significant amounts of Al_2O_3, Fe_2O_3 and MgO are also present.

Table T-1: XRF analysis of QEAF and LRF slag

Composition	QEAF Slag		LRF Slag	
	Reported by GPH (2022)	XRF (BUET)	Reported by GPH (2022)	XRF (BUET)
Fe_2O_3%	11-36	31	0-4	4
SiO_2%	8-17	17	14-36	23
Al_2O_3%	5-11	5	3-13	2
CaO%	18-33	31	40-64	59
MgO%	7-20	6	3-20	5
MnO%	4-9	4	0-2	1
SO_3%	<1	<1	0-2	1
Cr_2O_3%	1-4	2	<1	<1
P_2O_5%	<1	<1	<1	<1

Metallic iron content in slags were also determined by wet analysis method, it was found from the experiment that the QEAF slag contain 2.23% metallic iron and LRF slag contain 1.12% metallic iron.

Utilization of slag in cement production

QEAF and LRF slags were used in clinker in different percentages to determine the optimum percentages of clinker replacement in cement production. Table T-2 represents the mix design for clinker replacing by both QEAF and LRF slag of GPH Ispat and Table T-3 represents the tests performed of the prepared samples.

Table T-2: Mix design for cement production

Type of mixer	Serial No.	Clinker wt%	Gypsum wt%	LRF Slag wt%	QEAF Slag wt%	Total wt%
No addition of slag	S-1	97	3	-	-	100
Addition of LRF slag	S-2	92	3	5	-	100
	S-3	87		10		
	S-4	82		15		
	S-5	77		20		
	S-6	72		25		
	S-7	67		30		
Addition of QEAF slag	S-8	92	3	-	5	100
	S-9	87			10	
	S-10	82			15	
	S-11	77			20	
	S-12	72			25	

Table T-3: Tests performed for cement production

Tests Performed	Standard
Fineness test	ASTM C204-11
Normal Consistency test	ASTM C187-11
Initial and final setting time of cement	ASTM C191-08
Soundness test: Expansion of Cement Mortar Bars	ASTM C1038-18
Soundness test: Le-Chatelier accelerated test	BS 4550: Part 3
Compressive Strength test	ASTM C150-18
Loss On Ignition	EN 197-1
Free Lime Test	ASTM C150

a) The XRF results show that the chemical composition of both QEAF and LRF slags is very similar to the chemical compositions of clinker used in cement production; except that QEAF has higher percentages of Iron (Fe) oxide than the clinker and the LRF slag.

b) Normal consistency, initial and final setting time, and soundness properties of cement produced by replacing different percentages of clinker with both QEAF and LRF slags showed similar behavior as OPC cement meeting the respective standard.

c) The compressive strength of the mortar produced with cement replacing 5% clinker by LRF showed the highest value of 40.86 MPa and cement replacing 5% clinker by QEAF showed the highest value of 40.60 MPa. Also, all of the samples meet the minimum standard value for OPC cement according to ASTM C150-18. Figure F-2 and F-3 represents the compressive strength results.

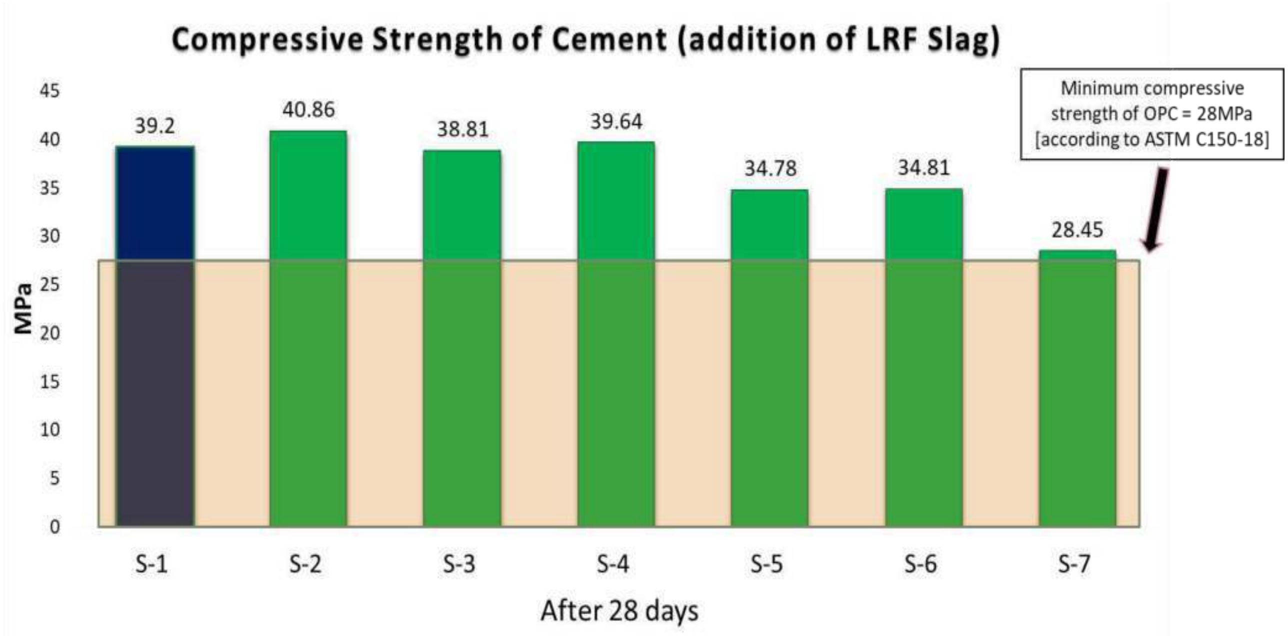


Figure F-2: Compressive strength result for clinker replaced by LRF slag

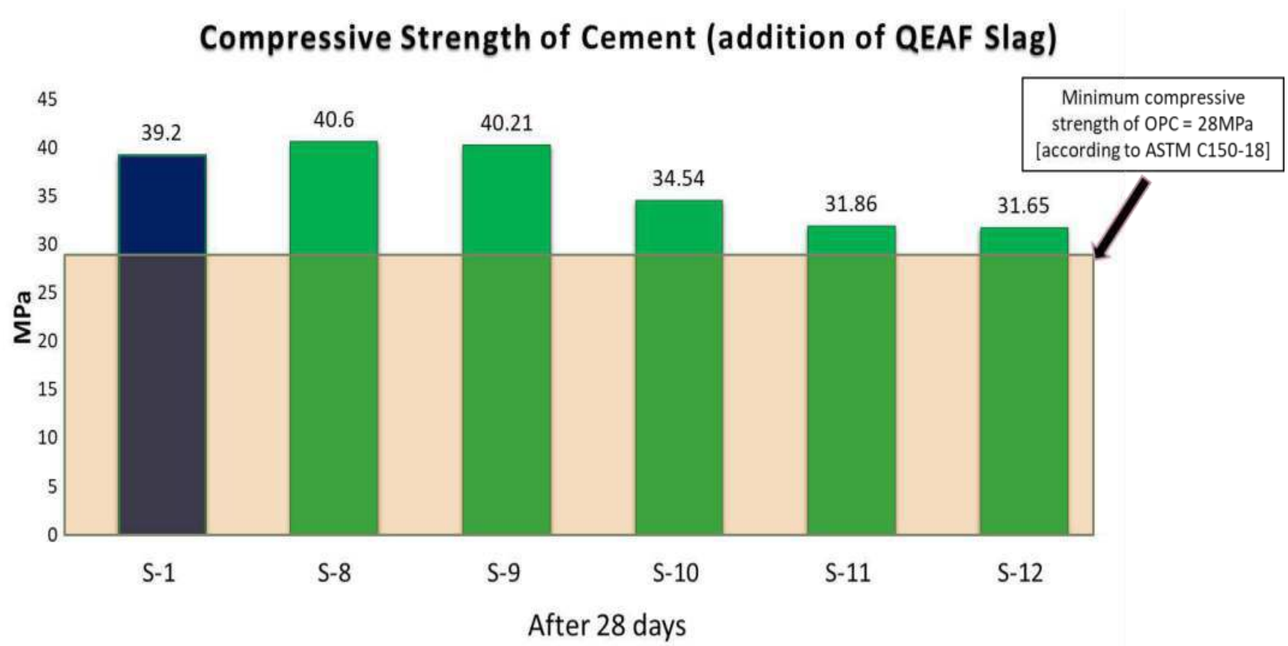


Figure F-3: Compressive strength result for clinker replaced by QEAF slag d)

Test	15% LRF slag	10% QEAF slag	Standard
Loss on ignition	3.47	2.85	meets EN 197-1
Free lime content	1.93	1.12	meets ASTM C150

e) It can be said that 15% LRF slag and 10% QEAF slag can be added to clinker without hampering the traditional cement clinker performances.

Further investigation may be conducted regarding the addition of more gypsum to the existing formula. Additionally, the inclusion of granulated blast furnace slag in conjunction with the desired combination of samples warrants exploration with respect to the strength and other properties of slag cement. To optimize the utilization of slag in cement production, it is recommended to decrease the percentage of iron in QEAF slag to improve overall output. Comprehensive analyses may be conducted to evaluate the long-term impact and physical properties of the final product to determine the optimal combination and maximize environmental sustainability while ensuring longevity.

Utilization of slag as replacement of coarse and fine aggregates in concrete

For the utilization of slags in concrete, optimum percentage of coarse aggregate replacement by QEAF slag, and optimum percentage of fine aggregate replacement by both QEAF and LRF slag were studied. Table T-4 represents the tests performed and Table T-5 represents the mix design for the experiments. Concrete mix ratio considered for cement, fine aggregates and coarse aggregates was 1:1.5:3; and water cement ratio was 0.45. The whole experiment was done in two steps. For the first step experiment, replacement of coarse aggregates and fine aggregates were done individually. In the second step, replacement of fine and coarse aggregates was done combinedly. Compressive strength tests on cylinder sample were done at 7, 14 and 28 days.

The concrete produced by replacing coarse aggregate and fine aggregate by QEAF slag met the minimum required compressive strength at 28 days. According to ASTM C39, minimum 28-day compressive strength should be 25 MPa (3626 psi). The compressive strength of concrete replaced by 80% of QEAF slag as coarse aggregate showed the highest strength of 4900 psi, Compressive strength of concrete replaced by 10% of QEAF slag as fine aggregate showed the highest strength of 4030 psi at 28 days of curing. Figure F-4 and F-5 represents the compressive strength of concrete replaced by QEAF slag.

Table T-4: Tests performed on aggregates and concrete

SI NO.	Performed Test	Standard	Sample Description
Aggregate Mechanical Property Test			
1	Angularity Number Test	BS 812	Coarse Slag of ¾" downgrade size
2	LA Abrasion Test	ASTM C131-89	
3	Unit Weight	ASTM C29	
4	AIV	BS 812	
5	ACV	BS 812	
6	TFV	BS 812	
7	Flakiness Index	BS 812	
8	Elongation Index	BS 812	
9	Absorption Capacity	ASTM C127	
10	Bulk Specific Gravity	ASTM C127	
Fresh Concrete			
11	Slump Value Test	ASTM C143	Fresh Concrete
Hardened Concrete			
12	Compressive Strength	ASTM C39/C39M-21	4"x8" Cylinder
13	Splitting Strength	ASTM C496	4"x8" Cylinder

Table T-5: Mix design for concrete

Mix No.	Slag Type	Stone Chips (% vol^{m})	Sand (% vol^{m})	Slag (Coarse) (% vol^{m})	Slag (Fine) (% vol^{m})	W/C ratio
Mix with no slag						
1	-	100	100	0	0	0.45
First Step Experiment						
2	QEAF slag (Coarse)	40	100	60	0	0.45
3		20	100	80	0	
4		0	100	100	0	
5	QEAF slag (Fine)	100	90	0	10	
6			80		20	
7			70		30	
8			60		40	
9			50		50	
10	LRF slag	100	90	0	10	0.45
11			80		20	
12			70		30	
13			60		40	
14			50		50	
Second Step Experiment						
15	QEAF slag (Coarse and Fine)	20	95	80	5	0.45
16		20	90	80	10	
17		20	85	80	15	
18		0	95	100	5	
19		0	90	100	10	
20		0	85	100	15	

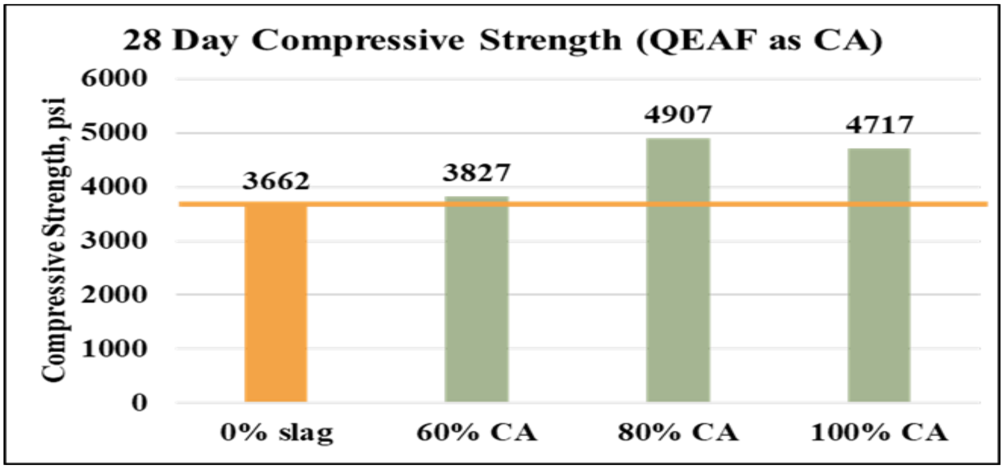


Figure F-4: Compressive strength of concrete CA replaced by QEAF slag

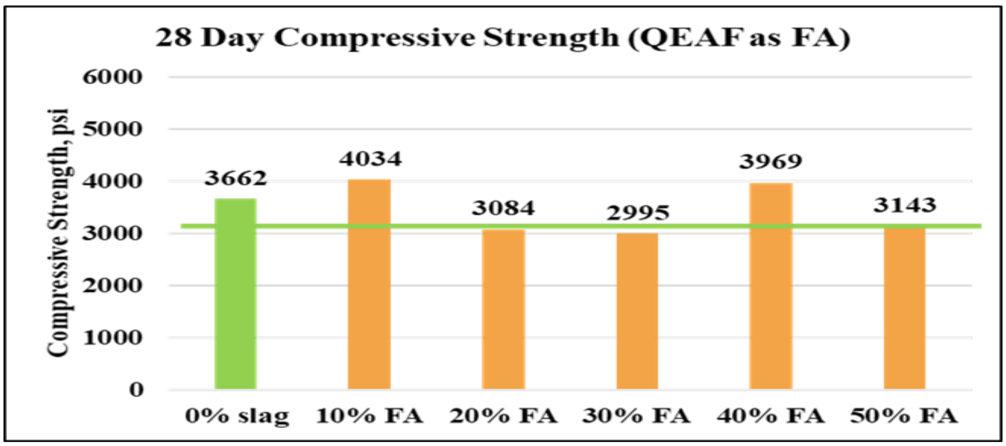


Figure F-5: Compressive strength of concrete FA replaced by QEAF slag

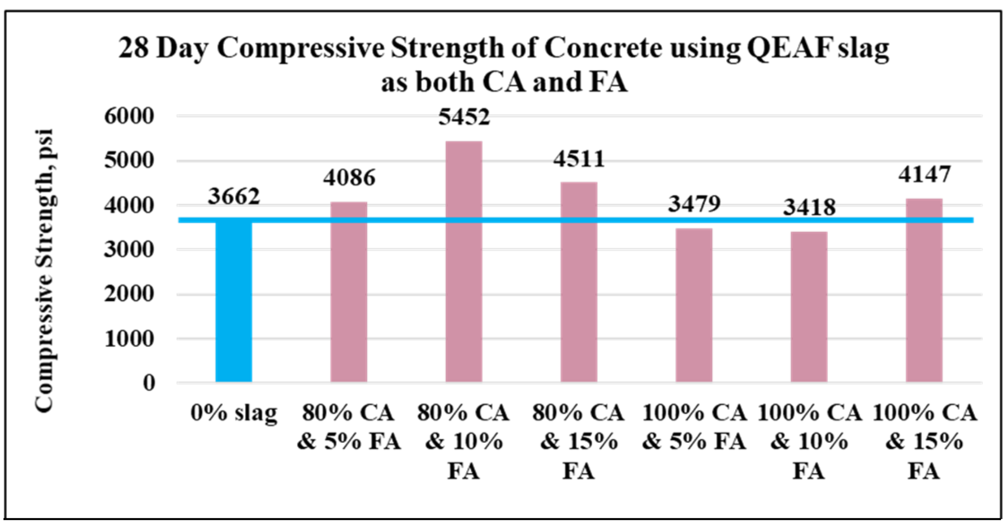


Figure F-6: Compressive strength for both CA and FA replaced by QEAF slag

c) Figure F-6 represents the result for compressive strength when both CA and FA were replaced by QEAF slag.

d) Compressive strength of concrete by partially replace fine aggregates by LRF slag was always less than the standard concrete strength (Figure F-7). Hence, LRF slag is not recommended to use as fine aggregate replacement in concrete.

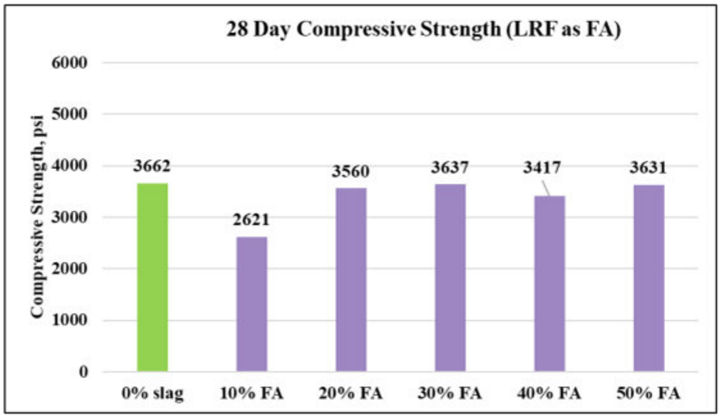


Figure F-7: Compressive strength for concrete for FA replaced by LRF slag

e) The splitting tensile strength for concrete produced with both QEAF and LRF slag showed increasing tensile strength due to adding slags.

Effect of atmosphere or the environment on concrete structure using partial replacement of QEAF slag aggregate can be studied. Corrosion test on raw QEAF slag can be done by simulating different temperature and environmental conditions in the laboratory. Life Cycle Assessment (LCA) of using as coarse aggregate is recommended.

Utilization of slag as coarse aggregate replacement in flexible pavement

QEAF coarse slag was utilized in wearing course of flexible pavement. Property tests for bitumen used in this experiment were done, and mechanical properties of the slag aggregate were also done before using them as coarse aggregate in this experiment. A total of six Marshall tests were done by replacing 20 to 60 percentages of coarse aggregates by QEAF slag. Table T-6 summarized the tests performed on bitumen, QEAF slag and pavement. Table T-7 represents the mix design for the Marshall tests using QEAF slag.

Table T-6: Tests performed on bitumen, CA and pavement

SI NO.	Performed Test	Standard	Sample Description
Bitumen Property Test			
1	Specific Gravity	AASHTO T43	Bitumen
2	Loss on Heating	AASHTO T47	
3	Penetration Test	AASHTO T49	
4	Softening Point Test	AASHTO T53	
5	Ductility	AASHTO T51	
6	Flash and Fire Point	AASHTO T48	
Aggregate Mechanical Property Test			
1	Angularity Number Test	BS 812	Coarse Slag of 1" downgrade size
2	LA Abrasion Test	ASTM C131-89	
3	Unit Weight	ASTM C29	
4	AIV, ACV, TFV	BS 812	
7	Flakiness & Elongation Index	BS 812	
9	Absorption Capacity and Bulk Specific Gravity	ASTM C127	
Hot Mix Asphalt (HMA) Pavement			
11	Marshall Test	ASTM D6927	4"x2.5" Cylinder

Table T-7: Mix design for Marshall test

Sample ID	Stone Chips (kg)	QEAF Slag	Bitumen
Standard	1155	0	4%, 4.5%, 5%, 5.5%, 6%
20% Replacement	925	231	
30% Replacement	809	346	
40% Replacement	693	462	
50% Replacement	578	578	
60% Replacement	462	693	

a) Unit weight increased up to 50% coarse aggregate replacement by slag.

b) Air void in the samples remained within the range of 3 to 5% for up to 50% coarse aggregate replacement by slag; but for 60% aggregate replacement, the air void increased to 15% exceeding the limit of 3-5%. Figure F-8 shows the result for air void in different mixtures.

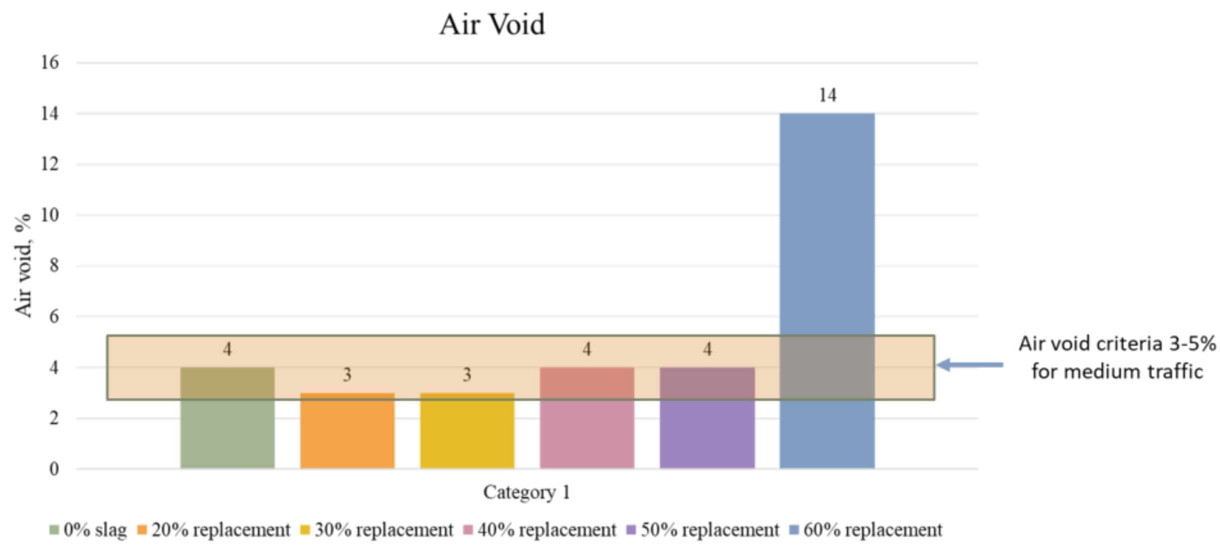


Figure F-8: Result for air void

c) Stability value indicates the strength of the wearing coarse. For 20 to 40% replacement, the stability values were higher than the standard batch. For 30% replacement of coarse aggregate by QEAF slag, the stability value was highest. For 50% replacement of coarse aggregate stability was lowest. Figure F-9 shows the result for stability.

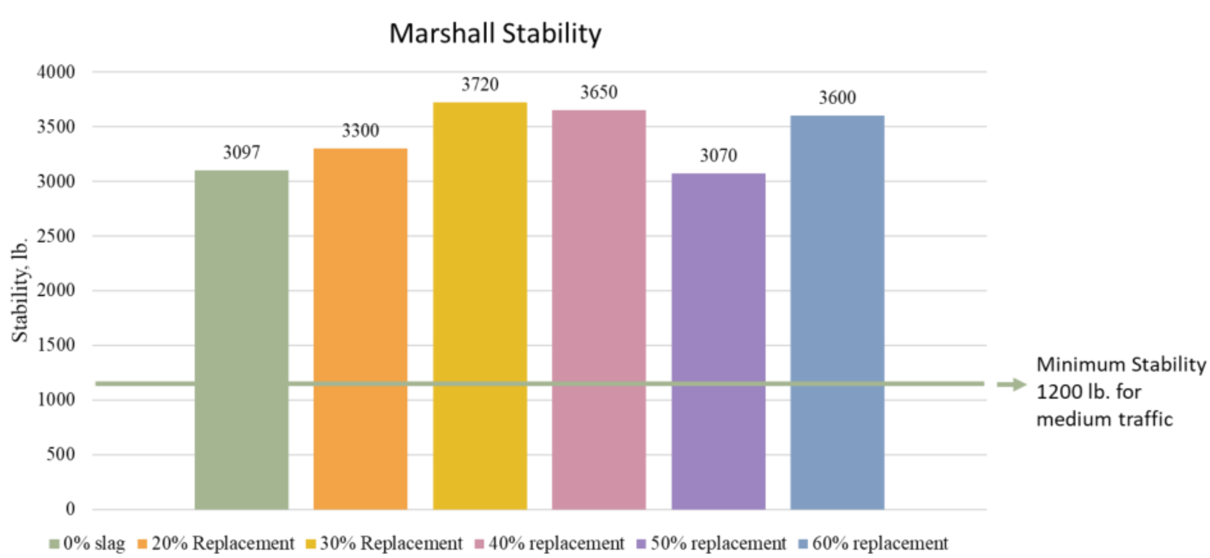


Figure F-9: Result for stability

d) From the Marshall testing on sample for flexible pavement, it was found that 20 to 40% of the stone chips of wearing courses can be replaced by the QEAF slag, also improvement in road performances was noted. Figure F-10 shows the result for Marshall Flow for different mixtures.

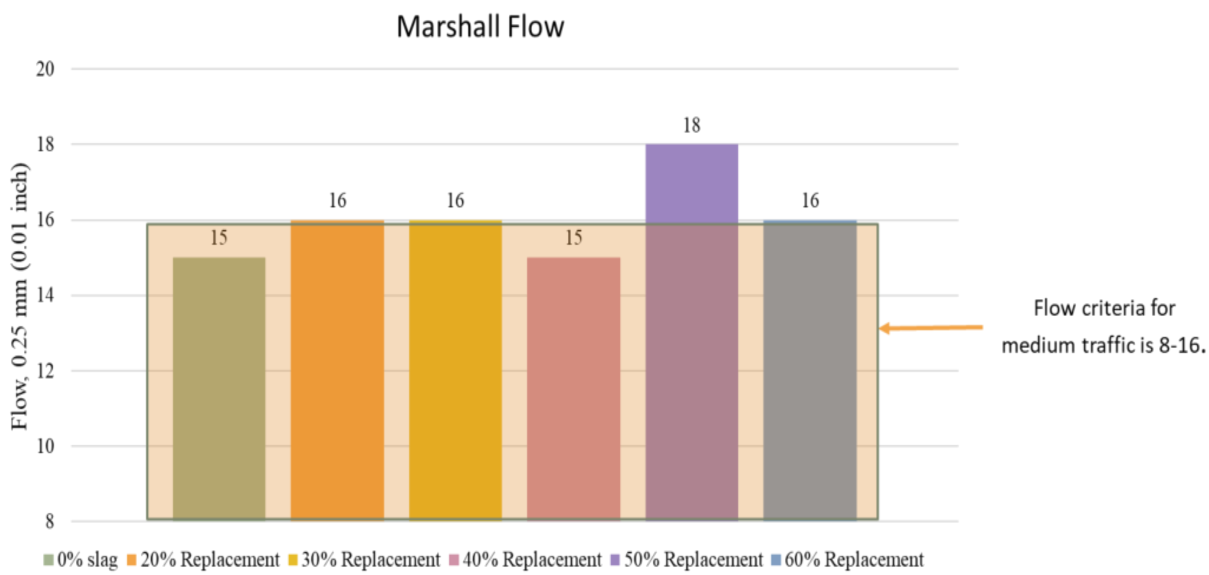


Figure F-10: Result for Flow

Extended field performance may be observed for a longer period. Drainage quality through the slag may be observed. Leachate test can be done to know if they are safe to use in the environment Investigations of LRF slag as base and sub-base material is highly recommended.

Utilization of slag as concrete block

Both QEAF and LRF slag were used to replace sand in concrete blocks. In this study, water, cement and sand were mixed in a volume ratio of 1:2:6. The slag materials were then added to the mix to replace 10%, 30% and 50% of the sand. Admixture was used additionally to replace the cement content in some experiments. In order to do that, compressive strength test, water absorption test and apparent density tests were done on the samples. Figure F-11 represents the mix design for concrete block.

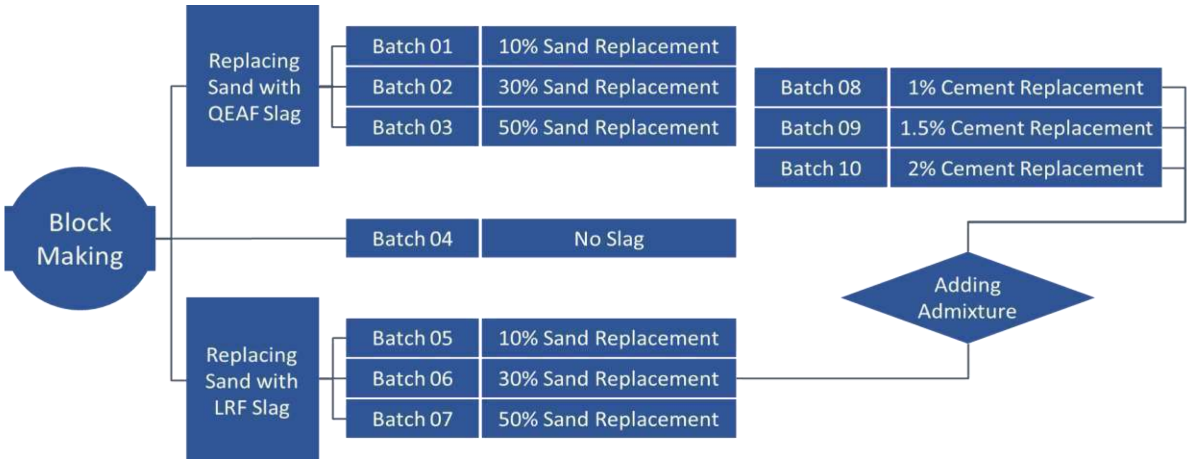


Figure F-11: Mix design for concrete block

a) The concrete blocks produced with QEAF slag met the required standards outlined in IS 2185:1 for block densities, compressive strength values, and water absorption.

b) The use of QEAF slag as a substitute for sand up to 30% in the production of concrete blocks resulted in higher compressive strength values, whereas LRF slag yielded unsatisfactory outcomes. Figure F-12 shows the compressive strength of the concrete block without the admixture. However, the properties of blocks made with LRF slag can be improved by adding a small amount of admixture (1% of cement amount). Figure F-13 shows the compressive strength of the concrete block with admixture. Figure F-14 shows result for apparent density of the concrete blocks. Figure F-15 shows the result of water absorption of the concrete blocks.

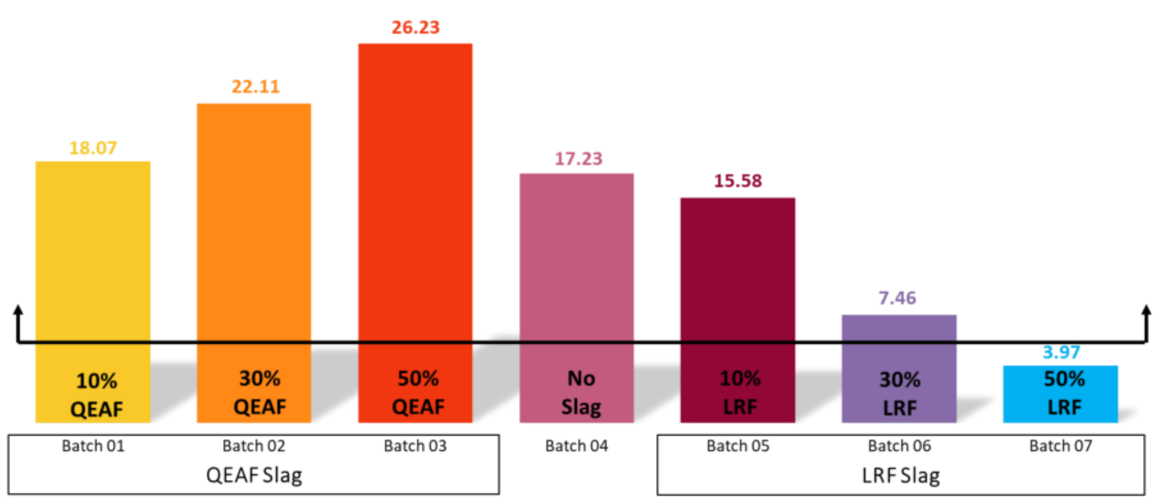


Figure F-12: Compressive strength for concrete block (without admixture)

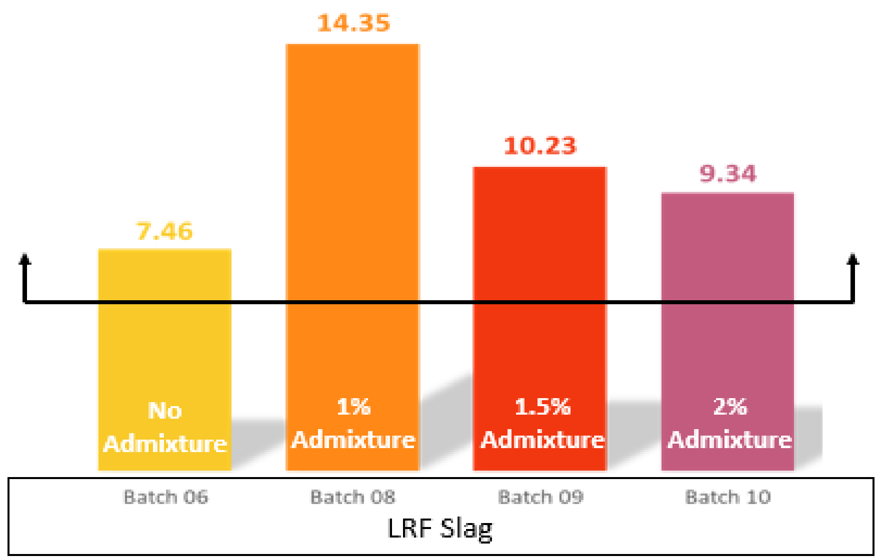


Figure F-13: Compressive strength result for concrete block (with admixture)

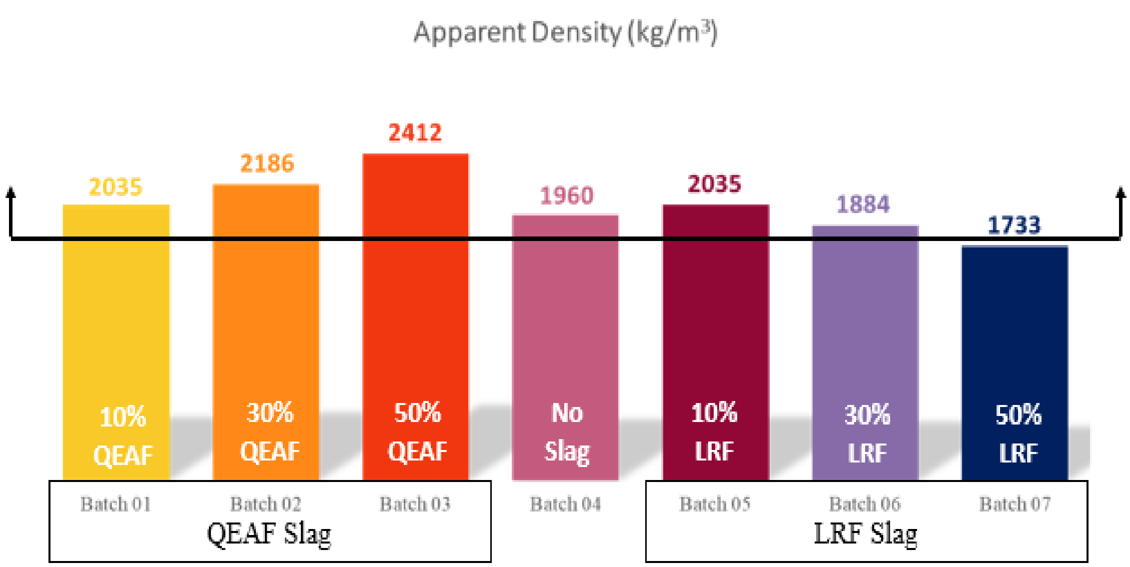


Figure F-14: Apparent density result for the concrete block

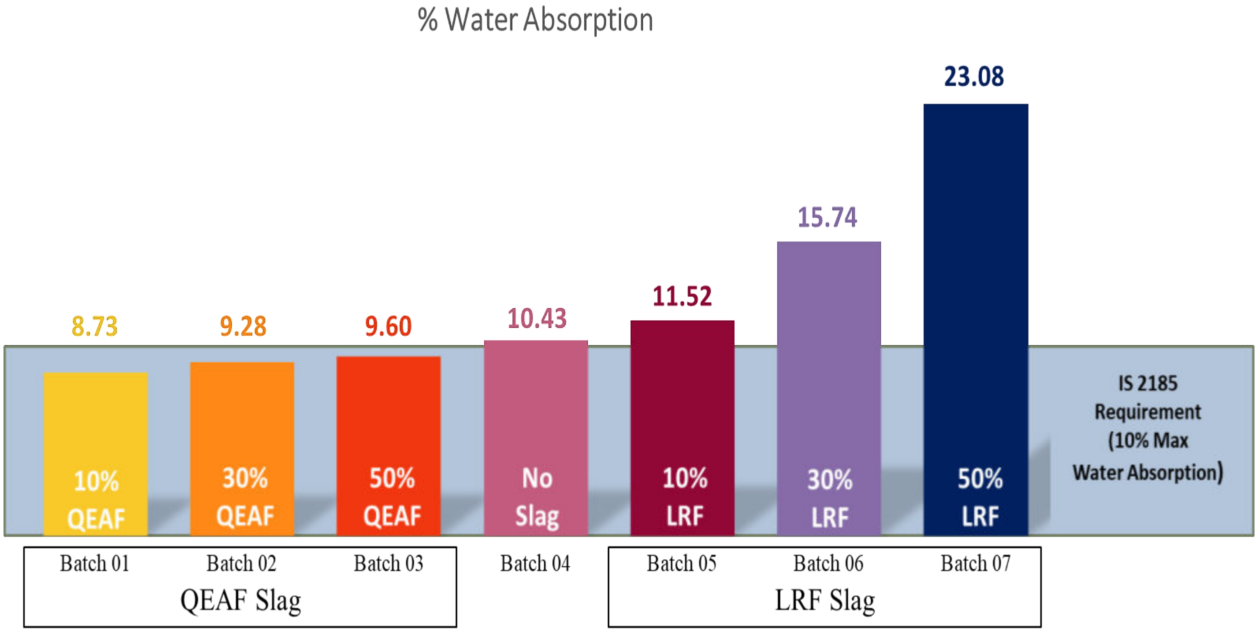


Figure F-15: Water absorption result for the concrete blocks

QEAF slag has shown promising results as a replacement for sand in concrete block production. Adding other materials, such as fly ash, silica fume or fibers, could lead to even more sustainable and cost-effective solutions for concrete block production. Advances in technology are constantly opening new production techniques for concrete blocks. For example, using 3D printing technology to produce concrete blocks could offer significant advantages in terms of speed, precision, and material efficiency.

Cost Savings per cubic feet of Construction

In general, the weight of a cement bag is 50 kg, accompanied by a corresponding volume of 1.23 cubic feet. Presently, the cost of a 50 kg cement bag ranges from 500 to 600 takas. Utilizing this information, the approximate price of one cubic foot of cement can be estimated to be within the range of 400 to 500 takas. Notably, when slag is employed as a partial substitute for clinker in cement production, savings of approximately 60 to 75 takas per cubic foot can be realized, owing to the replacement of 10% to 15% clinker with slag.

Current price of one cubic feet concrete is 300 to 350 takas. When slag is used as partial replacement of coarse aggregates in concrete, according to current price of stones, 210 to 250 takas can be saved in per cubic feet concrete, as 80% to 100% coarse aggregates can be replaced by QEAF slag.

40% of the stones can be replaced by QEAF slag in flexible pavement. This means a saving of 100 takas can be expected from one cubic feet of flexible pavement.

Financial benefit of GPH Ispat

Considering 8.4 lakh tons of steel production/year in GPH ISPAT: 84000-126000 tons of slag/year is generated. Considering slag as a replacement for stone chips could lead to a financial benefit of 34-50 crore BDT annually*.

(*At present market sale value of stone chips is 4000 BDT/per ton. Slag processing cost is not included in this calculation.)

Slag Processing Unit and Machinery List with Operational Expenditure

This research suggests a slag processing unit to process the slags before implementing in construction sectors. The details of the processing unit and machinery list with operational expenditure is shown next.

Project Plan and Machinery List with Operation Expenditure							
SLAG PROCESSING UNIT							
Serial No.	DESCRIPTION	SELECTED SUPLIER	CAPACITY	Q.TY	UNIT PRICE (USD)	TOTAL PRICE (Euro)	Manpower/Shift
1	ZSW38095 Vibrating Feeder	Beijing Yuyi	11 kw	1	$20,800	$20,800	1
2	PEY 400×750 Hydraulic Jaw Crusher	Beijing Yuyi	45 kw	1	$60,000	$60,000	1
3	GPY800/150 Cone Crusher	Beijing Yuyi	90 kw	1	$69,000	$69,000	1
4	3YK1545 Vibrating Screen	Beijing Yuyi	22 kw	1	$20,800	$20,800	1
5	2YK1545 Vibrating Screen	Beijing Yuyi	15 kw	1	$17,300	$17,300	1
6	RCYK6.5T3 Magnetic Separator	Beijing Yuyi	2.2 kw	2	$9,600	$19,200	1
7	GZG70/110 Vibrating Feeder	Beijing Yuyi	2x0.55 kw	1	$2,420	$2,420	1
8	Belt Conveyor	Beijing Yuyi	66.5 kw	1	$93,680	$93,680	
9	Compressore	As Standard	55 kw	1	$55,000	$55,000	
10	Payloders, Excavators & Cranes	As Standard		5	$60,000	$300,000	3
11	Auxiluries	As Standard		1	$100,000	$100,000	
	TOTAL EX-WORKS PRICE					$758,200	
	TRANSPORT & INSURANCE					$52,000	
	INSTALLATION & TRAINING					$18,955	

	CAPITAL MACHINERY PRICE (C&F CTG)	$829,155	
	RECOMMENDED SPARES	$41,458	
	TOTAL PRICE WITH SPARES (C&F CTG.)	$870,613	
	TOTAL PRICE WITH SPARES (C&F CTG.)	97,508,62	
			4

Land & Land development	8000 Sqm	2 Acr		1
Civil & Foundation	2000 Sqm	750 BDT/Sft	16,145,850	1
Building Shed	2000 Sqm	1500 BDT/Sft	32,291,700	
Electricals & Lighting			2,500,000	
Vehicles	4 nos Drump truck		20,000,000	4
Misc. Item			5,000,000	
Total Project Cost			**173,446,178**	20

Productivity (minimum)	35	MT/hr
Operational Expenditure (As 100% Capacity)		
Manpower	47	Tk/Mt
Electricity	107	Tk/Mt
Spares & Consumables	37	Tk/Mt
Wastage 3.0% (3.0% of diff. bet. Rod to scrap price)	0	Tk/Mt
Misc.	250	Tk/Mt
Total	441	Tk/Mt
Discounted Selling Price 3025 BDT/MT		

Investment Required (Project Cost)					
Particulars	**Equity**	**Debt**	**Total**	**Depreciation/ year**	**Projected Life**
Land & Land Development (2 Acr)	96,000,000		96,000,000	0	
Civil Foundation (750tk/sft)		16,145,850	16,145,850	807,293	20 years
Shed Structure (1500tk/sft)		32,291,700	32,291,700	1,614,585	20 years
Plant Machineries		97,508,628	97,508,628	6,175,546	15 years
Electrical & Lightings		2,500,000	2,500,000	500,000	5 years
Vehicles		20,000,000	20,000,000	4,000,000	5 years
Others & Misc.		5,000,000	5,000,000	500,000	10 years
	96,000,000	**173,446,178**	**269,446,178**	**13,597,424**	

Details of possible operation of machine:		
Particulars	**UOM**	**Value**
Working times per shift	Hrs	12
Number of working Shift per day	Nos	1
Working times per month	Days	25
Working times per year	Days	300
Production per hour	MT	30
Production per shift	MT	360
Production per day	MT	360
Production per month	MT	9000
Production per year	MT	108000

Details of Slag Generation:		
Particulars	**UOM**	**Value**
Capacity of Meltshop	MT	832,000
Practical Yield of Scrap	%	88.5%
Flux Use Per Ton in QEAF	Kg	42
Input in QEAF (Scrap + Flux)	MT	975,057
QEAF Slag per Year (As 100%)	MT	143,057
LF Slag per Year (As 100%)	MT	25,792
Total Slag (As 100%)	MT	168,849
Percentage of QEAF Slag	%	85%
Percentage of LF Slag	%	15%

Workings-01							
Manpower Cost (490000 Tk/month for 12 Hrs shift)							
	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year
% of Capacity Utilization	50%	60%	70%	80%	90%	100%	100%
Total (Yearly) Manpower cost	-	-	-	-	-	-	-

Workings-02							
Electricity Cost (107 Tk per ton & variable)							
	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year
% of Capacity Utilization	50%	60%	70%	80%	90%	100%	100%
Total (Yearly) Electricity cost	5,785,714	6,942,857	8,100,000	9,257,143	10,414,286	11,571,429	11,571,429

Workings-03							
Maintenance & Spares (31 Tk per ton & Variable)							
	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year
% of Capacity Utilization	50%	60%	70%	80%	90%	100%	100%
Total (Yearly) Maintenance cost	1,989,972	2,387,966	2,785,961	3,183,955	3,581,950	3,979,944	3,979,944

Workings-04							
MISC Cost (250 Tk per ton)							
	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year
% of Capacity Utilization	50%	60%	70%	80%	90%	100%	100%
Total (Yearly) Maintenance cost	13,500,000	16,200,000	18,900,000	21,600,000	24,300,000	27,000,000	27,000,000

Workings-05							
Wastage Cost (Raw materials is free of cost)							
	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year
% of Capacity Utilization	50%	60%	70%	80%	90%	100%	100%
Total (Yearly) wastage cost	-	-	-	-	-	-	-

Workings-06							
Depreciation (Fixed)							
	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year
% of Capacity Utilization	50%	60%	70%	80%	90%	100%	100%
Total (Yearly) wastage cost	13,597,424	13,597,424	13,597,424	13,597,424	13,597,424	13,597,424	13,597,424

Running Cost							
Particulars	**1st year**	**2nd year**	**3rd year**	**4th year**	**5th year**	**6th year**	**7th year**
% of Capacity Utilization	50%	60%	70%	80%	90%	100%	100%
Manpower	-	10,200,000	10,200,000	10,200,000	10,200,000	10,200,000	10,200,000
Electricity	5,785,714	6,942,857	8,100,000	9,257,143	10,414,286	11,571,429	11,571,429
Maintenance & Spares	1,989,972	2,387,966	2,785,961	3,183,955	3,581,950	3,979,944	3,979,944
Misc	13,500,000	16,200,000	18,900,000	21,600,000	24,300,000	27,000,000	27,000,000
Interest	14,991,576	13,253,292	11,353,202	9,276,246	7,005,959	4,524,347	1,811,738
Total (BDT)	36,267,263	48,984,116	51,339,163	53,517,344	55,502,195	57,275,720	54,563,111

Outputs & Selling price calculation						
Particular	**%**	**Market Price/T**	**Contribution to Per ton Selling Price (BDT/T)**	**Effective Aggregate Selling Price Per Ton**	**Discount**	**Final Selling Price (BDT/Ton)**
Pure Metal Recovery (as scrap)	1%	60000	600	6050	50%	3025
Slag Mixed with 25% Metal Recovery (Chargable in furnace 1000 kg/100T)	9%	15000	1350			
Fine Aggregate (Land filling)	10%	1000	100			
Coarse Aggregate/Flexible Pavement of Road	80%	5000	4000			

Projected Income Statement/Operating Performance							
Particulars	**1st year**	**2nd year**	**3rd year**	**4th year**	**5th year**	**6th year**	**7th year**
% of Capacity Utilization	50%	60%	70%	80%	90%	100%	100%
Expected Sales, MT	54,000	64,800	75,600	86,400	97,200	108,000	108,000
Sales Price, BDT/MT	3,025	3,116	3,209	3,305	3,405	3,507	3,612
Total Revenue	163,350,000	201,900,600	242,617,221	285,595,129	330,933,355	378,734,840	390,096,885
Less-Wastage	-	-	-	-	-	-	-
Less-Running Cost	32,899,289	31,689,068	30,282,421	28,661,063	26,805,008	24,692,411	21,399,392
Less-Depreciation	13,597,424	13,597,424	13,597,424	13,597,424	13,597,424	13,597,424	13,597,424
Net Earnings	116,853,287	156,614,108	198,737,376	243,336,642	290,530,923	340,445,005	355,100,070

Calculation of Payback Period:			
	Relative CF	**Cumulative Cash Flow**	**Balance**
Initial Outlay	269,446,178	0	269,446,178
Year 1	130,450,711	130,450,711	138,995,467
Year 2	170,211,532	300,662,242	(31,216,064)
Year 3	212,334,800	512,997,043	(243,550,865)
Year 4	256,934,066	769,931,109	(500,484,931)
Year 5	304,128,347	1,074,059,456	(804,613,278)
Year 6	354,042,429	1,428,101,885	(1,158,655,707)
Year 7	368,697,494	1,796,799,379	(1,527,353,201)
Year 8			(1,527,353,201)
Year 9			(1,527,353,201)
Year 10			(1,527,353,201)
Payback Period: 2.0 years (Approx.)			

CHAPTER 1

INTRODUCTION

1.1 Background

Slag is the main by-product generated during iron and crude steel production. The nature and composition of slag depend on the type of steel made and the raw materials used for steel making. Over the past decades, both the types of steel and the quantity of steel produced have increased. Consequently, slag is more diversified in composition and nature generating higher volumes. Investigations have been directed to reduce the quantity of slag generation, recover value materials contained in it and find suitable applications for this slag. Slag can be used for many valuable applications. When it is electric arc furnace slag, the composition is different than that of the induction furnace slag. In this case application of this slag can be different and especially treating the slag is quite different due to having different chemical composition. The reuse of slag can reduce CO_2 emissions. Especially in densely populated countries like Bangladesh, the sustainable use of slag can contribute to natural resource savings, reduction of energy consumption and CO_2 emissions. For better quality steel production, when more steel industries will have electric arc furnace technology, there will be an increasing need to manage the large volume of electric arc furnace slag.

1.2 Production and Current Management of Slag in Bangladesh

In Bangladesh, the bulk of steel is made by re-melting steel scrap. Most of the steel plants melt scrap in induction furnaces. Only two plants now melt scrap in EAF and raw materials like pig iron and lime are used in limited quantities. In the induction furnaces, a very small quantity of slag (about 6-8 percent) is generated. A slightly higher quantity of slag (10-15%) is generated in electric arc furnace steel making.

Table 1.1: Typical Composition of Bangladesh Steel Making Slag

	Composition (wt%)				
	FeO	SiO_2	MnO	Al_2O_3	CaO
Induction Furnace Slag	5-12	55	23	4	-
EAF Slag	27	25	2.3	4	55

Bangladesh consumes more than 7 million tons of steel per annum and per capita steel consumption is 45 kilograms. More than 400 steel mills of different categories and sizes currently produce steel in Bangladesh. With the progress of economy, the per capita consumption of steel and hence the production of steel in Bangladesh will increase leading to the generation of higher volumes of slag. About 900000 metric tons of steelmaking slag is generated in Bangladesh. The current utilization rate of steel slag in Bangladesh is far behind the developed countries like USA, Japan, German and France, of which the rates have been close to 100%. In these developed countries, 50% of slag has been used for the road project directly, with the remaining part for sintering and iron-making recycling in plant.

In Bangladesh most of the steel making plants dump these solid wastes only for landfill purpose. Due to land scarcity, landfill will no longer be the major methods for solid waste management. Only in recent years there has been some concern in the steel sector regarding the management of the ever-increasing amount of slag. Less scientific utilization of such slag in concrete structures are being attempted.

1.3 Research Opportunities Using Slags Generated in GPH Ispat

GPH ISPAT is one of the leading steel industries in Bangladesh which currently produce steel using latest Quantum Electric Arc Furnace (QEAF) technology followed by ladle refining. So GPH ISPAT is producing huge amount of quantum electric arc furnace (QEAF) slag and ladle refining (LRF) slag annually. Proper study is essential to make best use of this slags produced in GPH Ispat. This is not only to find some application, but most importantly it will be harder and harder to manage the large amount of slag anywhere else.

The ingredients of these slags are similar to those of natural aggregates, the exact composition is however different and varied. Moreover, the slag contains some valuable ingredients that could be extracted and reused. Brick aggregates now used in road and building construction are produced from burnt bricks. The production of bricks by burning clay mixes produces a significant quantity of CO_2 and is a major source of pollution in Bangladesh. There is enough indication that such slag can be converted into or incorporated in building materials and thus help manage the slag generated in GPH Ispat at the same time this will help reduce CO_2 emission while producing large quantity of steel from a leading steel industry GPH Ispat.

Steel slag, due to its high strength and durability, can be processed to aggregates of high quality comparable with those of natural aggregates. The high bulk density, the high level of strength and abrasion as well as the rough texture qualify steel slag as a construction material. Electric Arc Furnace (EAF) slag was used in Egnatia Odos, the 670 km project near Thessaloniki, Greece. Egnatia Highway is the greatest road construction project in Greece. In Germany, about 400000 tons per year is used as aggregate for the stabilization of rive bankers and riverbeds against erosion. Nippon Slag Association in Japan has since 1993 been involved in application technology research for the use of steelmaking slag in concrete as coarse material for ground improvement in port and harbor construction. Studying the nature of the slag produced in GPH Ispat, it is quite possible to make best utilization of this slag through proper investigation.

1.4 Objectives with Specific Aims

This study aims to examine the possible utilization of QEAF and LRF slag for manufacturing some useful products. The objectives with specific aims are written below:

1. Study the physical, chemical and mechanical properties of QEAF and LRF slags produced in GPH Ispat.
2. Investigate possible utilization of QEAF and LRF slags in the production of Cement
3. Determine optimum percentages of replacement by volume of coarse and fine aggregate in concrete by QEAF and LRF slag.
4. Observe the performance of QEAF slag in partial replacement of coarse aggregate in Flexible Pavement
5. Investigate possible utilization of QEAF and LRF slag in the production of Concrete Block

1.5 Outline of Methodology

1. The chemical composition and crystalline structure of the slag is determined by X-ray diffraction analysis and X-ray fluorescence analysis.
2. The physical and mechanical properties of the slag is ascertained.
3. Possibility of using slag generated in GPH in road surfacing and in concrete blocks is investigated.

4. Blocks for use in pavements and to contain river erosion and road sidings are prepared. The need for additives for the making of such blocks is also ascertained.
5. The properties of the blocks are evaluated for optimum composition of a mix for the best possible properties is determined.

The complete flow chart of the methodology followed for this research is shown in Figure 1.1.

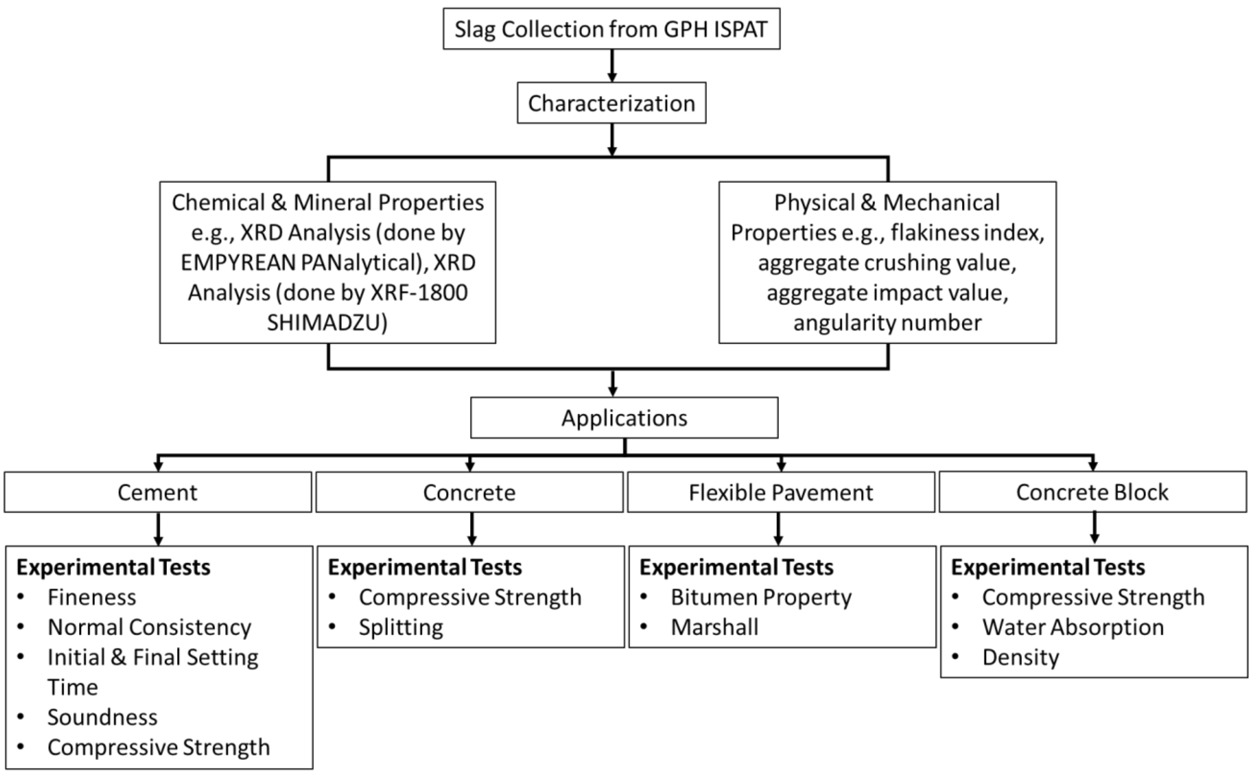


Figure 1.1: Flowchart of the methodology

1.6 Outline of This Report

This report has been divided into twelve chapters to present the research work.

Chapter One describes the background of the research along with the objectives and methodology.

Chapter Two contains the literature review where relevant theories, Codes, and concepts are described.

Chapter Three elaborates the characterization of slags by experimenting and analyzing the data from XRD and XRF tests conducted on the QEAF samples and LRF samples.

Chapter Four explains the experimental setup for utilization of slag in cement followed in this research. The properties of the used materials are summarized in this chapter. The process of preparation of specimens is described in detail. The experimental test setup is explained with necessary figures and the data acquisition techniques are described.

Chapter Five presents the test results for utilization of slag in cement with proper illustrations, graphs, tables, and charts. The test results of each specimen are summarized. On the basis of these results, a comprehensive comparison is made among the specimens.

Chapter Six explains the experimental setup for utilization of slag in concrete followed in this research. The properties of the used materials are summarized in this chapter. The process of preparation of specimens is described in detail. The experimental test setup is explained with necessary figures and the data acquisition techniques are described.

Chapter Seven presents the test results for utilization of slag in concrete with proper illustrations, graphs, tables, and charts. The test results of each specimen are summarized. On the basis of these results, a comprehensive comparison is made among the specimens.

Chapter Eight explains the experimental setup for utilization of slag in bituminous pavement followed in this research. The properties of the used materials are summarized in this chapter. The process of preparation of specimens is described in detail. The experimental test setup is explained with necessary figures and the data acquisition techniques are described.

Chapter Nine presents the test results for utilization of slag in bituminous pavement with proper illustrations, graphs, tables, and charts. The test results of each specimen are summarized. On the basis of these results, a comprehensive comparison is made among the specimens.

Chapter Ten explains the experimental setup for utilization of slag in concrete block followed in this research. The properties of the used materials are summarized in this chapter. The process of preparation of specimens is described in detail. The experimental test setup is explained with necessary figures and the data acquisition techniques are described.

Chapter Eleven presents the test results for utilization of slag in concrete block with proper illustrations, graphs, tables, and charts. The test results of each specimen are summarized. On the basis of these results, a comprehensive comparison is made among the specimens.

Chapter Twelve concludes the report with major findings and observations of the present study. In the end, recommendations and suggestions are provided for future research in the relevant field.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

For literature review, initially the background study on the types of slag and their utilization processes are studied. After that, the criteria that to be followed to use slag as granular material, basic properties of steel slag and their expansion mechanism are discussed.

2.2 Philosophy of Utilization of Slag in Civil Infrastructure Construction

Slag is a broad family comprised of many different types of slags: ferrous, nonferrous, and non-metallurgical. The comprehensive use of slag is becoming increasingly important in construction practices for energy, natural resources, and environmental conservation considerations. In the last couple of decades, researchers have conducted research on various slags' uses in construction, including use as aggregate in hot-mix asphalt (HMA) (Ahmedzade & Sengoz, 2009; Kavussi & Qazizadeh, 2014; Shen, Wu, & Du, 2009; Wu, Xue, Ye, & Chen, 2007; Xue, Wu, Hou, & Zha, 2006), use as granular materials (Akinwumi, 2014; Buzatu et al., 2014; Dayioglu, Aydilek, & Cetin, 2014; Dunster, 2002; Shen, Zhou, Ma, Hu, & Cai, 2009; Suer, Lindqvist, Arm, & Frogner-Kockum, 2009; Tasalloti, Indraratna, Chiaro, & Heitor, 2015), use as fine or coarse concrete aggregate (Alwaeli, 2013; Anastasiou & Papayianni, 2006; Beshr, Almusallam, & Maslehuddin, 2003; George & Sorrentino, 1982; JP, 1982; Kawamura, Torii, Hasaba, Nicho, & Oda, 1983; Li, Yao, & Wang, 2009; Manso, Polanco, Losañez, & González, 2006; Maslehuddin, Sharif, Shameem, Ibrahim, & Barry, 2003; Montgomery & Wang, 1991, 1992; Qasrawi, Shalabi, & Asi, 2009), and use in cement manufacturing (Conjeaud, George, & Sorrentino, 1981; Mahieux, Aubert, & Escadellas, 2009; Murphy, Meadowcroft, & Barr, 1997; Reddy, Pradhan, & Chandra, 2006; Sun & Yuan, 1983; Tsakiridis, Papadimitriou, Tsivilis, & Koroneos, 2008; Wang & Lin, 1983; Wang & Yan, 2010).

The successful utilization of slag in construction generally depends on an overall process consisting of several stages from the slag production to end uses. Any of the stages can affect the properties of slag and the performance of the end products. These stages include pretreatment and posttreatment of slag, chemical and physical characterization, identification of the factors that affect slag properties, and the evaluation of performance for the intended use (Figure 2.1).

Studies on the comprehensive utilization consist of three main stages: (i) selecting a treating and processing procedure, (ii) characterizing intrinsic properties, and (iii) evaluating performance properties of end products.

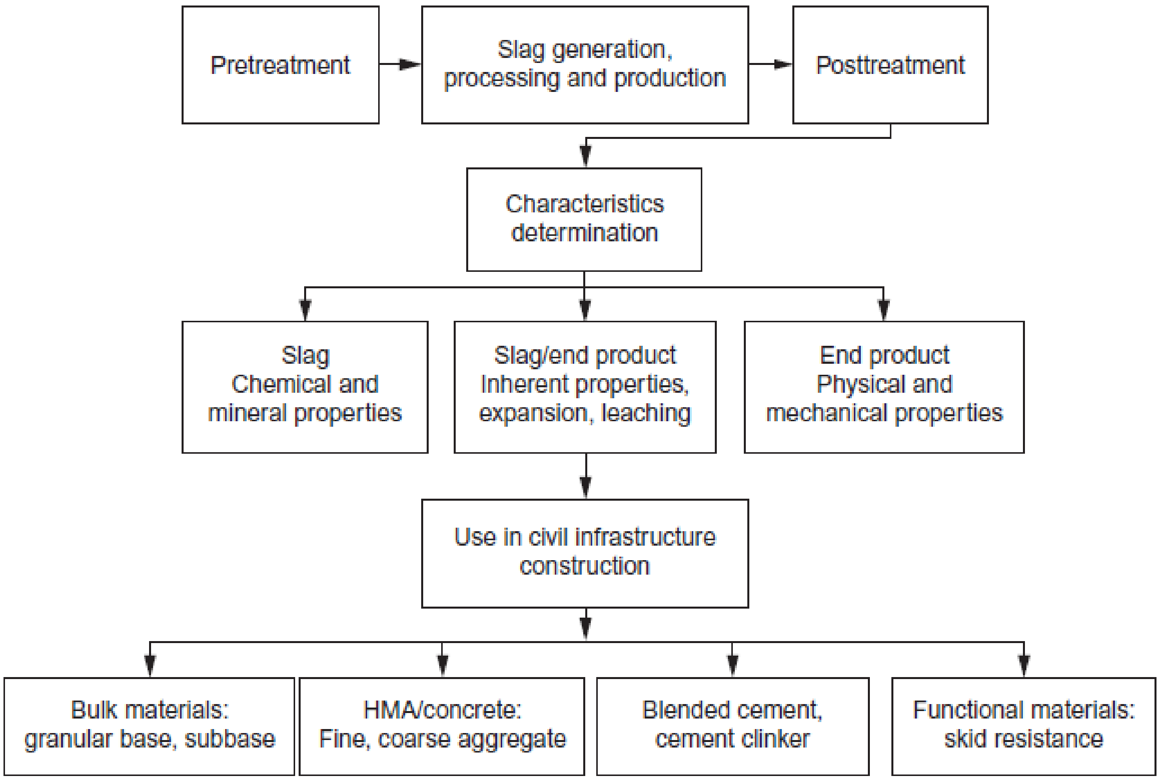


Figure 2.1: Overall process of slag utilization in civil infrastructure construction (Wang, 2016)

2.3 Usability Criteria for Slag Use as a Granular Material

Restrictions on slag aggregate use as a granular material come mainly from two aspects: the variation of volume stability of slag due to volume expansion of slag particles, and the lack of criteria developed to date to prove the relation between the expansion property of slag and the stability of unbound applications.

Different applications should have different criteria to guide appropriate use. For example, for the use of steel slag in concrete or other rigid matrices, expansion force of steel slag and the distribution of the force in the rigid matrices governs usability (Wang, 2010). There is no single criterion governing different uses of steel slag. When steel slag is used as a granular material (e.g., road base or subbase), the apparent volume expansion of the base or subbase is to be restricted to zero.

2.4 Basic Properties of Steel Slag and Expansion Mechanism

2.4.1 Chemical and Mineral Compositions

Solid steel slag exhibits a block, honeycomb shape and high porosity. Most steel slag consists primarily of CaO, MgO, SiO_2, and FeO. In low-phosphorus steelmaking practice, the total concentration of these oxides in liquid slags is in the range of 88–92%. Therefore, the steel slag can be simply represented by a CaO-MgO-SiO2-FeO quaternary system. However, the proportions of these oxides and the concentration of other minor components are highly variable and change from batch to batch (even in one plant) depending on raw materials, type of steel made, furnace conditions, and so forth. Steel slag can be air-cooled or water quenched. Most of the steel slag production for granular materials use natural air-cooling process following magnetic separation, crushing, and screening. Air-cooled steel slag may consist of big lumps and some powder. The mineral composition of cooled steel slag varies and is related to the forming process and chemical composition. Air-cooled steel slag is composed of $2CaO.SiO_2$, $3CaO.SiO_2$ and mixed crystals of MgO, FeO, and MnO (i.e., MgO·MnO·FeO), which can be expressed as RO phase. CaO can also enter the RO phase. In addition, $2CaO\text{-}Fe_2O_3$, $CaO \cdot Fe_2O_3$, CaO·RO·SiO2, $3CaO \cdot RO \cdot 2SiO_2$, $7CaO \cdot P_2O_3 \cdot 2SiO_2$, and some other oxides exist in steel slag (Sersale, Amicarelli, Frigione et al., 1986; Shi, 2004). It was reported that the X-ray diffraction pattern of steel slag is close to that of Portland cement clinker.

2.4.2 Expansion Mechanism

During the steelmaking process, fluxes that consist of lime (CaO) or dolomitic lime, with iron and scraps, are charged to the furnace. There is a certain amount of free lime (f-CaO) in steel slag. Free lime, with a specific gravity of 3.34, can react with water to produce $Ca(OH)_2$, with a specific gravity of 2.23, which results in volume increase (Figure 2.2). This is considered to be the primary reason to make steel slag expand volumetrically (Montgomery and Wang, 1993).

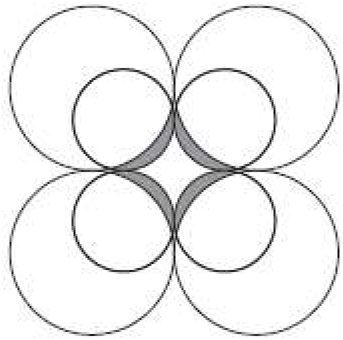


Figure 2.2: Effect of increase mechanism on the void volume (Wang, 2016)

MgO in steel slag is in the form of Fe (Mn, Mg, Ca) O, in glassy state, mixed crystal or solid solution mainly with FeO and MnO (i.e., RO phase). The free form of MgO (periclase) is volumetric unstable, which can only be formed in low-basicity condition. Due to the high basicity condition in molten steel slag and the close radii of Mg++, Fe++, and Mn++ (0.78, 0.83, and 0.91Å, respectively), MgO, FeO, and MnO usually form solid solution. In this study, free lime is considered to be the major contributor to the volume expansion of steel slag. The expansion mechanism of free MgO (periclase) can be explained similarly using the diagram in Figure 2.2.

2.5 Steel slag use in Cement

2.5.1 Ladle Refining Furnace (LRF) Slag as a Partial Replacement of Raw Materials in Cement Industry

The use of LFS in cement production, particularly Portland cement clinker manufacturing, has limited research. Using steel slags with high MgO as an additive in Portland cement, observing that only the final setting time increased as the MgO content was raised in samples containing 15 and 30 wt.% slag. However, a cement mix containing 45 wt.% steel slag with high MgO had an initial setting time of about 210 min and a volume expansion of 1 mm (Altun and Yılmaz, 2002). The exploration of steel slag's efficacy in Portland cement clinker production involved integrating 10.5% of steel slag into the raw meal. Although it remains undisclosed whether the steel slag was procured from an electric arc furnace, the report's raw material composition infers the slag's inception from primary steelmaking operations (i.e., EAF slag). This inference stems from the prominently elevated Fe_2O_3 content reported (26.36%), far surpassing the conventional Fe_2O_3 levels detected in LFS (<7 wt.%) (Tsakiridis et.al., 2008).

Study explores the potential of using Ladle Furnace slag (LFS) as a raw material in Portland cement production. The study investigates the impact of incorporating LFS into the raw meal to supplement the limited research on LFS. By adjusting the lime saturation factor (LSF) as well as the alumina and silica ratios (AR and SR), high Alite cement was produced. The chemical and mineralogical analyses show that the use of LFS did not adversely affect the mineralogical properties. The mechanical properties, such as compressive strength and volume expansion, were positively impacted by incorporating 39.2 wt.% slag into the raw meal. Although a slightly higher initial setting time was required for samples containing slag, this was attributed to the amount of MgO in the cement. Overall, the study demonstrates that LFS can be used as a raw material in Portland cement production to reduce natural raw material consumption, energy use, and CO_2 emissions. The samples containing LFS had a typical oxide composition comparable to the reference OPC sample, high C_3S content (about 60%), and higher compressive strengths exceeding the minimum specifications. No changes in volume expansion were observed. However, the initial setting time was 1.6 times higher than the minimum value required for cement with a compressive strength of 54 MPa at 28 days, classified as high early strength (42.5R) (Vilaplana et. al., 2015).

Study investigated the microstructure and mechanical behavior of Ladle Refining Furnace Slag (LRFS) in cement-slag systems. The results suggest that partially replacing Portland cement with LRFS could be beneficial for reducing cement usage and recovering waste from the steel industry. The evolution of the microstructure and physical properties of the cement-LRFS system were found to be correlated, and the hydration process in LRFS-cement systems was controlled by cement hydration reactions and the filler effect of non-reactive phases of LRFS. The LRFS-cement samples showed lower mechanical performance due to dilution and particle size distribution. However, LRFS-cement pastes still achieved considerable compressive strength values over 55 MPa and 85 MPa, making them suitable for the construction of temporary structures or buildings with a short lifespan. The LRFS mineralogical composition and the evolution of periclase were identified as crucial factors affecting volume instability, and the curing environment should also be considered for future use (Henríquez et. al., 2021).

LRFS contains a unique mineral component $C_{12}A_7$ (aluminate mineral mainly composed of CaO, Al_2O_3, SiO_2), which accelerates the hydration rate and promotes the heat release rate in cement. The presence of LRFS can also significantly promote the setting of a cement system. However, the content of LRFS should be less than 10% to improve the microstructure and mechanical properties of cement paste. The text also highlights that the influence of LRFS on the volume stability of cement is due to the hydration and hardening processes of $C_{12}A_7$ in the system. When the LRFS content is $\geq$ 30%, it may be unfavorable to the volume stability of the cement system. LRFS is different from other supplementary cementitious materials in the way that it provides hydration activity, mainly affecting the early hydration process of cement. As a supplementary cementitious material, LRFS will have a better early hydration activity (Fang et. al., 2021).

Study investigated the use of Ladle Metallurgy (LM) slag in Ordinary Portland Cement (OPC) clinker production. Three sets of samples were produced with varying amounts of LM slag, and the results showed that the addition of LM slag led to a decrease in CO_2 emissions during clinkering and a slight increase in C_3S formation. The setting time increased with the addition of LM slag, while the compressive strength remained comparable. The fine fraction of LM slag was enriched in C_2S and depleted in Cr, Mg, Al, and Fe, indicating a win-win scenario for both metal and cement producers. This process has the potential to become industrially realistic in the framework of industrial symbiosis (Iacobescu et. al., 2016).

2.5.2 Electric Arc Furnace Slag as a Partial Substitute for Raw Materials in the Cement Industry

Research investigated the potential use of electric arc furnace slag (EAF slag) as a blending material for Portland cement. The hydration characteristics of EAF slag-Portland cement mixtures were investigated by varying the ratios of EAF slag (5, 10, and 20 wt%) in the solid mix. The study evaluated the compressive strength, chemically combined water, and free lime contents as a function of hydration times (1, 3, 7, 28, and 90 days), and examined the phase composition of the formed hydrates using XRD technique and differential thermal analysis. Results showed that the compressive strength of the mixtures containing 5 and 10 wt% EAF slag were comparable to those of the neat Portland cement paste at most hydration ages. However, the compressive strength values decreased as the EAF slag content increased, with the mix containing 20 wt% EAF slag exhibiting the lowest strength values. The study also found that the EAF slag had no significant pozzolanic reactivity, as indicated by the results of chemically combined water, free lime, XRD analysis, and thermal analysis (Hekal et. al., 2013).

An experimental study on the use of electric arc furnace steel slag (EAFS) and steel sludge as cement replacement in concrete, investigating their effects on workability, compressive strength, permeability, water absorption, and heavy metal leaching. The results showed that up to 10% replacement of EAFS and steel sludge improved the compressive strength of concrete without affecting workability, and also reduced permeability, indicating potential application in green and advanced concrete technology. The study also demonstrated the safe solidification of the steel by-products in a cement-based system, with good leaching properties. Microstructure analysis revealed denser concrete with fewer voids, further supporting the potential use of EAFS and steel sludge in improving the water-tightness of concrete (Roslan and Ismail et. al., 2020).

Tsakiridis (2008) conducts an investigation of the feasibility of incorporating steel slag, a by-product of the iron to steel conversion process, into raw meal for the production of Portland cement clinker is the primary objective of this research. Two raw meal samples were prepared: one with conventional raw materials (PCRef), and the other with 10.5% steel slag (PCS/S), both sintered at 1450◦C. The results of chemical and mineralogical analyses and microscopic examinations indicate that the use of steel slag did not impact the mineralogical features of the produced Portland cement clinker. The physical and mechanical properties of the clinkers were evaluated using grindability, setting times, compressive strength, and soundness tests, and the hydration products were studied using XRD analysis at 2, 7, 28, and 90 days. The research findings demonstrate that incorporating 10.5% steel slag into raw meal does not have a detrimental impact on the quality of the cement produced, and the compressive strength of the clinker with steel slag was at least equal to that of the reference sample.

2.6 Steel Slag Use in Concrete

2.6.1 Strength and Mechanical Properties

Much research has been done on strength and mechanical properties of steel slag aggregate concrete, and the chemical and mineral properties and their effect on concrete (Rojas & Rojas, 2004). The methods are generally to replace natural aggregate, coarse and/or fine, by steel slag aggregate, or blend use with other natural or by-products (eg, fly ash and steel slag) (Sinha, 2014; Sumi & Malathy, 2013; Yi et al., 2012). Papayianni and Anastasiou (2010) used electric arc furnace (EAF) slag as a concrete aggregate, and ground ladle furnace (LF) slag as a supplementary cementing material to make concrete for use in heavy-traffic road pavements or in high-requirements industrial floors, with a 500 m long pilot road pavement mixed in a ready-mixed concrete plant. A survey conducted on the road after 10 years of continuous use showed that it performed in an excellent way with high strength up to 70 MPa. The concrete met the durability requirements for application in road pavements, airport or marine port fields, paving blocks, or industrial floors. The study also shows that mortar mixes with 20% cement was replaced by ground ladle slag and developed 90–95% of the reference mortar strength. A pilot production of shotcrete with LF slag proved very successful.

Pellegrino and Gaddo (2009) conducted research on concrete made with EAF slag as aggregate that showed good strength characteristics and total comparability (or even better) with those of traditional concrete. It is suggested the durability of the concrete can be strongly improved even in critical freezing–thawing environmental conditions by a small amount of air-entraining agent. A study on the use of EAF slag in concrete showed that high substitution ratios of coarse natural aggregates by EAF slag are possible without decreasing mechanical properties of concrete; however, conversely, replacement of fine natural aggregates seems feasible at lower substitution ratios only (Pellegrino, Cavagnis, Faleschini, & Brunelli, 2013). Qasrawi, Shalabi, and Asi (2009) used fine steel slag to replace sand in concrete. The tensile strength was increased by 1.4–2.4 times of normal concrete when the replacement is in the range of 30–50%. The compressive strength is increased for concrete by 1.1–1.3 times when the replacement is in the range of 15–30%. Therefore, the use of steel slag in concrete would enhance the strength of concrete, especially tensile strength, provided the correct ratio is used. Qasrawi (2014) found that concrete with pure recycled concrete aggregate (RCA) causes strength decrease; however, if 67% of steel slag aggregate with 33% RCA blend is used it can increase the strength of the concrete. Carbonated granulated steel slag aggregate was used to replace common natural aggregate in concrete. The results showed that carbonation treatments can significantly improve the strength and volume stability and reduce water absorption, porosity, and free calcium oxide of the slag and concrete. The workability of concrete with the slag was not significantly affected by the high-water absorption. Besides, there was less bleeding and segregation and the porosity of the cement matrix was greatly reduced. After carbonation, harmful pores in aggregate were reduced by 24.4% while harmless pores increased by 67.9%. Strength of concrete exceeded the control concrete at 60 days (Pang, Zhou, & Xu, 2015).

2.6.2 Durability

The durability of the concrete containing EAF slag aggregate was analyzed in comparison with the fundamental requirements of the structural concrete. The steel slag aggregate concrete showed better behavior than the limestone concrete. The limestone concrete lost strength, but the strength of the concrete with EAF slag (CEAF) slightly increased from the outset. This improvement could be attributed to the fact that there was no loss of adhesion between the aggregate and the matrix, a loss that was observed in the reference concrete around its aggregates. Following exposure to high temperature and relative humidity, the CEAF has proven itself to be a more stable concrete than the ordinary concrete with regard to linear expansion and contraction, with no appreciable external signs of physical deterioration or loss of mechanical compressive strength (which even increased). There was less expansion in the slag mortars than in the reference mortar as a result of the sulfate attack, which after one year of exposure did not exceed the standard threshold (ASTM C452). Over time, these slag mortars showed a greater increase of strength than the reference concrete, thereby confirming the absence of internal damage and the null reactivity of the fine fraction of the slag aggregate. As regards the aggregate–alkali reaction, the expansion of the slag aggregate mortars did not exceed the limit and may, therefore, be considered nonreactive when used in cement mixes. With regard to the exposure of the concretes to sea tides, chloride penetration was greater (or similar) in the CEAF than in the reference concrete (CR). Finally, the corrosion of the steel rebars in the reinforced EAF slag concrete, after a year in the tidal seawater environment, showed greater susceptibility to corrosion than in the limestone reference concrete. The study confirms the viability of producing steel-reinforced concrete with slag aggregate (Arribas, Vegas, San-Jose, & Manso, 2014).

Other researchers (Brand & Roesler, 2015) also confirmed that steel slag aggregates in concrete can produce acceptable strength properties, suitable freeze–thaw durability, and exceptional fracture properties.

When using EAF slag concrete, high compressive strength and low water penetration should be the main characteristics to ensure the correct level of durability. Systematic testing to verify the efficiency of slag stabilization treatment is strongly suggested as such measures allow any possible expansivity to be carefully monitored. Research conducted by Manso, Polanco, Losañez, and González (2006) shows that the performance of EAF slag concrete is similar to that of a more traditional concrete in terms of its strength and slightly less so in terms of its durability. The high porosity of EAF slag is an obstacle to making a concrete resistant to freezing. Eventual improvements can be done by adding specific admixtures.

2.6.3 Workability

Study has shown that the workability of steel slag aggregate concrete can be maintained by adjusting the fine particle portion and W/C ratio. The more porous slag aggregates could perform quite well in slag concrete for structural purposes, as the three main properties (workability, and physical and mechanical aspects) are well balanced. Higher steel slag content may absorb much higher amounts of water than the natural aggregates, which is a very relevant question for concrete workability and effective W/C ratio. EAF concrete workability improves as the percentage of fine slag is replaced by fine natural aggregates or in the smaller-sized portion (sizes between 0 and 1 mm) of slag. An Abrams cone slump of 200 mm can be reached (San-Jose, Vegas, Arribas, & Marcos, 2014).

2.6.4 Practical Use

A concrete structure that incorporated black steel slag was constructed as the foundation for the Kubik building laboratory. The results set out in this study cover the dosage phases of the steel slag aggregate concrete, with volumes of over 75% black slag. It is a pioneering structural application involving slightly over 140 m^3 (cu yd) of reinforced concrete (basement walls and foundation slab), which was manufactured in a concrete factory (Hormigones y Minas SA) and poured on-site without interruption by means of a concrete pump. This is principally due to it being a relatively low-cost, easily manufactured material, which has excellent qualities, both in terms of durability and mechanical strength (Arribas, San-Jose, Vegas, Hurtado, & Chica, 2010).

2.7 Use of EAF and LRF Slag Aggregate in Road Construction

Each specific slag, in terms of type, process, and source, should be fully evaluated for each proposed use, given the significant differences in properties that can be involved and the specific performance requirements for bulk uses.

2.7.1 Granular Base and Subbase

EAF slags have proven successful for the construction of unbound rural roads. Recently, road trials have been conducted in EAF and ladle slag use as road base and subbase. Ladle slag contains a high content of lime contributing to quick self-hardening, which results in a higher load-bearing capacity and a lower dust generation on rural roads and surrounding areas. Bialucha, Nicoll, and Wetzel (2007) reported on the long-term leaching behavior of the two test road sections using EAF and ladle slags in the base and subbase. The subject test road was built with two different aggregates or mixtures: (i) 40 cm of natural stone as the base and 10 cm of a mixture of EAF and ladle slag (1:1) in the unbound surface layer; and (ii) 50 cm 100% EAF slag. All materials are characterized concerning technical qualities, mineral and chemical composition, and leaching properties.

Laboratory and road tests were carried out to investigate the leaching behavior of the slag materials. Suction cups were used to collect the seepage water in the middle and the edge zone of both sections with either EAF slag and natural aggregate in the road base as well as 5 m (16.4 ft.) to the side of the test road. The results have proved that no environmentally relevant amounts of heavy metals or salts had leached out of the material and have influence on the groundwater. Also, by using the slag materials, no appreciable amounts of dust covering the road and surrounding areas was observed. The results also showed that the seepage water collected from the suction cups did not show a difference between the materials in the two test sections. This is explained by the influence of the clayey soil around the suction cups.

Vazquez et al. (2010) reported on test road sections in both unbound and cement stabilized base courses using EAF and ladle slag. The unbound granular consists of two layers of EAF and ladle slag mixtures. Each layer is 20 cm (8 in.) thick and aged independently for three months. All the expansion test results correspond to 168 h of testing. An average expansion rate on the construction site showed 2.25%, which was similar to the results tested in the laboratory. The bearing capacity tracked for 6 months in various points of the test road showed a continuous increase of the modulus.

The cement stabilized section consisted of 10 cm (4 in.) natural subbase course, 30 cm (12 in.) of hydraulic bound base course, combining 10 cm of natural soil, 20 cm (8 in.) of EAF and ladle slag together with 2% of cement and 16 cm (5/8 in.) bituminous mixture (three layers) was constructed. Studies also showed how mixed use of EAF and ladle slag can reduce the binding agent required in stabilized base and subbase course. The results showed that the minimum compressive strength required can be obtained by adding 2% of cement. The mixture of natural soil and EAF and ladle slag presented a higher strength than the slag alone. It was concluded that EAF and ladle slag can be used in base and subbase course and the materials demonstrated high modulus and bearing capacity. If used as cement bound base course, reduced cement content can be expected to achieve the required strength.

2.8 Steel Slag Use in Concrete Block Making

Brick kilns in Bangladesh are one of the largest contributors to greenhouse gas emissions. In 2016, the Asian Development Bank reported that the country produces 22.71 billion bricks each year. The production process consumes 3.5 million tonnes of coal and 1.9 million tonnes of firewood, resulting in 9.8 million tonnes of greenhouse gas emissions annually, according to a World Bank report. During the dry season, brick kilns cause 58 percent of the air pollution in Dhaka city. These emissions have harmful effects on public health.

The process of making bricks also causes environmental damage. Marginal farmers in Bangladesh are often coerced or incentivized to sell topsoil from their agricultural lands to brick kiln owners, which reduces soil fertility and affects food security. India and China have banned the collection of topsoil from agricultural land due to these negative effects. Bangladesh's Brick Burning Control Act, 1989 (revised in 2013) also prohibits such use of soil of agricultural land where two crops are grown a year.

Concrete blocks offer a viable alternative to burnt clay bricks. These blocks can be made from recycled materials such as fly ash and construction waste, without the need for fossil fuels. Concrete blocks have similar strength and durability to burnt clay bricks, and they can be used for various construction purposes. The Bangladesh government has already made it mandatory to use blocks in public construction since 2019 as it moves to cut the reliance on bricks for building structures, walls and roads, an official document showed (Figure 2.3). By using concrete blocks instead of burnt clay bricks, Bangladesh can reduce its greenhouse gas emissions, protect agricultural land, and improve food security.

Figure 2.3: Eco-friendly blocks made mandatory in govt projects of Bangladesh (The Daily Star, Dec 16, 2019)

Studies have been conducted worldwide on the use of Electric Arc Furnace Slag (EAFS) and Ladle Refining Slag (LFS) in hydraulic mixes, mortar, and concrete blocks. These slags have been found to be successful when used as aggregates in hydraulic mixes, although the hydraulicity of EAFS is minimal and requires high particle fineness. LFS has a slight hydraulicity and is presented in the form of dust (Lun et. al., 2008, Mäkelä et. al., 2015, Hekal, et. al., 2013). The long-term behavior of mixes with these slags is acceptable, which suggests that they can be used under suitable conditions (Arribas et. al., 2014, Chinnaraju et. al., 2013, Etxeberria et. al., 2010). Studies have also shown that slag can be used as a good surrogate material for natural aggregates, protecting the environment and natural resources (Sharba, 2019). Blocks containing slag has comparable or slightly higher strengths than traditional burnt clay bricks. However, a study by Pellegrino et al. (Pellegrino et. al., 2013) has reported that slag can negatively impact the workability of concrete, especially at high replacement levels.

In China, concrete armour blocks have been manufactured for sea coast projects, partially replacing sand with steel slag and cement with fine slag powder (Xu, 2010). Steel slag powder has been found to have more continuous hydration activity than cement at late ages.

Additionally, the use of blast furnace slag as a replacement for coarse aggregate in concrete production has been shown to increase compressive strength by 61% at 7 days and 78% at 28 days. However, there are risks associated with using slag in concrete, and a maximum limit of about 15% as a percentage of natural aggregate has been suggested to limit the amount of superplasticizer required to attain the same workability as the reference mix (Coppola et al.). Increasing the amount of slag used increases the density, elastic modulus in compression, and compressive strength of concrete.

2.9 Summary

The literature review conducted in this study showed that slag as aggregate is being extensively used in construction purposes throughout the world. Though it surely increases mechanical and strength properties of construction works, proper physical, chemical and environmental study is required to implement slag in actual projects.

CHAPTER 3

CHARACTERIZATION OF SLAG

3.1 As Received Samples of QEAF Slag and LRF Slag from GPH Ispat

The QEAF Samples were received from GPH Ispat in two sizes; namely, $^{3}/_{4}$ inch downgrade and $^{1}/_{5}$ inch downgrade. QEAF slag is a stable and hard form of slag and can be investigated both as coarse aggregates and fine aggregates. But LRF slag is like a fine powder form and cannot be investigated as coarse aggregate replacement that's why LRF slag is investigated only as fine aggregate replacement.

QEAF Slag (3/4-inch downgrade)

QEAF Slag (1/5-inch downgrade)

LRF Slag

Figure 3.1: As received samples from GPH Ispat

3.2 X-Ray Diffractometric Analysis of Slag Samples

The X-ray diffraction patterns of quantum electric arc furnace (QEAF) slag and ladle refining furnace (LRF) slag performed by using EMPYREAN PANalytical, Netherlands are shown in Figure 3.2 and Figure 3.3.

For QEAF slag (Figure 3.2), it is evident that wustite (FeO) and magnettite (Fe_3O_4) phases are predominant in the x-ray diffraction pattern of QEAF slag. Sodium aluminosilicate ($NaAlSiO_4$), Quartz (SiO_2), Larnite (Ca_2SiO_4) and Hematite (Fe_2O_3) is minor mineral phases present. This is in good agreement with the x-ray fluorescence analysis results. The XRD pattern of the slag was relatively complicated due to the slag consisted of various complex oxides.

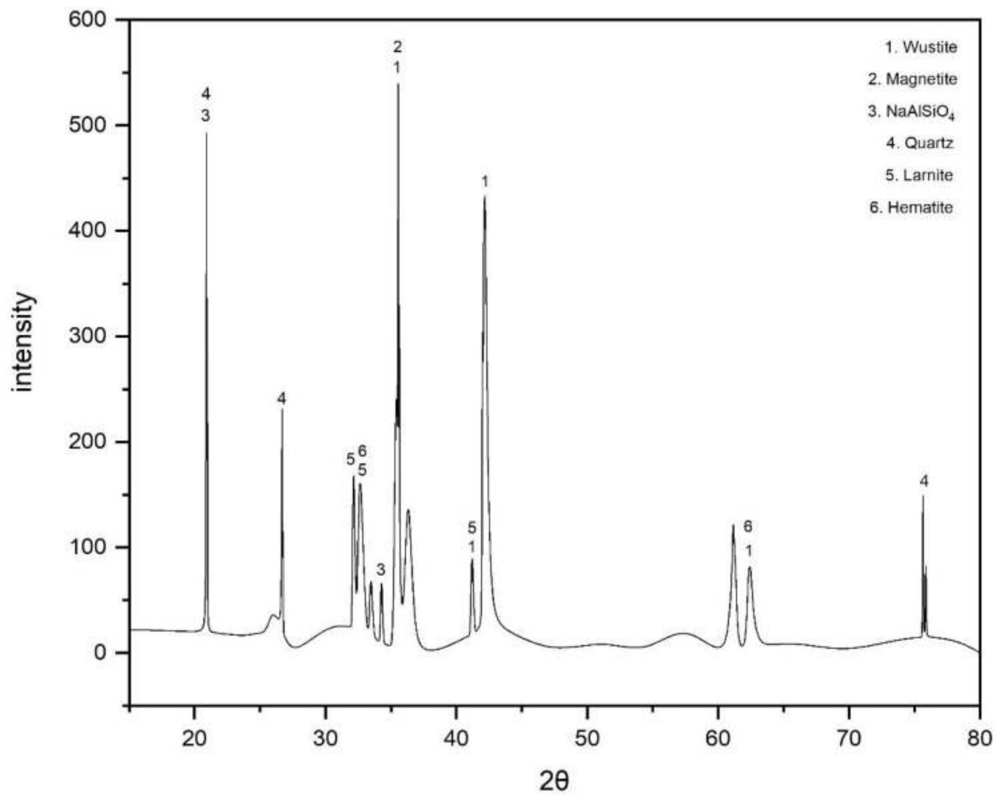


Figure 3.2: X-ray diffraction patterns of Quantum Electric Arc Furnace (QEAF) Slag

For LRF slag (Figure 3.3) Belite (C_2S), Alite (C_3S) are major phases while Tricalcium aluminate (C_3A), Calcite ($CCaO_3$), Periclase (MgO), Portlandite ($Ca(OH)_2$), Ferrite (C_4AF), Gehlenite (C_2AS), and Calcium sulfoaluminate (CSA) are minor phases present in the slag.

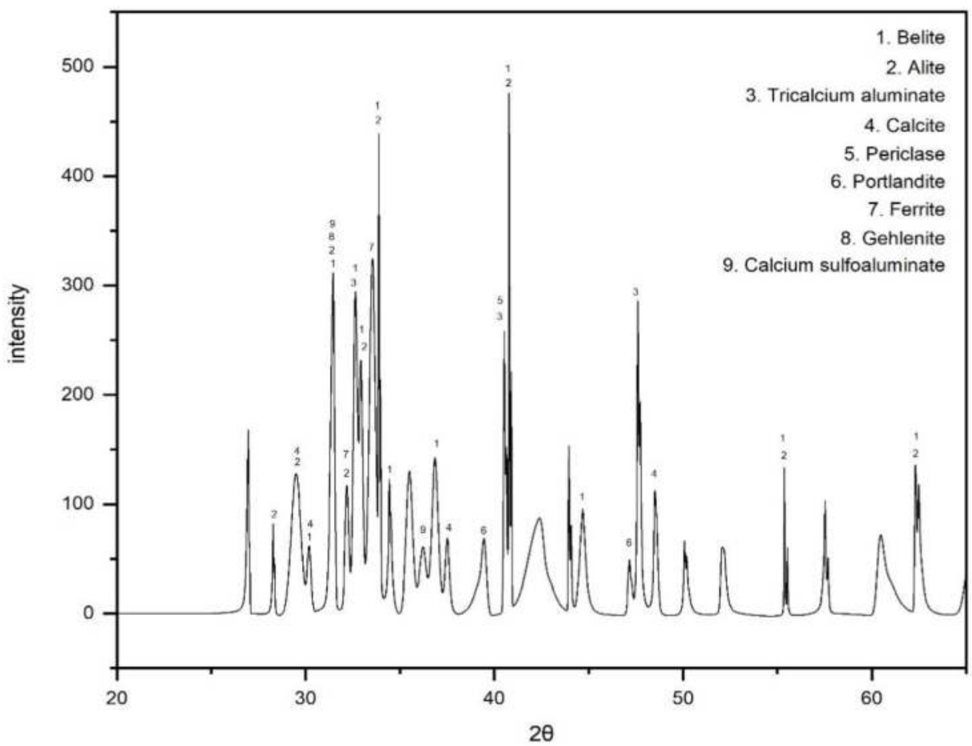


Figure 3.3: X-ray diffraction patterns of Ladle Refining Furnace (LRF) Slag

3.2 Chemical Composition of Raw Materials

The samples of steel slag collected from GPH Ispat were analyzed by x-ray fluorescence analysis using XRF-1800 SHIMADZU, Japan. Table 3.1 and 3.2 show the chemical compositions of the QEAF slag and LRF slag samples.

The major components of quantum electric arc furnace (QEAF) slag are: Fe_2O_3, CaO and SiO_2. Significant amounts of Al_2O_3, MnO and MgO are also present. The major components of LRF slag are: CaO and SiO_2. Significant amounts of Al_2O_3, Fe_2O_3 and MgO are also present. Chemical compositions of the raw materials are shown in Table 3.1 and Table 3.2 and compared with Blast furnace slag with available literatures.

Table 3.1: Chemical composition of QEAF slag, alongside with Gypsum, Clinker and Blast furnace slag

Composition	QEAF Slag			Gypsum	Clinker		Blast Furnace Slag (Lit.)
	(Lit.)	Reported by GPH	XRF (BUET)		Reported by Crown Cement	(Lit.)	
FeO%		11.84-36.47					
Fe_2O_3%	26.36		31.96		3.65	2.66	1 max
SiO_2%	17.53	8.79-17.53	17.69		21.73	22.18	30-35
Al_2O_3%	6.25	5.46-11.10	5.32		5.04	3.97	12-18
CaO%	35.70	18.17-33.70	31.71	33.73	65.69	68.67	35-41
MgO%	6.45	7.67-20.87	6.05	0.97	1.46		10 max
MnO%	2.50	4.73-9.69	4.60				
SO_3%		0.05-0.11	0.45	42.27	0.34	0.30	
Cr_2O_3%		1.21-4.30					
P_2O_5%		0.33-0.66	0.46				

Table 3.2: Chemical composition of LRF slag, alongside with Gypsum, Clinker and Blast furnace slag

Composition	LRF Slag			Gypsum	Clinker		Blast Furnace Slag (Lit.)
	(Lit.)	Reported by GPH	XRF (BUET)		Reported by Crown Cement	(Lit.)	
FeO%		0.32-4.00					
Fe_2O_3%	3-4.4		4.21		3.65	2.66	1 max
SiO_2%	26.4-26.8	14.15-36.37	23.76		21.73	22.18	30-35
Al_2O_3%	4.7-5.2	3.15-13.15	2.84		5.04	3.97	12-18
CaO%	55.9-57.0	40.26-64.99	59.58	33.73	65.69	68.67	35-41
MgO%	3.2-4.2	3.52-20.11	5.87	0.97	1.46		10 max
MnO%	0.5-1.0	0.12-2.71	1.59				
SO_3%		0.04-2.07	1.14	42.27	0.34	0.30	
Cr_2O_3%		0.01-0.23	0.65				
P_2O_5%		0.07-0.25	0.04				

3.3 Metallic Iron Content Determination

%Metallic Iron (Fe) in Slag was calculated by Wet Analysis Method using Mercuric Chloride ($HgCl_2$) solution-

- Metallic Iron in QEAF slag = 2.23%
- Metallic Iron in LRF slag = 1.12%

Utilization of Quantum Electric Arc Furnace (QEAF) and Ladle Refining Furnace (LRF) Slag Generated in GPH ISPAT in CEMENT production

CHAPTER 4

MATERIALS AND METHODS

4.1 Introduction

LRF and QEAF slags have numerous desirable properties for use in cement manufacturing, such as high compressive strength, low permeability, and good workability. These properties can enhance the strength and durability of concrete, leading to longer-lasting infrastructure and decreased maintenance costs. The following sections will discuss the preparation of slags for cement production and the tests procedures undertaken for this research.

4.2 Sample Preparation

Steel slags were collected in boulder state and subsequently subjected to a crushing and grinding process to facilitate further analysis. The resulting crushed material was then meticulously sieved to isolate specific size fractions deemed appropriate for subsequent study. The steel slag utilized in this research initiative was generously provided by GPH Ispat industry.

4.3 Experimental Design

4.3.1 Chemical and Mineralogical Characterization of Slags

The QEAF slag was initially acquired in $^3/_4$ inch downgrade and $^1/_5$ inch downgrade form, which was then crushed and ground to obtain a powdered form (sieve size 100 i.e., 150μm). The resulting powder was then subjected to sieving to achieve the desired size fractions for subsequent analysis and the LRF slag was collected as a fine powder form (sieve size 100 i.e., 150μm).

The chemical compositions of the slags were identified by means of X-ray fluorescence spectroscopy. The details of characterization are discussed in Chapter 3. In addition, a laboratory-based loss on ignition (LOI) test was performed using a muffle furnace to evaluate the amount of volatile matter present in the samples. Furthermore, a free lime test was conducted under controlled laboratory conditions using Ethanediol to determine the quantity of unreacted calcium oxide (CaO) in the samples.

❖ QEAF slag

Loss on ignition (L.O.I) = 0.85%

Percentage of free lime = 0.168%

❖ LRF slag

Loss on ignition (L.O.I) = 17.35 %

Percentage of free lime = 1.204 %

4.3.2 Experimental design in aspect of cement

For experimental design in aspect of cement mix, firstly clinker and gypsum were mixed in powder form using a ball mill which is performed in Crown Cement PLC. Then, in accordance with the experimental mix design, LRF slag and QEAF slag were separately added to the clinker along with a constant percentage of gypsum. Experimental Process of slag addition to the cement mixer is given in Figure 4.1. The details of mix design are given in Table 4.1.

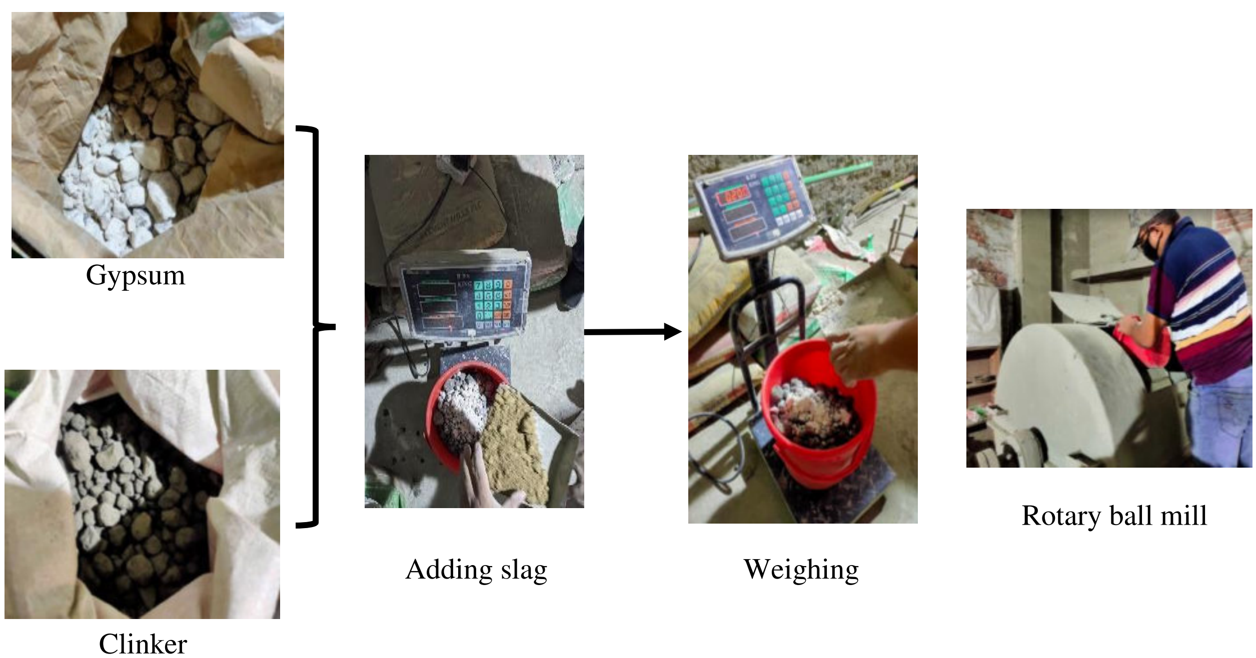


Figure 4.1: Experimental Process of slag addition to the cement mixer.

Table 4.1: Cement mix design

Type of mixer	Serial No.	Clinker wt%	Gypsum wt%	LRF Slag wt%	QEAF Slag wt%	Total wt%
No addition of slag	S-1	97	3	-	-	100
Addition of LRF slag	S-2	92	3	5	-	100
	S-3	87		10		
	S-4	82		15		
	S-5	77		20		
	S-6	72		25		
	S-7	67		30		
Addition of QEAF slag	S-8	92	3	-	5	100
	S-9	87			10	
	S-10	82			15	
	S-11	77			20	
	S-12	72			25	

4.4 Bogue's Compound Composition

The term "phase composition" is commonly used to refer to the overall composition of Portland cement, which comprises four primary phases. These phases are represented by their abbreviated symbols and are listed in Table 4.2. It is essential to emphasize that among these compounds, C_3S is widely considered to be the primary compound in Ordinary Portland Cement (OPC).

Table 4.2: Phases of Portland Cement

Major compounds of Portland cement (Bogue's compound composition)		
Compound	**Chemical formula**	**Abbreviation**
Tricalcium silicate	$3CaO.SiO_2$	C_3S (Alite)
Dicalcium silicate	$2CaO.SiO_2$	C_2S (Belite)
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A (Aluminate)
Tetracalcium aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF (Ferrite)

C_3S is widely considered the primary factor responsible for the cement's strength, particularly during the initial 28-day curing period. In contrast, C_2S takes a relatively long time to hydrate and is chiefly responsible for the cement's long-term strength. On the other hand, C_3A undergoes rapid hydration, generating most of the heat of hydration that occurs within the first few days. To regulate the fast-paced hydration of C_3A, gypsum is added to the clinker before grinding. However, it's worth noting that the C_3A portion of the cement is highly susceptible to deterioration when exposed to water containing sulfates. Lastly, C_4AF has minimal effects on the physical properties of the cement.

When assessing the chemical composition of Portland cement, it is customary to conduct an oxide analysis. The relative amounts of the four crystalline compounds present in the cement are subsequently computed based on this analysis. To determine the weight percentages of the crystalline compounds, the following equations are utilized:

$$C_3S = 4.07\ C - 7.6\ S - 6.72\ A - 1.43\ F - 2.85\ SO_3$$

$$C_2S = 2.87\ S - 0.754\ C_3S$$

$$C_3A = 2.65\ A - 1.69\ F$$

$$C_4AF = 3.04\ F$$

These equations are valid as the weight ratio of Al_2O_3 to Fe_2O_3 present is greater than 0.64. Table 4.3 summarizes standard ranges for the crystalline compounds (Bogue, R. H. et. al., 1929; Kohlhaas, B. et. al., 1983; Allahverdi, A., & Ahmadnezhad, S. et. Al., 2014).

Table 4.3: Recommended ranges of crystalline compounds for Standard cement

Standard	
Al_2O_3 /Fe_2O_3	>0.64
C_3S	40 to 80
C_2S	0 to 30
C_3A	7 to 15
C_4AF	4 to 15

4.5 Tests for cement

4.5.1 Fineness Test

The fineness of cement, also known as the specific surface area of cement, refers to the size of the particles of cement. It affects the hydration rate and thus the rate of strength gain. A smaller particle size means a greater surface area-to-volume ratio, which leads to more area available for water-cement interaction per unit volume. The fineness of cement is determined by the air permeability method, as specified in ASTM specification C204-11, using the Blaine Air-permeability apparatus. This test method measures the air flow through a prepared bed of cement under a specific pressure, and the permeability of the cement is calculated using an empirical equation based on its relationship with the air flow rate.

The fineness test was determined by the Crown Cement; a leading cement production company in Bangladesh, for all the samples immediately after the cement was prepared to check if the adequate fineness is achieved.

4.5.2 Normal Consistency Test

Normal consistency, also known as standard consistency, refers to the wetness or consistency of a cement paste and is a measure of its plasticity and workability. It is expressed as a percentage of water by mass of dry cement and is important for determining other quality tests such as setting times, compressive and tensile strengths, and soundness tests. Factors such as fineness of cement, temperature, mixing method, and the presence of admixtures can affect normal consistency. For ordinary Portland cement (OPC-Type I), normal consistency ranges from 22-30%. The test for normal consistency is conducted according to ASTM standard specification C187-11, which uses the Vicat's apparatus to measure the depth of penetration of a 10 mm diameter plunger under its own weight as shown in Figure 4.2. The water content at which the plunger penetrates 10 ± 1 mm within 30 seconds is considered the normal consistency of the cement.

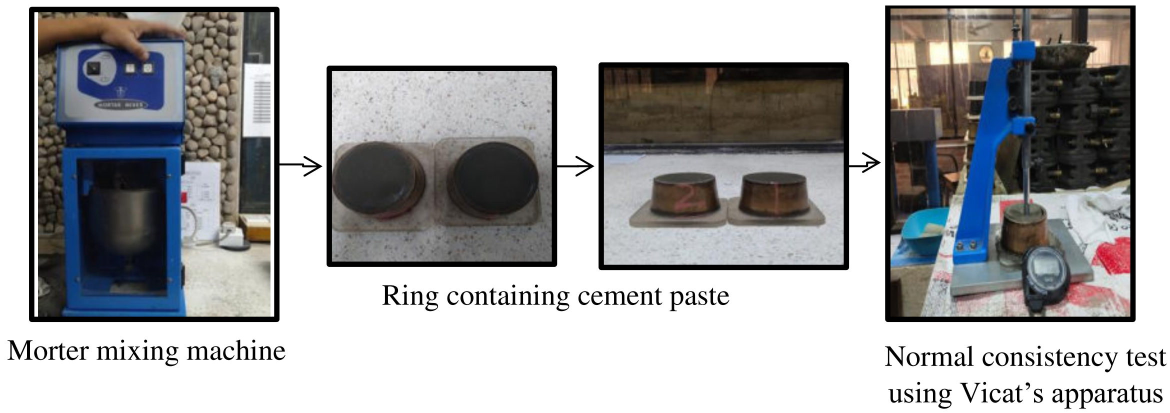


Figure 4.2: Steps for normal consistency test on cement

4.5.3 Initial and Final Setting Time Determination

The setting time of cement, which is the time it takes for cement paste, mortar or concrete to lose its plasticity and solidify, is crucial for determining the amount of time available for mixing, transporting and placing the material. A cement's setting time is defined by two parameters: initial setting time and final setting time. Initial setting time is the beginning of solidification or the point at which the cement paste loses its plasticity, while final setting time is when the cement paste attains sufficient stiffness to resist a certain amount of pressure. Factors such as the w/c ratio, gypsum content, composition, and fineness of cement can affect setting time. Inadequate gypsum content or high temperature grinding of clinker can cause flash or false set, respectively. According to ASTM C150-12 specification, the setting time of ordinary Portland cement (OPC) is to be determined (Figure4.3). Table 4.4 lists the standard initial and final setting for OPC cement.

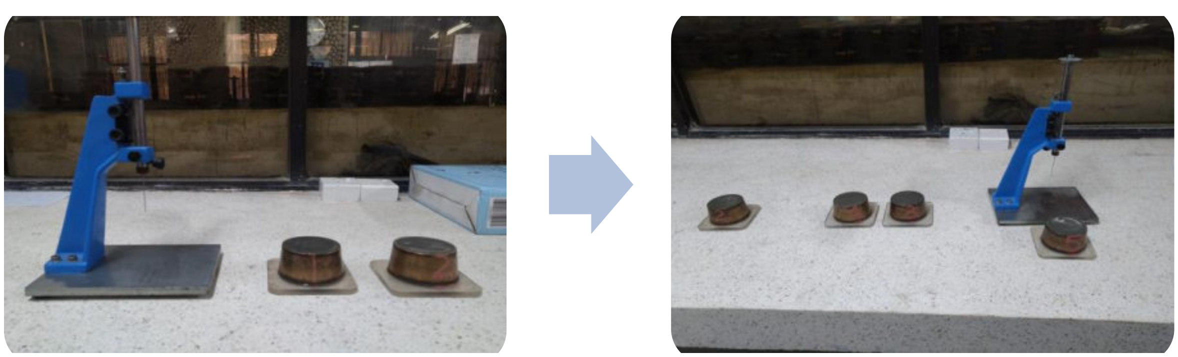


Figure 4.3: Determination of initial setting time and final setting time of sample using Vicat's apparatus

Table 4.4: Initial and final setting time for OPC cement

Type of cement	Initial setting time	Final setting time
OPC (ASTM C191-08)	Not less than 45 mins	Not more than 375 mins

4.5.4 Soundness Test

The stability of cement after it sets is crucial, as any expansion or change in volume can lead to cracking and deterioration of the strength and durability of the structure. Unsoundness, an undesirable property of cement, causes expansion and leads to minor cracks. Soundness of hardened cement can be defined as its resistance to swelling, cracking, or disintegration resulting from changes in volume due to expansive chemical reactions. Unsound behavior of cement mix or concrete can be caused by a number of factors, including excess lime or unburnt lime, adding too much gypsum to the mix, high levels of magnesium, presence of sulfate ions etc.

A) Soundness of Cement by Expansion of Cement Mortar Bars

Soundness of cement test is performed in accordance to ASTM specification C1038-18 in which the amount of expansion of cement mortar bar over a specific period of time is measured. The mortar-bar expansion is related to the sulfate reaction of hardened cement. When sulfate ions react with hydrated cement products, it causes expansion and cracking in the concrete, known as sulfate attack. This can occur due to the presence of various types of sulfate salts in the soil, such as ammonium sulfate which is commonly found in agricultural soil and water. Sulfate attack can also occur due to the decay of organic matter in marshy areas, shallow lakes, mining pits and sewer pipes which can lead to the formation of H_2S. There are three main modes of concrete deterioration associated with sulfate attack: expansion type reaction of sulfates with reactive hydrated aluminates forming Ettringite or Candlot's salt, acidic type deterioration due to the formation of gypsum, and scaling of the concrete surface in successive layers (onion peeling). For most constructions, a maximum mortar bar expansion of 0.02 percent is allowed for all types of ordinary Portland cement (OPC) Figure 4.4 represents the steps of the soundness test followed in this research.

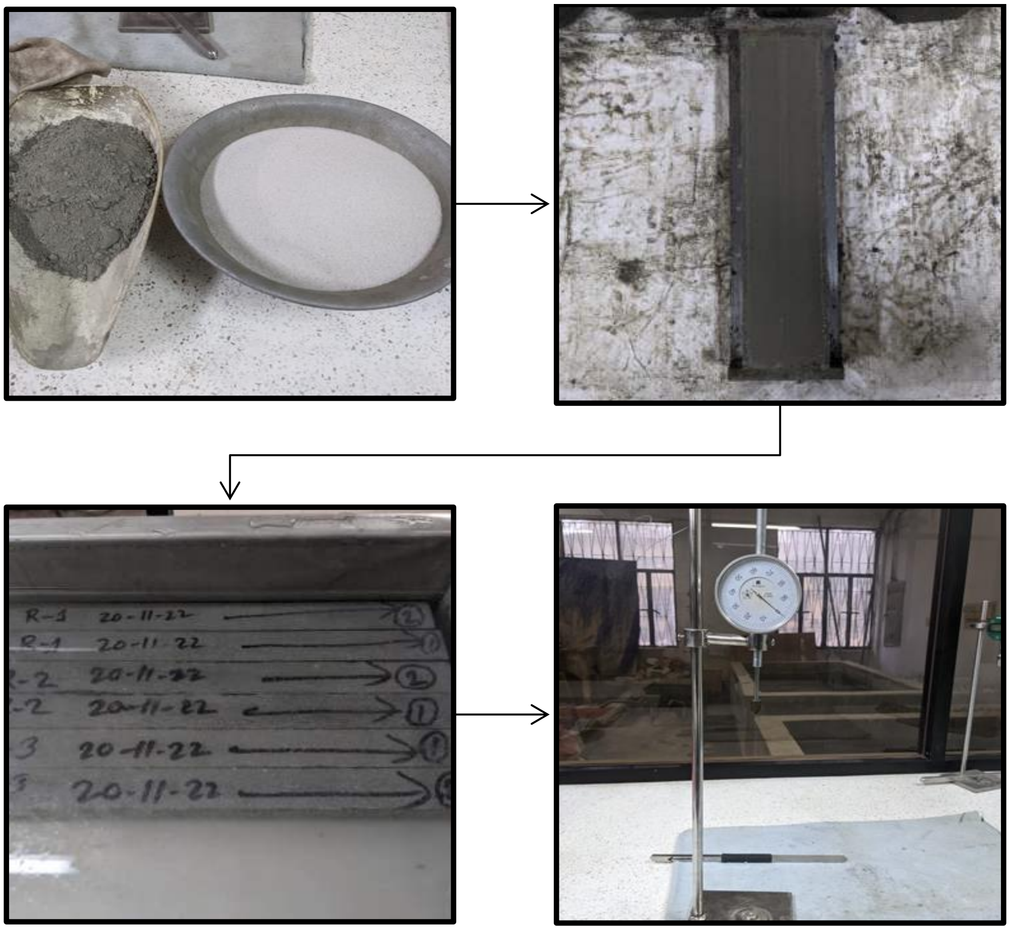


Figure 4.4: Soundness of cement by expansion of cement mortar bars

B) Le-Chatelier Accelerated Test

The Le-Chatelier accelerated test is a widely employed method in the cement industry to evaluate the likelihood of unsoundness in cement that arises from an excess of free lime. This test entails immersing cement specimens in boiling water for a specified duration, followed by cooling and scrutinizing them for any indications of cracking or deformation. Its purpose is to expedite the cement's hydration process, which can uncover potential problems related to excess free lime that might remain undetected under slower curing circumstances. The outcomes of this test can furnish valuable insights into the quality and applicability of the cement for different purposes. The expansion limit for OPC cement and slag cement is 10 mm according to Standard Le-Chatelier accelerated test (BS 4550: Part 3) method.

Composition of mortars used for Le-Chatelier accelerated test

- Water/Cement =0.485
- Cement: Sand = 1: 2.75
- Cement = 436.33 gm; Ottowa sand = 1200 gm; Water = 211.62 gm

4.5.5 Compressive Strength Test

Compressive strength is the most important property as cement is a brittle material and has very low tensile strength (one tenth of its compressive strength). The process of strength development in cement is called hardening, which occurs through the crystallization of calcium-silicate-hydrates gel (C-S-H gel) over weeks or months. The strength of cement increases over time, and it is important to specify the time at which the strength test is to be conducted. Typical compressive strength is measured at 3 days, 7 days, 28 days, and 90 days (for low heat of hydration cement). The development of strength can be affected by several factors including water-cement ratio, cement-fine aggregate ratio, type and grading of fine aggregate, mixing and molding methods, curing conditions, size and shape of specimen, moisture content, loading conditions and age. Table 4.5 lists the minimum compressive strength for different curing ages.

Table 4.5: Minimum compressive strength to be attained at 3, 7, and 28 days

Age (days)	Minimum compressive strength, psi (MPa)
	OPC (Type-1) [ASTM C150-18]
3	1740 (12)
7	2760 (19)
28	4060 (28)

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Overview

The cement product is manufactured using raw materials such as clinker, gypsum, quantum electric arc furnace slag, and ladle refining slag. Slag is introduced into the mixture of raw materials by substituting clinker due to their similar chemical properties. To ensure quality, the standard properties of the cement product are tested in accordance with ASTM standards. The cement samples obtained from the experiment are carefully examined to investigate a more effective and less expensive formula for the raw material mixture.

5.2 Chemical Composition of Cement Mixes

Chemical composition of cement mixes i.e. twelve samples of cement mixes (S-1 to S-12) were given in Table 5.1. From 5.1 table, it is evident that the chemical compounds of the samples replaced by LRF slag is quite similar to the OPC cement (S-1, 0% slag). Also, the samples replaced by QEAF slags show similar chemical compositions except for the Fe_2O_3 compound.

Table 5.1: Chemical composition of cement mixes

Element	**S-1**	**S-2**	**S-3**	**S-4**	**S-5**	**S-6**	**S-7**	**S-8**	**S-9**	**S-10**	**S-11**	**S-12**
	0% slag	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**5%**	**10%**	**15%**	**20%**	**25%**
		LRF slag						**QEAF slag**				
Fe_2O_3	3.54	3.57	3.60	3.62	3.65	3.68	3.71	4.96	6.37	7.79	9.20	10.62
SiO_2	21.08	21.18	21.28	21.38	21.48	21.59	21.69	20.88	20.67	20.47	20.27	20.07
Al_2O_3	4.89	4.78	4.67	4.56	4.45	4.34	4.23	4.90	4.92	4.93	4.94	4.96
CaO	64.73	64.43	64.12	63.81	63.51	63.20	62.90	63.03	61.33	59.63	57.94	56.24
MgO	1.45	1.67	1.89	2.11	2.33	2.55	2.77	1.67	1.90	2.13	2.36	2.59
MnO	0.00	0.08	0.16	0.24	0.32	0.40	0.48	0.23	0.46	0.69	0.92	1.15

SO_3	1.60	1.64	1.68	1.72	1.76	1.80	1.84	1.60	1.61	1.61	1.62	1.63
TiO_2	0.00	0.03	0.07	0.10	0.13	0.16	0.20	0.04	0.08	0.12	0.16	0.21
P_2O_5	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.05	0.07	0.09	0.12
Na_2O	0.00	0.01	0.02	0.03	0.03	0.04	0.05	0.02	0.03	0.05	0.06	0.08

Using the formula of Bogue's compound composition, the weight percentages of four crystalline compounds of the cement samples are calculated theoretically and given in Table 5.2. Bogue's compound composition formula is valid for Al2O3/Fe2O3 >0.64. That is why the theoretical composition for S-10, S-11 and S-12 were not determined as their value was lower than 0.64. For the rest of the samples, formation of the C_3S, C_2S value after 28 days are in recommended range which is given in Table 4.3. The C_3A after 28 days was less than the recommended range for all of the samples; and for S-9, C_4AF value is lower.

Table 5.2: Weight percentage of crystalline compounds in the cement samples

Element	**S-1**	**S-2**	**S-3**	**S-4**	**S-5**	**S-6**	**S-7**	**S-8**	**S-9**	**S-10**	**S-11**	**S-12**
	0% slag	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**5%**	**10%**	**15%**	**20%**	**25%**
		LRF slag						**QEAF slag**				
Al_2O_3/Fe_2O_3	1.38	1.34	1.30	1.26	1.22	1.18	1.14	0.99	0.77	0.63	0.54	0.47
C_3S	60.8	59.4	57.9	56.5	55.1	53.6	52.2	53.3	45.8	-	-	-
C_2S	14.7	16.0	17.4	18.8	20.1	21.5	22.9	19.7	24.8	-	-	-
C_3A	6.97	6.63	6.29	5.96	5.62	5.28	4.94	4.6	2.3	-	-	-
C_4AF	10.8	10.9	10.9	11.0	11.1	11.2	11.3	15.1	19.4	-	-	-

5.3 Fineness Test Results

Though for OPC cement (without slag) minimum fineness required is 300 m^2/kg; for the cement prepared using different percentages of slag, it is required to achieve fineness more than 400 m^2/kg. It can be seen that except for the S-1 (without slag), fineness of all the cement samples used in this research is more than 400 m^2/kg. Fineness report is listed in Table 5.3 (performed by Crown Cement PLC).

Table 5.3: Fineness of the samples

Sample	Clinker wt%	Gypsum wt%	LRF Slag wt%	QEAF Slag wt%	Blaine Test m^2/kg
S-1	97	3	-	-	307
S-2	92		5		403
S-3	87		10		411
S-4	82		15		400
S-5	77		20		407
S-6	72		25		422
S-7	67		30		417
S-8	92		-	5	411
S-9	87			10	422
S-10	82			15	426
S-11	77			20	433
S-12	72			25	407

5.4 Normal Consistency Test Results

The normal consistency test conducted according to ASTM standard specification C187-11, and the results are listed in Table 5.4. It can be observed from the results that, normal consistency does not vary with the addition of slags in cement.

Table 5.4: Normal consistency of the cement samples

Serial No.	Clinker wt%	Gypsum wt%	LRF Slag wt%	QEAF Slag wt%	Normal Consistency
S-1	97	3	-	-	23.5%
S-2	92		5		24.5%
S-3	87		10		21.0%
S-4	82		15		21.0%
S-5	77		20		21.5%
S-6	72		25		22.0%
S-7	67		30		22.5%
S-8	92		-	5	24.0%
S-9	87			10	23.0%
S-10	82			15	22.5%
S-11	77			20	22.5%
S-12	72			25	22.5%

5.5 Initial and Final Setting Time Results

Determination of setting time conducted following ASTM C191-08 specification, and the result for all the samples is given in Figure 5.1. It can be observed from the figure that initial and final setting time of all the samples are within the range of the initial and final setting time of OPC cement. The details of the calculations are presented in Appendix A. According to ASTM C191-08 standard, for OPC initial setting time is not less than 45 minutes and final setting time is not more than 375 minutes.

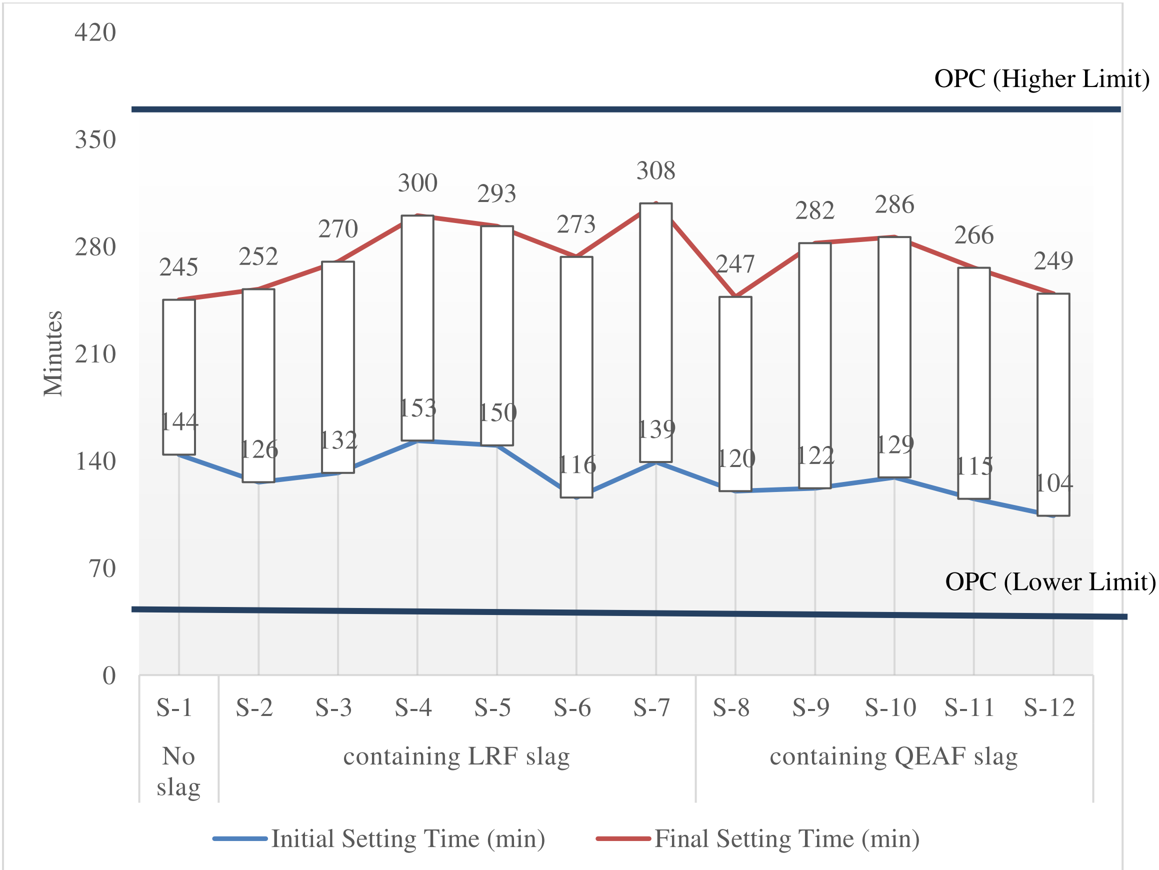


Figure 5.1: Initial and final setting time for the samples

5.6 Soundness Test Results

5.6.1 Soundness of Cement by Expansion of Cement Mortar Bars

The soundness result is summarized in Table 5.5 for all the mortar samples using the cements produced by no clinker replacement as well as replacing clinker by LRF slag and QEAF slag.

All the expansions are within the limit which is 0.02% except the S-9 which is 10% replacement of clinker by QEAF slag. Maximum samples show shrinkage rather than expansion (negative value indicates shrinkage of cement mortar bars)

Table 5.5: Soundness results of cement by expansion of cement mortar bars

Serial No.	Clinker wt%	Gypsum wt%	LRF Slag wt%	QEAF Slag wt%	Average mortar bar expansion, %
S-1	97	3	-	-	-0.014
S-2	92		5		-0.012
S-3	87		10		-0.006
S-4	82		15		-0.008
S-5	77		20		-0.012
S-6	72		25		-0.012
S-7	67		30		-0.008
S-8	92		-	5	0.020
S-9	87			10	0.030
S-10	82			15	0.000
S-11	77			20	-0.010
S-12	72			25	-0.004

5.6.2 Le-Chatelier Accelerated Test (BS 4550: Part 3)

After conducting the soundness test using Le-Chatelier accelerated test, most of the samples show shrinkage that's why another soundness test was performed which is Le-Chatelier accelerated test. The details of the calculations are presented in Appendix A.

The results for soundness test using Le-Chatelier accelerated test is listed in Table 5.6. All the expansion was within the standard limit (which is 10 mm expansion according to BS 4550: part 3) for the mortar samples using OPC cement and slag cement.

Table 5.6: Soundness test results according to Le-Chatelier accelerated test

Serial No.	Clinker wt%	Gypsum wt%	LRF Slag wt%	QEAF Slag wt%	Average expansion, mm
S-1	97	3	-	-	1.00
S-2	92		5		0.50
S-3	87		10		0.50
S-4	82		15		0.83
S-5	77		20		0.50
S-6	72		25		1.17
S-7	67		30		1.00
S-8	92		-	5	1.00
S-9	87			10	0.50
S-10	82			15	0.50
S-11	77			20	0.83
S-12	72			25	0.67

5.7 Compressive Strength Test Results

Compressive strength for the mortars using twelve cement samples were determined at 3, 7 and 28 days after curing them properly. The compressive strength results for cement mortar with different proportions of LRF slag mix are given in Figure 5.2. From the figure it can be observed that clinker can be replaced up to 25% by LRF slag in cement as strength properties are higher or similar to normal OPC cement (according to ASTM C150-18 i.e., 28MPa as well as EN 196-1 standard which is 32.5 R; R indicates for high early strength class i.e., more than 10MPa after 7 days). It was found that S-4 i.e.15% of the LRF slag can be added without hampering the traditional cement clinker performances. 10% of QEAF slag (sample S-9) can be added without hampering the traditional cement clinker performances. The details of the calculations are presented in Appendix A.

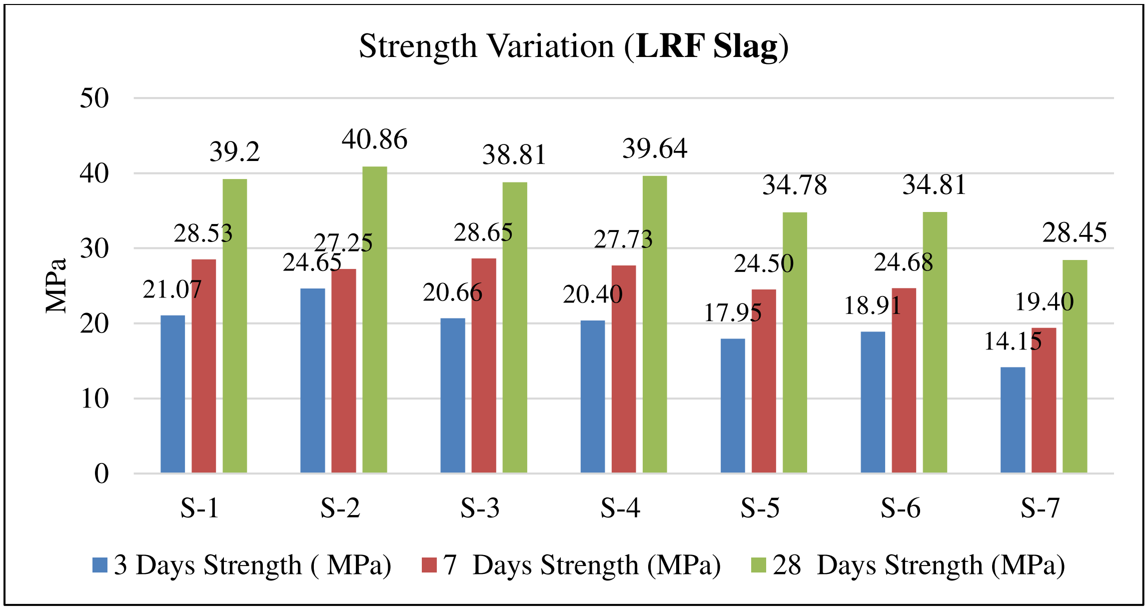


Figure 5.2: Compressive strength for cement mortar mix with LRF slag

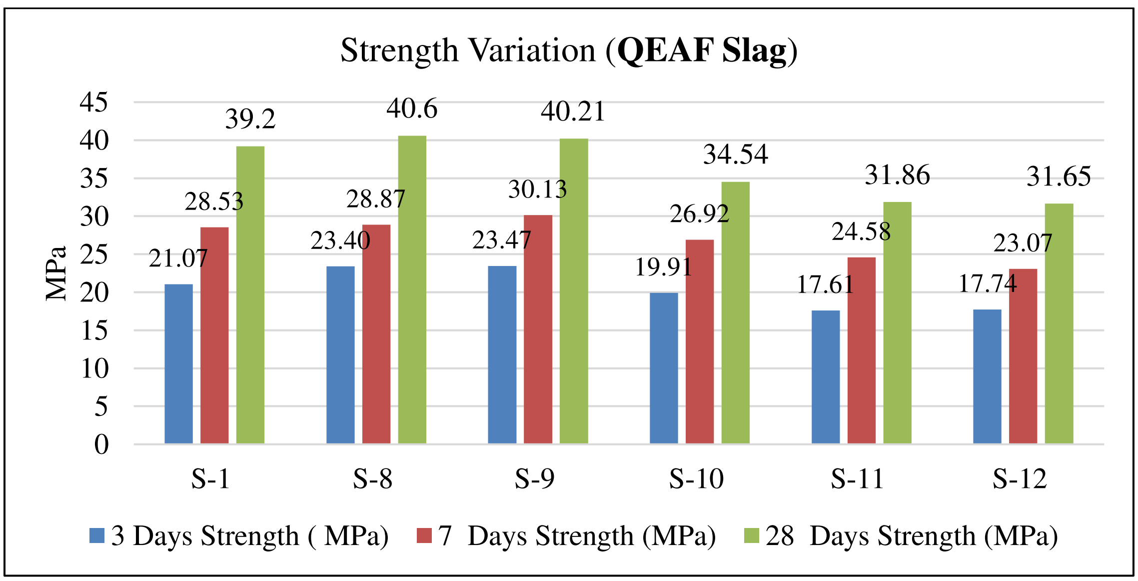


Figure 5.3: Compressive strength for cement mortar mix with QEAF slag

5.8 Free Lime Test and Loss on Ignition (L.O.I) Test Results

After conducting the fineness test, normal consistency test, initial and final setting time of cement, soundness test and compressive strength test the recommendable samples are 5-15% LRF slag addition (S-1 to S-4) and 5-10% QEAF slag addition (S-8 and S-9) for the replacement of clinker in the cement mixer. Free lime test and loss on ignition (L.O.I) test were conducted on S-4 and S-9 to evaluate their compliance with the standard specifications. The purpose of this investigation was to assess the data obtained from the test and determine whether the samples satisfy the required standards. Table 5.7 and Table 5.8 shows that results meet the standard values.

Table 5.7: Free lime test according to ASTM C150

Free Lime Test		
Sample	Value %	Standard ASTM C150
S-4 (15% LRF Slag)	1.93	should not exceed 4%
S-9 (10% QEAF Slag)	1.12	

Table 5.8: Loss on ignition test according to EN 197-1

Loss on Ignition Test		
Sample	Value %	European Standard EN 197-1
S-4 (15% LRF Slag)	3.47	should not exceed 5%
S-9 (10% QEAF Slag)	2.85	

Utilization of Quantum Electric Arc Furnace (QEAF) and Ladle Refining Furnace (LRF) slag Generated in GPH ISPAT as Fine Aggregate and Coarse Aggregate Replacement in CONCRETE

CHAPTER 6

MATERIALS AND METHODS

6.1 Introduction

In this part experiments were carried out to study the utilization of QEAF slag and LRF slag as replacement of both coarse and fine aggregates in concrete. Concrete's compressive strength and splitting strength tests for different combinations of replacement were investigated to find the optimum percent of replacement for coarse and fine aggregates individually and for coarse and fine aggregates combined. Aggregate mechanical properties were determined before the application in concrete.

In this chapter, the properties of the materials used in this research, the details of the selected specimens, the description and preparation technique of the specimens, are discussed.

6.2 Material Properties

The main constituents of concrete used for this research are cement, fine aggregate, coarse aggregate, QEAF slag of size 3/4-inch (19 mm) downgrade, QEAF slag of size 1/5-inch (5 mm) downgrade, and LRF slag of size 1/5-inch (5 mm) downgrade. Cement type used was OPC, Sylhet sand was used as fine aggregates, and stone chips of size 3/4-inch downgrade were used as coarse aggregates. The properties of these materials were tested in the laboratory prior using them in concrete.

6.2.1 Cement

OPC cement was used in this experiment. The chemical composition of the OPC cement is provided in Table 6.1.

Table 6.1: Chemical composition of OPC cement used in this research

Constituents	wt(%)
SiO_2	21.08%
Al_2O_3	4.89%
Fe_2O_3	3.54%
CaO	64.73%
MgO	1.45%
SO_3	1.6%

6.2.2 Sand as Fine Aggregate

Sylhet sand was used in this experiment as fine aggregates (Figure 6.1). The sieve analysis was performed in accordance with ASTM C136/C136-19 (Figure 6.2). The fineness modulus of this sand was determined to be 3.13. The gradation data of the fine aggregates are shown in the Appendix B.

Figure 6.1: Sylhet sand as fine aggregate

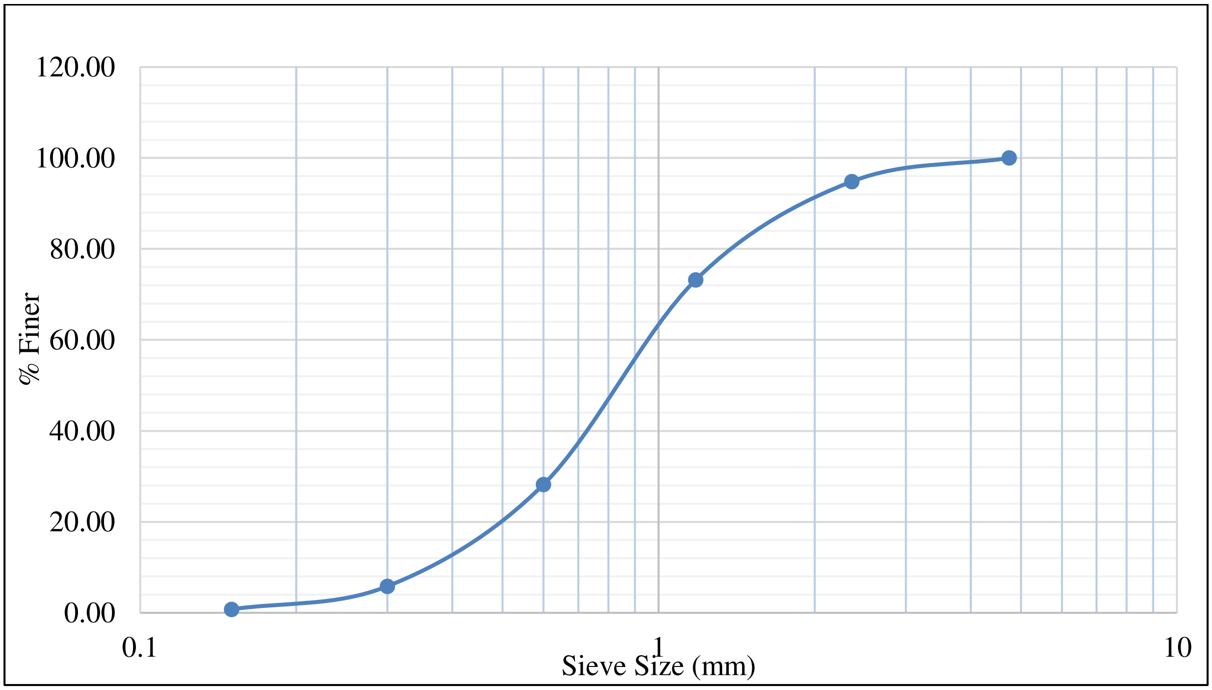


Figure 6.2: Grain size distribution of Sylhet sand used in this experiment

6.2.3 QEAF Slag as Fine Aggregate Replacement (Size 5 mm Downgrade)

QEAF slag of size below 5 mm (1/5-inch) was used as fine aggregate replacement in concrete (Figure 6.3). Sieve analysis and fineness modulus of fine slag was determined according to ASTM C136/C136-19 (Figure 6.4). The fineness modulus was determined to be 3.5. The gradation data is given in Appendix B.

Figure 6.3: QEAF slag of size 5 mm downgrade used as fine aggregate replacement

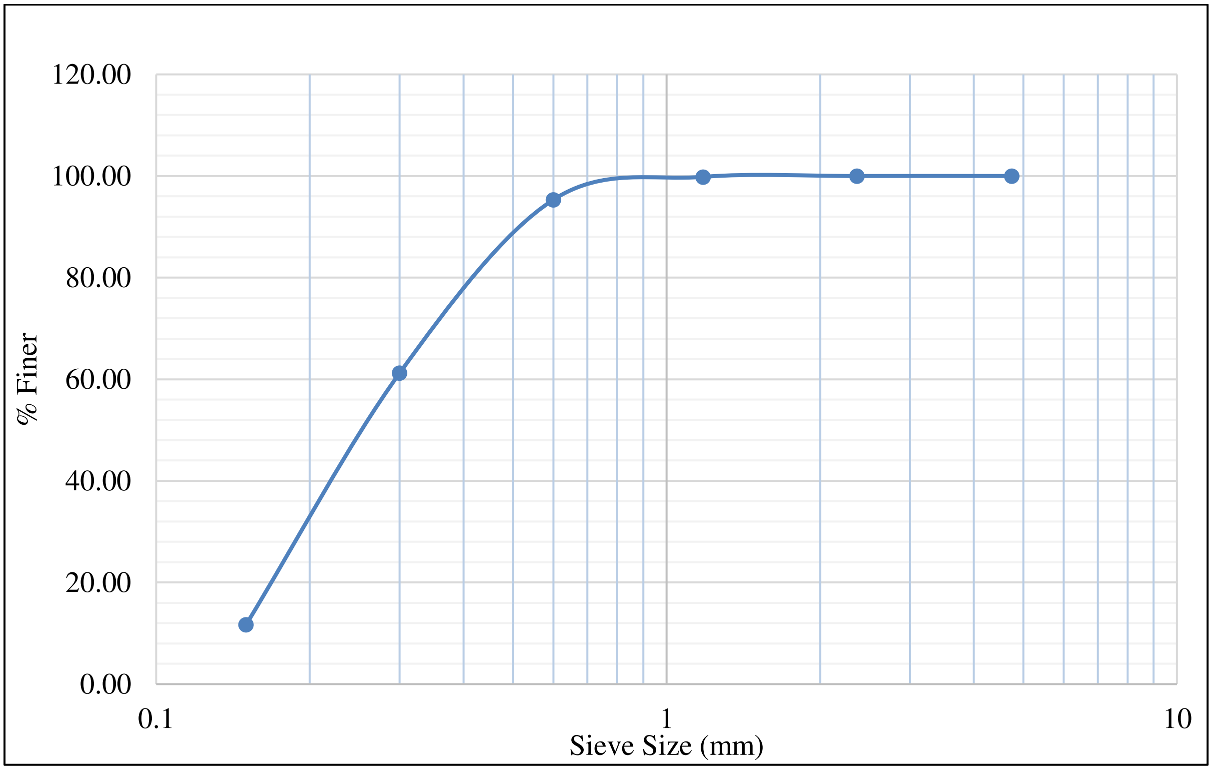


Figure 6.4: Grain size distribution of QEAF slag as fine aggregate replacement

6.2.4 LRF Slag as Fine Aggregate Replacement

LRF slag of size below 5 mm (1/5-inch) was used as fine aggregate replacement in concrete (Figure 6.5). Sieve analysis and fineness modulus of fine slag was determined according to ASTM C136/C136-19 (Figure 6.6). The fineness modulus was found to be 1.47. The gradation data is given in Appendix B.

Figure 6.5: LRF slag used as fine aggregate replacement

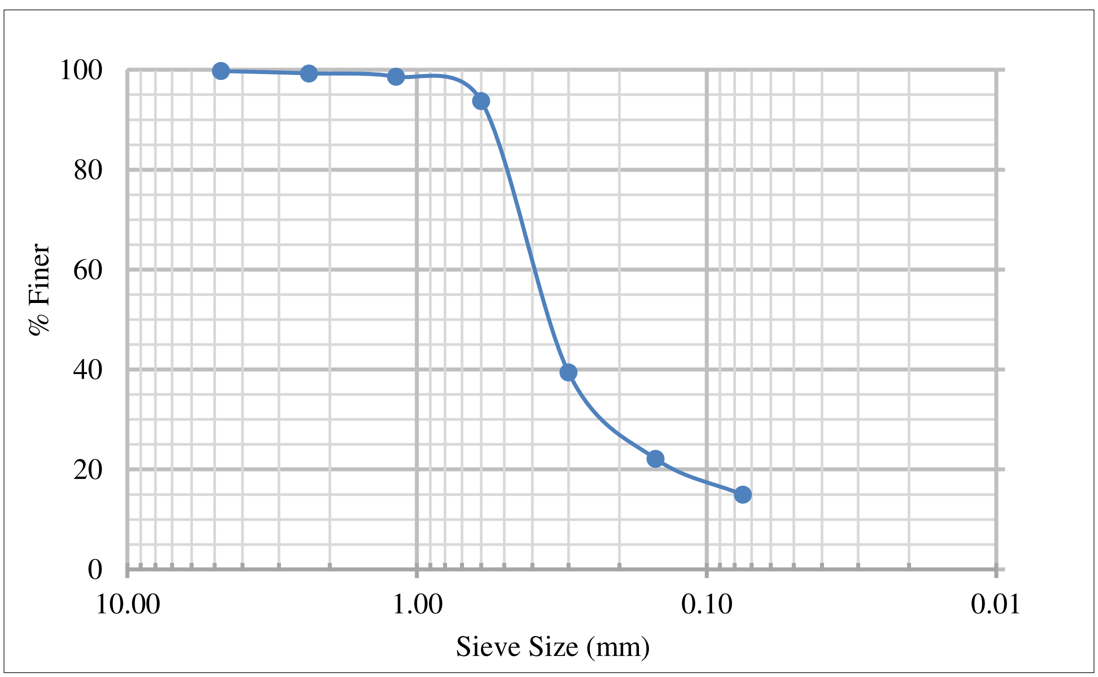


Figure 6.6: Grain size distribution of LRF slag as fine aggregate replacement

6.2.5 Stone Chips as Coarse Aggregate

Stone chips of size 3/4-inch downgrade was used in this experiment (Figure 6.7). Sieve analysis was performed in accordance with ASTM C136/C136M-19. Size distribution of stone chips are represented in Figure 6.8. The gradation data is given in Appendix B.

Figure 6.7: Stone chips used as coarse aggregates

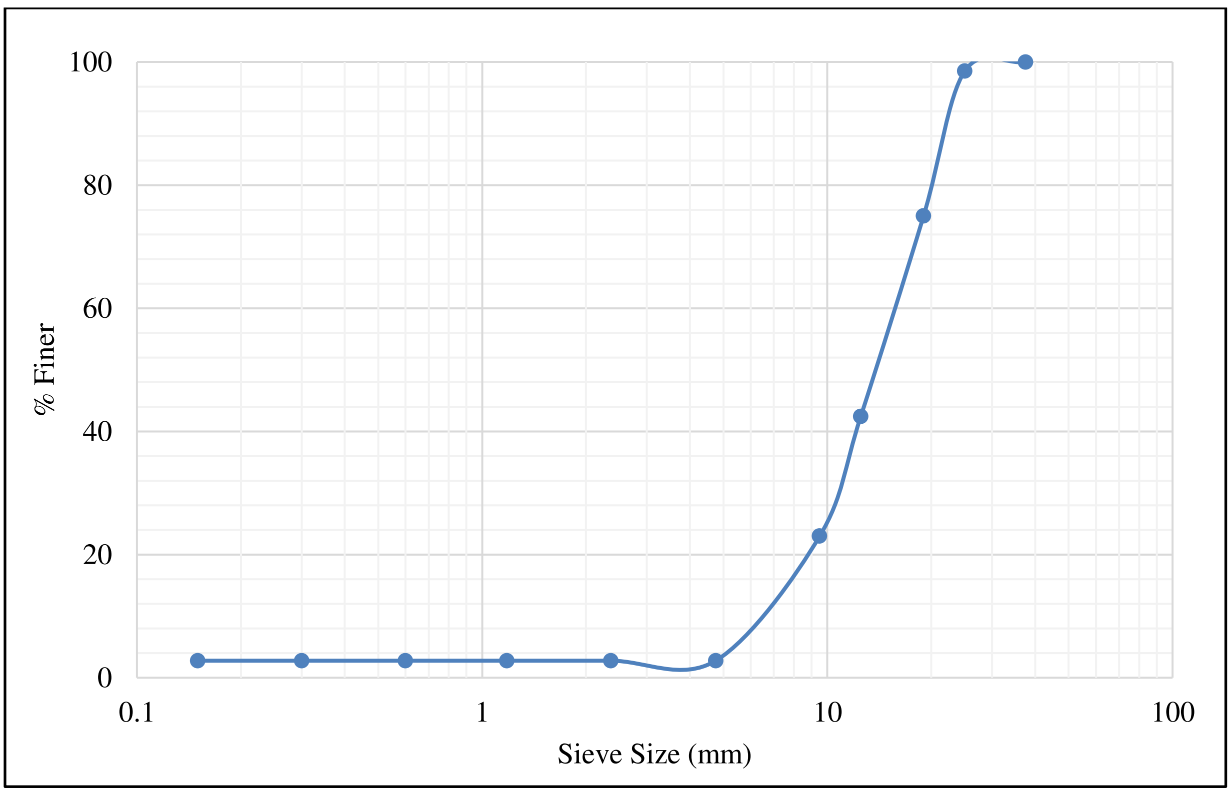


Figure 6.8: Grain size distribution of stone chips used in this experiment

6.2.6 QEAF Slag as Coarse Aggregate Replacement

QEAF slag of size 3/4-inch downgrade was used to replace coarse aggregate in concrete (Figure 3.9). Grain size distribution of slag is represented in Figure 6.10. The gradation data is given on Appendix B.

Figure 6.9: QEAF slag of size ¾ inch downgrade used as coarse aggregate replacement

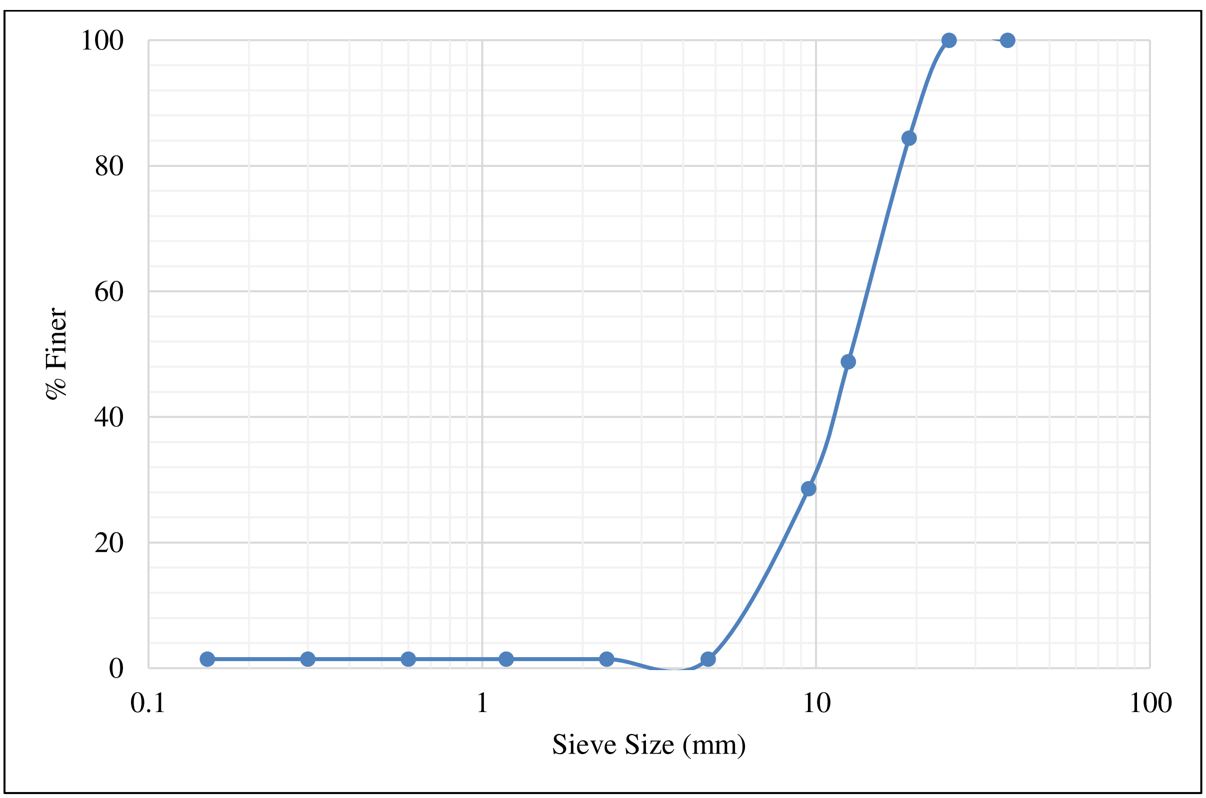


Figure 6.10: Grain size distribution of QEAF slag of size ¾ inch downgrade

6.2.7 Concrete

Concrete mix ratio considered for cement, fine aggregates and coarse aggregates was 1:1.5:3; and water cement ratio was 0.45. For the first step experiment, replacement of coarse aggregates and fine aggregates were done individually. In the second step of this experiment, replacement of fine and coarse aggregates was done combinedly. The considered combinations were based on the results of the first step experiment; and given in Table 6.2.

Table 6.2: Mix design of concrete for first and second step experiment

Mix No.	Slag Type	Stone Chips (% vol^{m})	Sand (% vol^{m})	Slag (Coarse) (% vol^{m})	Slag (Fine) (% vol^{m})	W/C ratio
Mix with no slag						
1	-	100	100	0	0	0.45
First Step Experiment						
2	QEAF slag (Coarse)	40	100	60	0	0.45
3		20	100	80	0	
4		0	100	100	0	
5	QEAF slag (Fine)	100	90	0	10	
6			80		20	
7			70		30	
8			60		40	
9			50		50	
10	LRF slag	100	90	0	10	0.45
11			80		20	
12			70		30	
13			60		40	
14			50		50	
Second Step Experiment						
15	QEAF slag (Coarse and Fine)	20	95	80	5	0.45
16		20	90	80	10	
17		20	85	80	15	
18		0	95	100	5	
19		0	90	100	10	
20		0	85	100	15	

6.3 Aggregate Mechanical Properties

It was important to understand if the coarse slag would behave like stones. So, mechanical properties of the coarse slag were determined.

6.3.1 Aggregate Impact Value

The aggregate impact value gives a relative measure of the resistance of an aggregate to "sudden shock or impact", which in some aggregates differs from its resistance to a slowly applied compressive load. With aggregate of aggregate impact value (AIV) higher than 30 the result may be anomalous. Also, aggregate sizes larger than 14 mm are not appropriate to the aggregate impact test.

6.3.2 Aggregate Crushing Value

The aggregate crushing value gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. With aggregate of an aggregate crushing value higher than 30 the result may be anomalous, and in such cases the ten percent fines value (clause 8) should be determined instead.

6.3.3 Ten Percent Fines Value

The ten percent fines value gives a measure of the resistance of an aggregate to crushing which is applicable to both weak and strong aggregate. The standard ten percent fines shall be made on aggregate passing a 14.0 mm BS test sieve and retained on a 10.0 mm BS test sieve.

6.3.4 Flakiness Index

This method is based on the classification of aggregate particles as flaky when they have a thickness (smallest dimension) of less than 0.6 of their nominal size, this size being taken as the mean of the limiting sieve apertures used for determining the size fraction in which the particle occurs. The flakiness index of an aggregate sample is found by separating the flaky particles and expressing their mass as a percentage of the mass of the sample tested. The test is not applicable to material passing a 6.30 mm BS test sieve or retained on a 63.0 mm BS test sieve.

6.3.5 Elongation Index

This method is based on the classification of aggregate particles as elongated when they have a length (greatest dimension) of more than 1.8 of their nominal size, this size being taken as the mean of the limiting sieve apertures used for determining the size fraction in which the particle occurs. The elongation index of an aggregate sample is found by separating the elongated particles and expressing their mass as a percentage, of the mass of the sample tested. The test is not applicable to material passing a 6.30 mm BS test sieve or retained on a 50 mm BS test sieve.

6.3.6 Angularity Number

The angularity number is determined from the proportion of voids in a sample of aggregate after compaction in the specified manner. This property is used mainly in the design of mix proportions and in research. Angularity or absence of rounding of the particles of an aggregate is a property which is of importance because it affects the ease of handling of a mixture of aggregate and binder (e.g., the workability of concrete) or the stability of mixtures that rely on the interlocking of the particles. The least angular (most rounded) aggregates are found to have about 33% voids and the angularity number is defined as the amount by which the percentage of voids exceeds 33. The angularity number ranges from 0 to about 12. Since considerably more compactive effort is used than in the test for bulk density and voids, the percentage of voids will be different. Weaker aggregates may be crushed during compaction and the results will be anomalous if this method is applied to any aggregate which breaks down during the test.

6.4 Specimen Preparation

The test samples were prepared in the concrete laboratory of the Department of Civil Engineering, BUET.

6.4.1 Mixing of Concrete

A motorized mixing machine was used for mixing concrete by filling it with the proper amounts of cement, sand, coarse aggregate, and water (Figure 6.11). It was ensured that the concrete was thoroughly mixed. The slump has been measured to ensure that the concrete is sufficiently workable. The slump value was kept between 75-100 mm.

Figure 6.11: Mixing of Concrete

6.3.2 Concrete Casting

The fresh concrete mix was carefully poured on the cylinder (Figure 6.12). Compaction of concrete was done using a mechanical vibrator to ensure that no air void exists in the concrete.

Figure 6.12: Concrete Casting

6.3.3 Concrete Curing

The hydration process of concrete is required for ensuring better quality of concrete. Proper curing ensures that the reaction process is completed sufficiently and concrete gains its required strength. Water curing method has been applied after the final setting of the specimens. The cylinders were poured into the pond fully to cure for 7 days, 14 days and 28 days (Figure 6.13).

Figure 6.13: Concrete curing

6.3.3. Compressive Strength Test

The compressive strengths of concrete have been determined by performing compression tests in accordance with ASTM C39/C39M-21. After the curing period, these cylinders were tested in a compression testing machine (Figure 6.14).

Figure 6.14: Cylinder Test

Twelve sets of cylinders were casted for each combination. Among them three were tested at 7 days, three were tested at 14 days, and lastly three were tested at 28 days. Another three of them were tested for splitting strength test after 28th days of curing. Though cylinders were tested for 7 days, 14 days and 28 days of curing. Compressive strength development after 28 days of curing is considered to be the exact compressive strength of the concrete.

6.3.4 Splitting Tensile Strength Test

One of the important properties of concrete is "tensile strength" as structural loads make concrete vulnerable to tensile cracking. Tensile strength of concrete is much lower than its compressive strength (that's why steel is used to carry the tension forces). To determine the tensile strength, indirect methods are applied due to the difficulty of the direct method. These indirect techniques are: split cylinder test and flexural test. Splitting test for this experiment is done after curing the concrete for 28 days (Figure 6.15).

Figure 6.15: Splitting Tensile Strength Test

CHAPTER 7

RESULTS AND DISCUSSIONS: CONCRETE

7.1 Aggregate Mechanical Properties

The mechanical properties of QEAF slags are all satisfied compared to that of desired properties of aggregates. The properties like Aggregate Impact Value (AIV), Aggregate Crushing Value (ACV), Los Angeles Abrasion values were all lower than 30, Angularity Number was lower than 12, Flakiness and Elongation Index was very low for QEAF coarse slag; satisfying all the criteria of a coarse aggregate. Table 7.1 represents the mechanical properties of the coarse QEAF slag (3/4 inch downgrade), their test standards and recommended values.

Table 7.1: Aggregate Mechanical Properties of Coarse QEAF Slag

	QEAF Slag	Standard	Recommended
Angularity Number Test	11	BS 812	0-12
Los Angeles Abrasion Test	24	ASTM C131-89	< 30
Unit Weight	4800 kg/m^3	ASTM C29	
AIV	28	BS 812	< 30
ACV	25	BS 812	< 30
TFV	130	BS 812	
Flakiness Index	6	BS 812	The lower the better
Elongation Index	20	BS 812	The lower the better
Absorption Capacity	1.8	ASTM C127	
Bulk Specific Gravity	3.68	ASTM C127	

As QEAF coarse slag behaves similar to that of typical coarse aggregates used in construction purposes, in this experiment coarse aggregate replacement was varied from 60% to 100%. But, for fine aggregates, there is no such criteria to match and compare. That's why in this experiment, for both QEAF and LRF fine slag, replacement varied from 10% to 50%.

7.2 Compressive Strength Test Result of First Step Experiment

Strength data for 7 days and 14 days are used to understand the strength gain rate of certain combinations. The compressive strength results of coarse aggregate replacement by QEAF, fine aggregate replacement by both QEAF and LRF slag is discussed in the next sections. The details of the calculations are presented in Appendix B.

7.2.1 Result of Coarse Aggregate Replacement by QEAF Slag

Figure 7.1 represents the experimental result for the replacement of coarse aggregates in concrete using QEAF coarse slag. It can be observed that, for 60% of replacement, the compressive strength is almost similar to that of the standard concrete. But, when coarse aggregates are replaced by 80% and 100%, the compressive strength increases by 34% and 29% respectively. So, QEAF slag as coarse aggregates can be used in regular concrete as well as in high strength concrete.

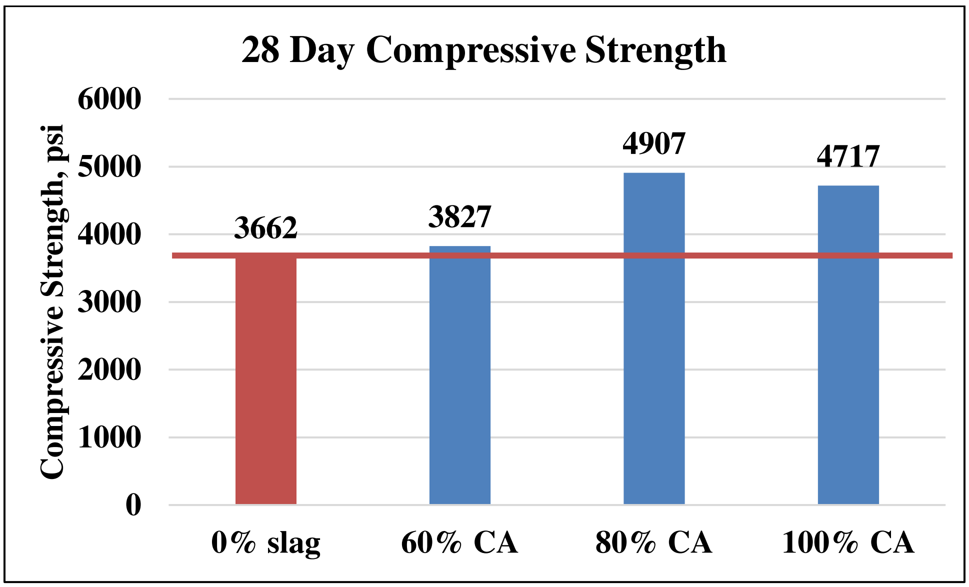


Figure 7.1: Compressive strength test result for coarse aggregates replaced by QEAF in concrete

7.2.2 Strength Gain Rate for 80% and 100% Coarse Aggregate Replacement

As compressive strength for 80% and 100% coarse aggregate replacement is higher than the standard, their strength gaining rate with curing period is analyzed. Compressive strength was measured at 7 days, 14 days and 28 days of curing for all of the samples. Standard concrete gains 22% more strength at 14 days of curing than 7 days; and 13% more strength at 28 days of curing than 14 days. Figure 7.2 represents the strength gaining rate for 80% and 100% coarse aggregate replacement by QEAF slag in concrete. For 80% coarse aggregate replacement with QEAF slags, it seemed that the strength at 14 days is lower than the strength at 7 days which is unusual; it may happen due to experimental mistakes. This result is therefore discarded from the discussion of strength gaining rate. For 100% coarse aggregate replacement by QEAF slag, concrete gains 10% more strength at 14 days of curing than 7 days; and 11% more strength at 28 days of curing than 14 days. It is observed that the strength gaining rate decreases with replacement of coarse aggregate with slag.

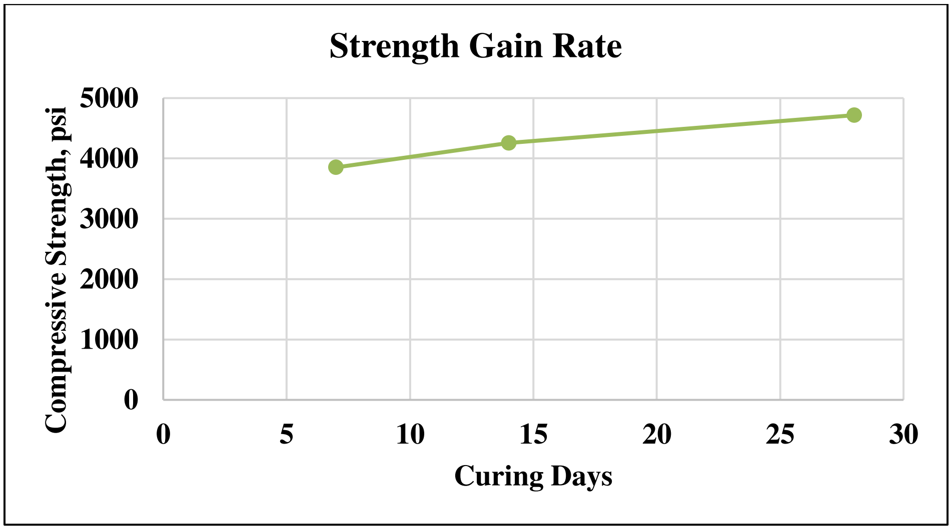


Figure 7.2: Strength gaining rate for coarse aggregate replacement in concrete

7.2.3 Result of Fine Aggregate Replacement by QEAF Slag

Figure 7.3 represents the experimental result for the replacement of fine aggregates in concrete using QEAF fine slag. It can be observed from the figure that 10% fine aggregates can be replaced by QEAF fine slag; as the strength also improved by 10% than the standard. It also shows that for 40% replacement of QEAF slag, strength seems higher than the standard. The result of this figure is a bit confusing, that’s why the experiment was repeated for the 40% replacement by QEAF fine slag. But again, the compressive strength was found to be 4420 psi for 40% replacement; which is again higher than the standard. But it is recommended to not replace the fine aggregates by more than 10%. Because, the silica in sand takes part in the cement hydration reaction in concrete, that’s why sand as fine aggregates cannot be replaced too much by slags, else the strength development of concrete might be hindered in the long run. As, concrete continues to develop its strength for consecutive two years.

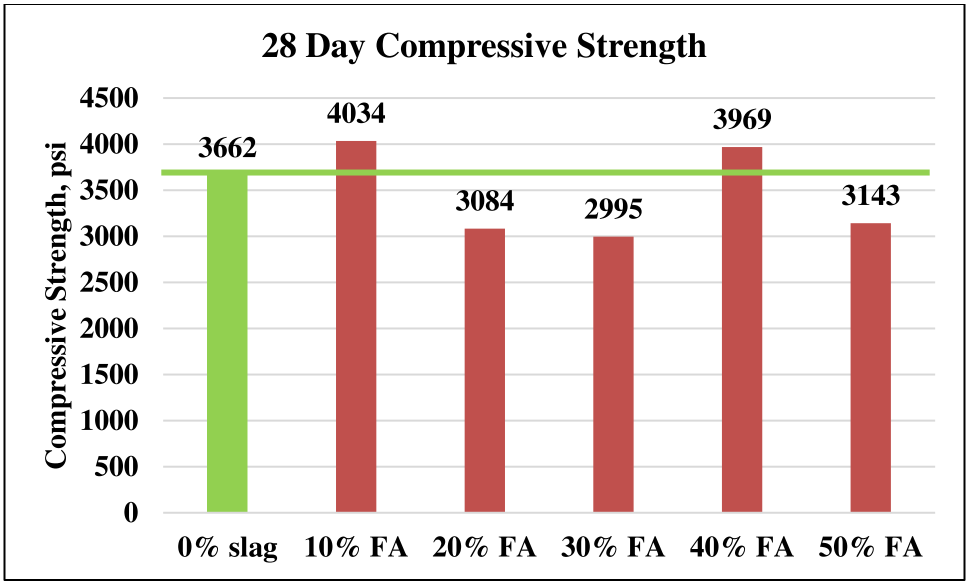


Figure 7.3: Compressive strength test result for fine aggregates replaced by QEAF in concrete

7.2.4 Strength Gain Rate for 10% Fine Aggregate Replacement

As, compressive strength for 10% fine aggregates replacement by QEAF fine slag is higher than the standard concrete; the strength gain rate is analyzed here. Figure 7.4 represents the strength gain rate for 10% replacement of fine aggregates. 8% more strength improvement was observed at 14 days than 7 days; and 17% more strength was observed at 28 days than 14 days. So, it is evident that, replacing 10% fine aggregates with QEAF fine slags improve faster strength gain rate at later stages.

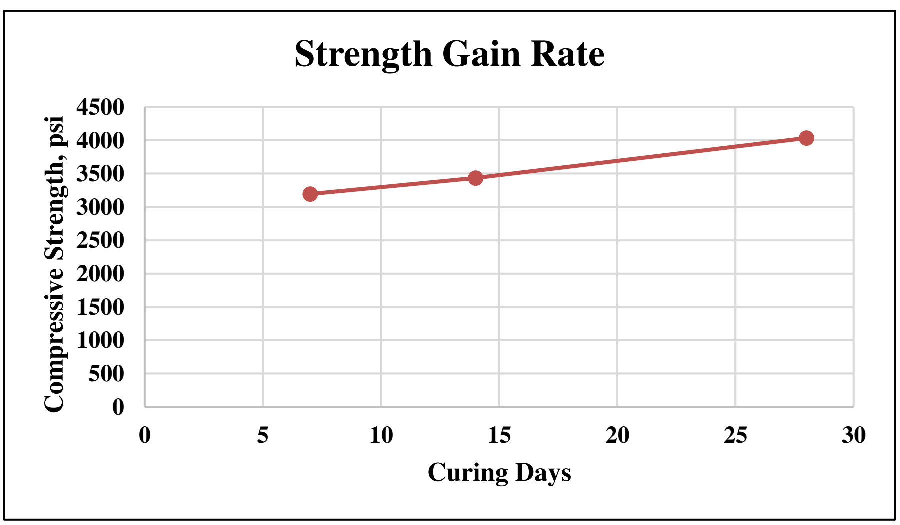


Figure 7.4: Strength gaining rate for fine aggregate replacement in concrete

7.2.5 Result of Fine Aggregate Replacement by LRF Slag

Figure 7.5 represents the compressive strength test result of concrete for the replacement of fine aggregates by LRF slag. It is clear from the figure that, LRF slag cannot be used as fine aggregate replacement in concrete; as strength of all the combinations are lower than the standard. A possible explanation for this behavior is that LRF slag behaves more like cement than fine aggregates when present in concrete as its chemical composition is almost similar to that of clinker composition.

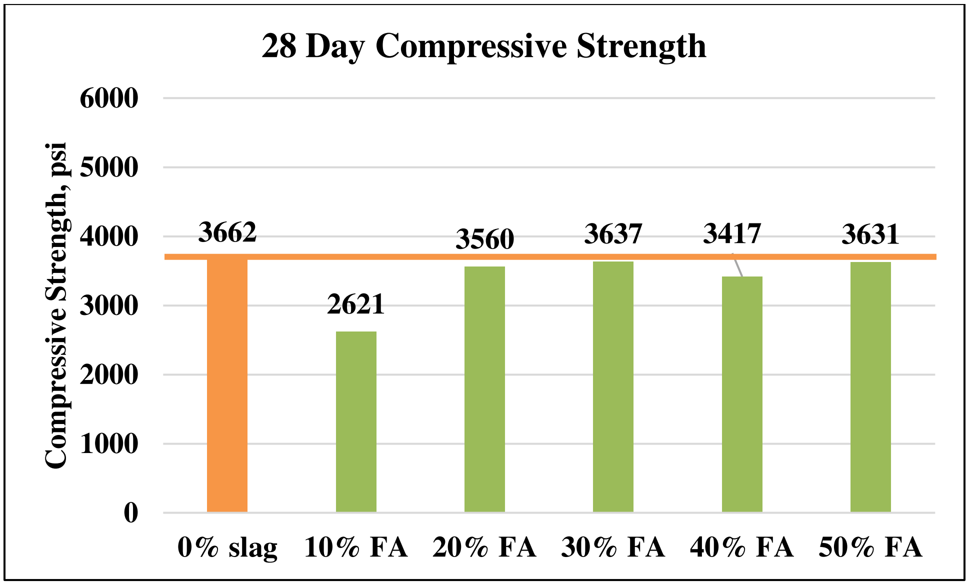


Figure 7.5: Compressive strength test result for fine aggregates replaced by LRF in concrete

7.3 Splitting Tensile Strength Test Result of First Step Experiment

Splitting tensile strength test results for first step experiment investigated the performances of QEAF slag as both coarse and fine aggregates and of LRF slag as only fine aggregates.

7.3.1 Result of QEAF Slag as Both Coarse and Fine Aggregate Replacement

Figure 7.7 represents the splitting tensile strength test results for coarse and fine aggregates replacement by QEAF slags in concrete. It is observed that, QEAF slags considerably increased the tensile strength of concrete for any combinations; as for each combination the strength is higher than the standard concrete.

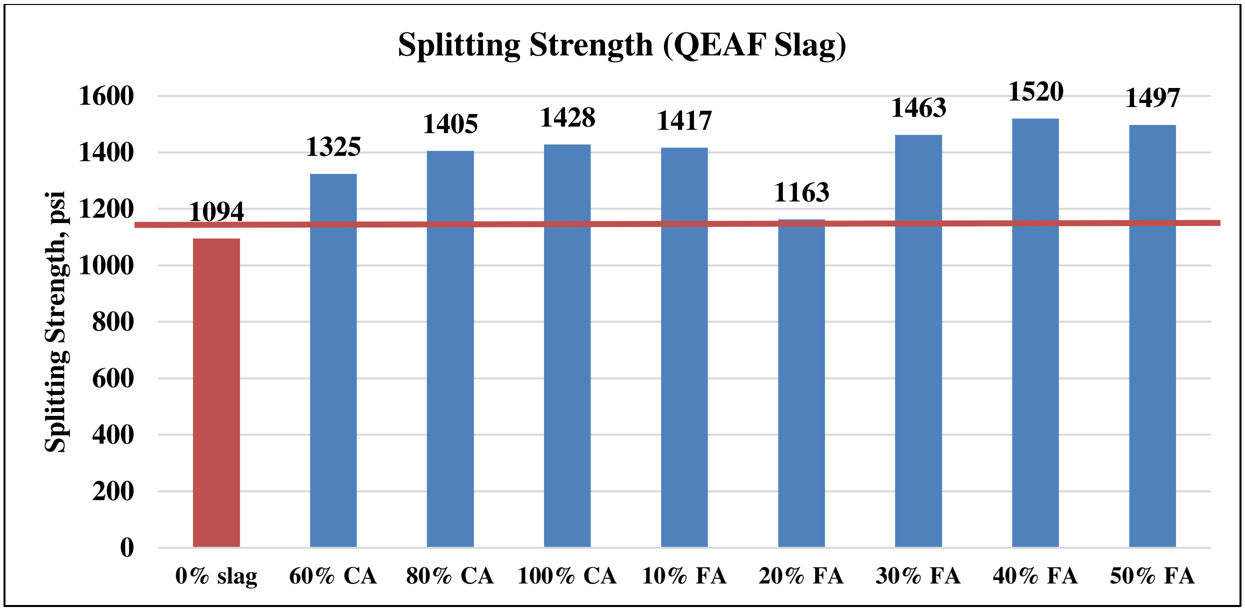


Figure 7.7: Splitting tensile strength for replacement of both coarse and fine aggregates by QEAF slag in concrete

7.3.2 Result of LRF Slag as Fine Aggregate Replacement

Figure 7.8 represents the splitting tensile strength test results for fine aggregates replacement by LRF slag in concrete; and it can be observed that though LRF slag does not helping in increase in compressive strength, it helps in increasing the tensile strength of concrete.

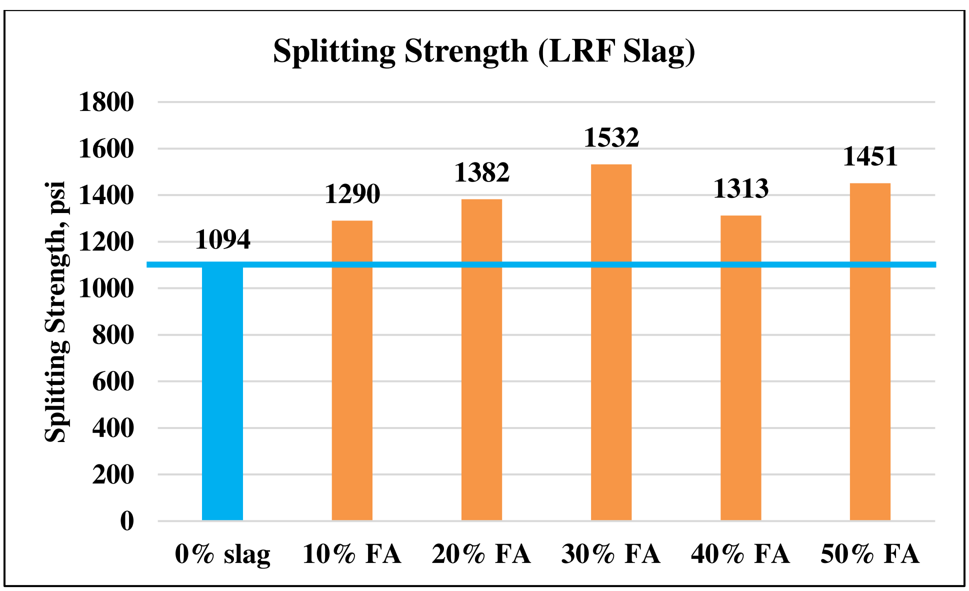


Figure 7.8: Splitting tensile strength for replacement of fine aggregates by LRF slag in concrete

7.4 Compressive Strength Test Result of Second Step Experiment

7.4.1 28 Day Compressive Strength Test

Figure 7.9 represents the compressive strength results for coarse and fine aggregates replaced combinedly by QEAF slag in concrete. The combination was considered based on the findings of the first step experiment. As, for 80% and 100% coarse aggregates replacement and 10% fine aggregates replacement, compressive strength found to be higher than the standard concrete; in this phase, coarse aggregate was replaced by 80 and 100%, and fine aggregate was replaced by 5% to 15%. From the figure it can be observed that, for combined replacement, 80% coarse and 10% fine replacement is the optimum combination. Another observation is that, though 100% coarse replacement individually increased the strength of concrete, for combined replacement of coarse and fine aggregates, it does not work very well. So, it is not recommended to replace the fine aggregates by slags when coarse aggregates are replaced 100% by slag.

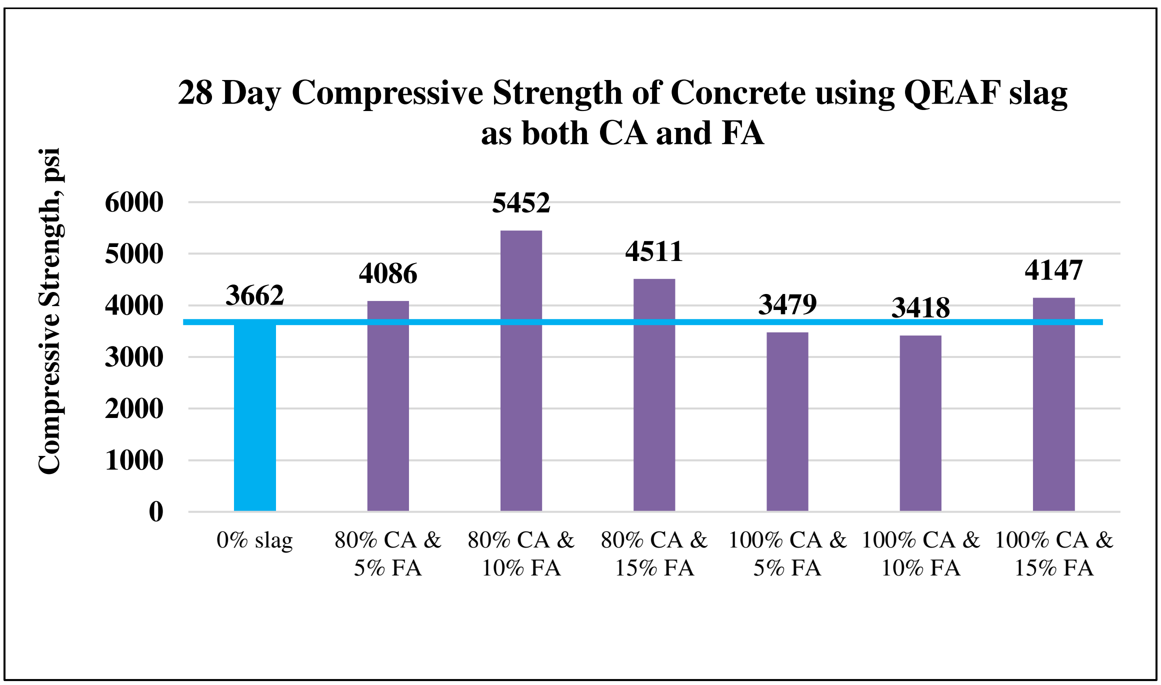


Figure 7.9: Compressive strength for replacement of coarse and fine aggregates combinedly by QEAF slag in concrete

7.4.2 Strength Gain Rate

As compressive strength for 80% coarse aggregates and 5 to 15% fine aggregate replacement by QEAF is higher than the standard, their strength gain rate with curing period is analyzed. The strength gain for 14 days curing is 40% and 31% more than 7 days curing for 5% and 15% fine aggregate replacement, respectively. Whereas for 10% replacement the rate is a bit slower and it is 13%. On the other hand, the strength gain for 28 days curing is 20%, 27% and 29% more than the strength in 14 days curing period for 5%, 10% and 15% replacement in fine aggregates. The strength gain rate at later stages is higher for coarse and fine aggregates replaced concrete than the standard concrete.

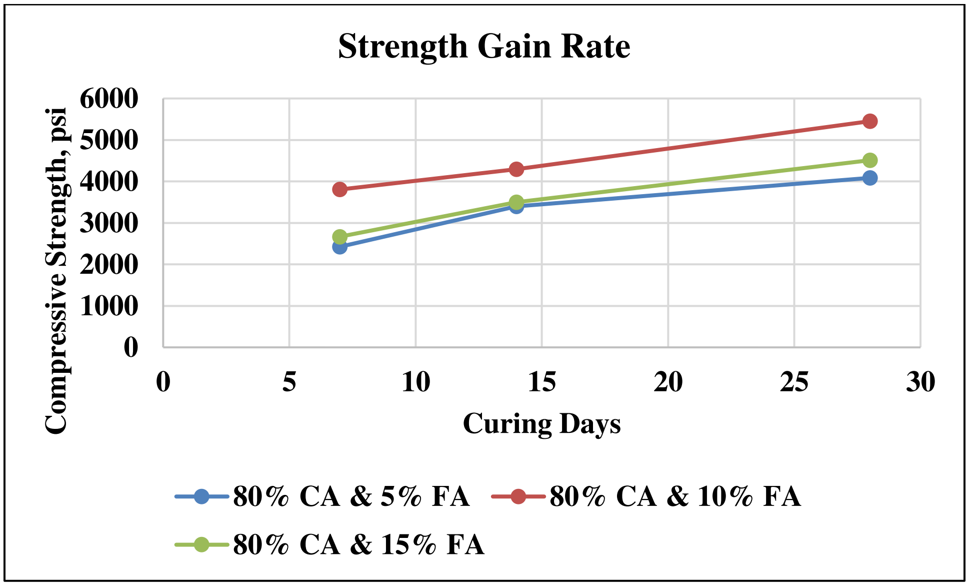


Figure 7.10: Strength gaining rate for replacement of coarse and fine aggregates combinedly by QEAF slags in concrete

7.5 Splitting Tensile Strength Test Result of Second Step Experiment

As already known, coarse and fine aggregate replacement by slags helps in increasing the tensile strength of concrete. For the second phase experiment, this again stands true. Figure 7.11 represents the splitting tensile strength results for coarse and fine aggregate replacement combinedly by QEAF slag. It is also clear from the figure that, for any combination coarse and fine aggregate replacement, splitting tensile strength was higher than the standard concrete.

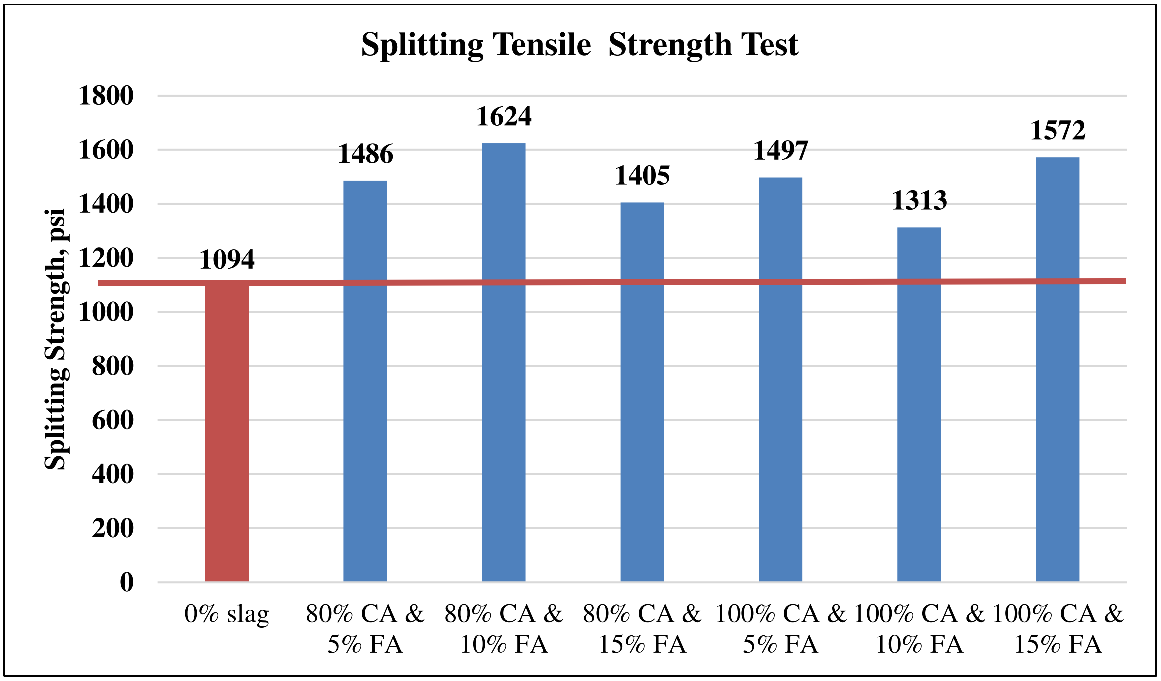


Figure 7.11: Splitting tensile strength for replacement of coarse and fine aggregates combinedly by QEAF slag in concrete

Utilization of Quantum Electric Arc Furnace (QEAF) and Ladle Refining Furnace (LRF) Slag Generated in GPH ISPAT as Coarse Aggregate Replacement in FLEXIBLE PAVEMENT

CHAPTER 8

MATERIALS AND METHODS

8.1 Introduction

In this research, experiments were carried out to utilize QEAF slag produced in GPH Ispat, as coarse aggregate replacement in the wearing course of flexible pavement. Before the experimental procedure, properties of the bitumen and the QEAF slag were determined. Marshall test was performed on laboratory for different mix design for varied stone chips and slag combinations. Finally, test property curves were examined to decide the possible utilization of QEAF slag as coarse aggregate replacement in flexible pavement.

8.2 Characteristics of Bitumen

8.2.1 Specific Gravity of Bitumen

The specific gravity of semi-solid bituminous materials is expressed as the ratio of the mass of a given volume of the material at 25°C (77 °F) or at 15.6°C (60°F) to that of an equal volume of water at the same temperature, and is expressed thus: Specific gravity, 25/25°C (77/77°F) or 15.6/15.6°C (60/60°F). In this research, the specific gravity is measured at 25/25°C (77/77°F).

8.2.2 Loss on Heating

This test method covers the determination of the loss in mass (exclusive of water) of oil and asphaltic compounds when heated according to prescribed in ASTM Standards: E1 Specification for ASTM Thermometers and E145 Specification for gravity-convection and forced-ventilation ovens.

8.2.3 Penetration of Bitumen

This test method covers determination of the penetration of semi-solid and solid bituminous materials using penetrometer. Materials having penetrations below 350 can be tested by the standard apparatus and procedure described. Materials having penetrations between 350 and 500 can be determined using the special apparatus and modifications. The penetration of a bituminous material is the distance in tenths of a millimeter that a standard needle penetrates vertically into a sample of the material under fixed conditions.

8.2.4 Softening Point of Bitumen

The ring and ball softening point is extensively used to evaluate the consistency of bituminous binders. It is a very simple one, consisting of placing a 3/8 in diameter steel ball on a binder sample placed in a steel ring and immersed in a water bath. Heat is applied to the water and its temperature is raised until a value is reached when the test sample has become sufficiently soft to allow the ball, enveloped in binder to fall down. The water temperature at which this occurs is called the ring and ball softening point.

The softening point is not a melting point; bituminous binders do not melt but instead gradually change from semi-solids to liquids on the application of heat. It is useful for determining the temperature susceptibilities of bitumen which are to be used in thick films, such as in crack fillers. When two bitumen have the same penetration value, the one with the higher softening point is normally less susceptible to temperature changes.

8.2.5 Ductility of Bitumen

The ductility of a bituminous material is measured by the distance to which it will elongate before breaking when two ends of a briquette specimen of the material, are pulled apart at a specified speed and at a specified temperature. Unless otherwise specified, the test shall be made at a temperature of 77°±0.9°F (25°±0.5°C) and with a speed of 5 cm/min, + 5.0 percent. At other temperatures the speed should be specified.

8.2.6 Flash and Fire Points of Bitumen

The flash point is the temperature at which a bituminous material, during heating, will evolve vapors that will temporarily ignites or flash when a small flame is brought in contact with them. The fire point is the temperature at which the evolved vapors will ignite and continue to burn. The flash and fire point test are purely a safety test. It indicates the maximum temperature to which the material can be safely heated.

8.3 Volumetric Properties of Compacted Paving Mixtures

The volumetric properties of a compacted paving mixture (air voids (V_a), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and effective asphalt content (P_{be})) provide some indication of the mixture's probable pavement service performance. The intent of laboratory compaction is to simulate the in-place density of Hot Mix Asphalt (HMA) after it has endured several years of traffic. How well the laboratory compaction procedure simulates either the compacted state immediately after construction or after years of service can be determined by comparing the properties of an undisturbed sample removed from a pavement with the properties of a sample of the same paving mixture competed in the laboratory.

It is necessary to understand the definitions and analytical procedures to be able to make informed decisions concerning the selection of the design asphalt mixture. The information here applies to both paving mixtures that have been compacted in the laboratory, and to undisturbed samples that have been removed from a pavement in the field.

A comparison of field and laboratory compacted mix properties has been made in several research studies. Statistical analysis of these data has failed to establish one laboratory compaction method that consistently produces the closest simulation to the field for all of the measured properties. However, there is a trend toward the gyratory method of compaction based on these findings and other subjective factors. This is a very complicated issue. Compaction method, level of compaction, structural concerns, construction conditions and other influences can all make a difference in these comparisons. Assuming that a reasonable degree of simulation is achieved by whatever compaction procedures are used, it is universally agreed that the air void analysis is an important part of mix design.

8.4 Definitions

Mineral aggregate is porous and can absorb water and asphalt to a variable degree. Furthermore, the ratio of water to asphalt absorption varies with each aggregate. The three methods of measuring aggregate specific gravity take these variations into consideration. The methods are ASTM bulk, ASTM apparent and effective specific gravities. The differences among the specific gravities come from different definitions of aggregate volume.

Bulk Specific Gravity, Gsb - the ratio of the weight in air of a unit volume of permeable material (including both permeable and impermeable voids normal to the material) at a stated temperature to the weight in air of equal density of an equal volume of gas free distilled water at a stated temperature. See Figure 8.1.

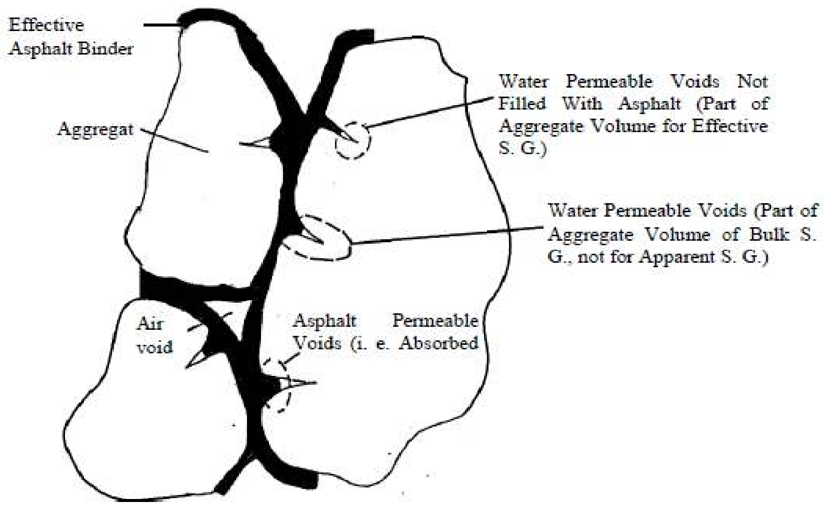


Figure 8.1: Illustrating bulk, effective, and apparent specific gravities; air voids and effective, asphalt content in compacted asphalt paving mixture

Apparent Specific Gravity, Gsa - the ratio of the weight in air of a unit volume of an impermeable material at a stated temperature to the weight in air of equal density of an equal volume of gas free distilled water at a stated temperature. See Figure 8.1.

Effective Specific Gravity, Gse - the ratio of the weight in air of a unit volume of a permeable material (excluding voids permeable to asphalt) at a stated temperature to the weight in air of equal density of an equal volume of gas free distilled water at a stated temperature. See Figure 8.1.

V_{ma} = Volume of voids in mineral aggregate
V_{mb} = Bulk volume of compacted mix
V_{mm} = Void less volume of paving mix
V_{fa} = Volume of voids filled with asphalt
V_a = Volume of air voids
V_b = Volume of asphalt
V_{ba} = Volume of absorbed asphalt
V_{sb} = Volume of mineral aggregate (by bulk specific gravity)
V_{se} = Volume of mineral aggregate (by effective specific gravity)

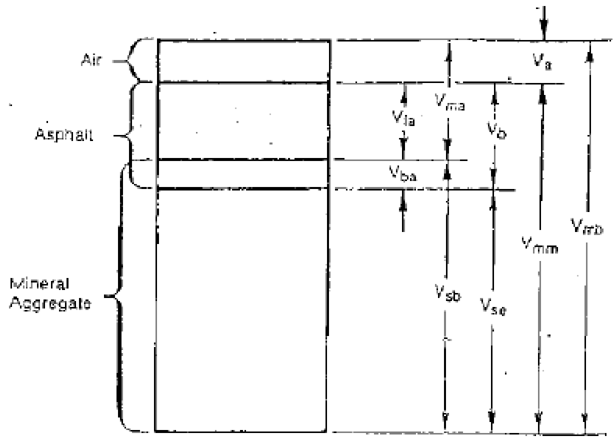


Figure 8.2: Representation of volumes in a compacted asphalt specimen

Voids in the Mineral Aggregate, VMA - the volume of inter granular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective asphalt content, expressed as a percent of the total volume of the sample. See Figure 8.2.

Effective Asphalt Content, Pbe - the total asphalt content of a paving mixture minus the portion of asphalt that is lost by absorption into the aggregate particles. See Figure 8.2.

Air Voids, Va - the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as percent of the bulk volume of the compacted paving mixture. See Figure 8.2.

Voids Filled with Asphalt, VFA - the portion of the volume of intergranular void space between the aggregate particles (VMA) that is occupied by the effective asphalt. See Figure 8.2. The Asphalt Institute recommends that VMA values for compacted paving mixtures should be calculated in terms of the aggregate's bulk specific gravity, Gsb. The effective specific gravity should be the basis for calculating the air voids in a compacted asphalt paving mixture.

The type of aggregate specific gravity used in the analysis of a compacted paving mixture can have a very dramatic effect on the values reported for air voids and VMA. These differences are enough to make it appear that a mixture may satisfy or fail the design criteria for air voids and VMA depending on the aggregate specific gravity used for analysis. Asphalt Institute mix design criteria do not apply unless VMA calculations are made using bulk specific gravity and air void content calculations are made using effective specific gravity.

Voids in the mineral aggregate (VMA) and air voids (V_a) are expressed as percent by volume of the paving mixture. Voids filled with asphalt (VFA) is the percentage of VMA that is filled by the effective asphalt. Depending on how asphalt content is specified, the effective asphalt content may be expressed either as percent by weight of the total weight of the paving mixture, or as percent by weight of the aggregate in the paving mixture.

Because air voids, VMA and VFA are volume quantities and therefore cannot be weighed, a paving mixture must first be designed or analyzed on a volume basis. For design purposes, this volume approach can easily be changed over to a weight basis to provide a job mix formula.

8.5 Marshall Method of Mix Design

The concepts of the Marshall method of designing paving mixtures were formulated by Bruce Marshall, a former Bituminous Engineer with the Mississippi State Highway Department. The U.S. Army Corps of Engineers, through extensive research and correlation studies, improved and added certain features to Marshall's test procedure, and ultimately developed mix design criteria. The Marshall test procedures have been standardized by the American Society for Testing and Materials. Procedures are given by ASTM D 6927, Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures.

The original Marshall method is applicable only to hot mix asphalt (HMA) paving mixtures containing aggregates with maximum sizes of 25 mm (1 inch) or less. A modified Marshall method has been proposed for aggregates with maximum sizes up to 38 mm (1.5 inch). The Marshall method is intended for laboratory design and field control of asphalt hot mix dense graded paving mixtures. Because the Marshall stability test is empirical in nature, the meaning of the results in terms of estimating relative field behavior is lost when any modification is made to the standard procedures.

In this research, to know exactly which percentages of coarse materials can be replaced by QEAF slag, six batches of Marshall test were conducted in the laboratory. For each batch of coarse aggregate replacement, standard gradation test calculations were adjusted. Table 8.1 is the standard gradation according to the standard. And Table 8.2 to Table 8.5 show the adjusted gradation for different batch of aggregate mix.

- Batch 01: Standard (see Table 8.1)
- Batch 02: 20% coarse aggregate replacement by QEAF slag (see Table 8.2)
- Batch 03: 30% coarse aggregate replacement by QEAF slag (see Table 8.3)
- Batch 04: 40% coarse aggregate replacement by QEAF slag (see Table 8.4)
- Batch 05: 50% coarse aggregate replacement by QEAF slag (see Table 8.5)
- Batch 06: 60% coarse aggregate replacement by QEAF slag (see Table 8.6)

Table 8.1: Standard Gradation for Batch 01

Sieve Size	**% Passing**	**%Retained (cumulative)**	**%Retained (individual)**	**Batch Weight (gm)**
1 inch (25 mm)	100	0	0	0
¾ inch (19 mm)	95	5	5	57
1/8 inch (9.5 mm)	68	32	27	312
No.4 (4.75 mm)	50	50	18	208
No.8 (2.36 mm)	36	64	14	162
No. 50 (300 µm)	12	88	24	277
No. 200 (75 µm)	5	95	7	81
M.F	0	100	5	58
Total			**100**	**1155**

Table 8.2: Standard Gradation for Batch 02

Sieve Size	**% Passing**	**%Retained (cumulative)**	**%Retained (individual)**	**Batch Weight (gm)**	**Stone (gm)**	**Slag (gm)**
1 inch (25 mm)	100	0	0	0	0	0
¾ inch (19 mm)	95	5	5	57	46	11
1/8 inch (9.5 mm)	68	32	27	312	250	62
No.4 (4.75 mm)	50	50	18	208	166	42
No.8 (2.36 mm)	36	64	14	162	130	32
No. 50 (300 µm)	12	88	24	277	222	55
No. 200 (75 µm)	5	95	7	81	65	16
M.F	0	100	5	58	46	13
Total			**100**	**1155**	**925**	**231**

Table 8.3: Standard Gradation for Batch 03

Sieve Size	% Passing	%Retained (cumulative)	%Retained (individual)	Batch Weight (gm)	Stone (gm)	Slag (gm)
1 inch (25 mm)	100	0	0	0	0	0
¾ inch (19 mm)	95	5	5	57	40	17
1/8 inch (9.5 mm)	68	32	27	312	218	94
No.4 (4.75 mm)	50	50	18	208	146	62
No.8 (2.36 mm)	36	64	14	162	113	49
No. 50 (300 μm)	12	88	24	277	194	83
No. 200 (75 μm)	5	95	7	81	57	24
M.F	0	100	5	58	41	17
Total			**100**	**1155**	**809**	**346**

Table 8.4: Standard Gradation for Batch 04

Sieve Size	% Passing	%Retained (cumulative)	%Retained (individual)	Batch Weight (gm)	Stone (gm)	Slag (gm)
1 inch (25 mm)	100	0	0	0	0	0
¾ inch (19 mm)	95	5	5	57	34	23
1/8 inch (9.5 mm)	68	32	27	312	187	125
No.4 (4.75 mm)	50	50	18	208	125	83
No.8 (2.36 mm)	36	64	14	162	97	65
No. 50 (300 μm)	12	88	24	277	166	111
No. 200 (75 μm)	5	95	7	81	49	32
M.F	0	100	5	58	35	23
Total			**100**	**1155**	**693**	**462**

Table 8.5: Standard Gradation for Batch 05

Sieve Size	% Passing	%Retained (cumulative)	%Retained (individual)	Batch Weight (gm)	Stone (gm)	Slag (gm)
1 inch (25 mm)	100	0	0	0	0	0
¾ inch (19 mm)	95	5	5	57	29	29
1/8 inch (9.5 mm)	68	32	27	312	156	156
No.4 (4.75 mm)	50	50	18	208	104	104
No.8 (2.36 mm)	36	64	14	162	81	81
No. 50 (300 μm)	12	88	24	277	139	139
No. 200 (75 μm)	5	95	7	81	41	41
M.F	0	100	5	58	29	29
Total			**100**	**1155**	**578**	**578**

Table 8.6: Standard Gradation for Batch 06

Sieve Size	% Passing	% Retained (cumulative)	% Retained (individual)	Batch Weight (gm)	Stone (gm)	Slag (gm)
1 inch (25 mm)	100	0	0	0	0	0
¾ inch (19 mm)	95	5	5	57	34	23
1/8 inch (9.5 mm)	68	32	27	312	187	125
No.4 (4.75 mm)	50	50	18	208	125	83
No.8 (2.36 mm)	36	64	14	162	97	65
No. 50 (300 μm)	12	88	24	277	166	111
No. 200 (75 μm)	5	95	7	81	49	32
M.F	0	100	5	58	35	23
Total			**100**	**1155**	**693**	**462**

CHAPTER 9

RESULTS AND DISCUSSIONS

9.1 Properties of Bitumen

The characteristics of the bitumen utilized in this research was determined by specific gravity test, loss on heating test, penetration test, softening test, ductility test, and finally the flash and fire test. Details of testing procedure has been discussed in Section 8.2. The results are summarized in Table 9.1.

Table 9.1: Properties of bitumen tested for this research

	Bitumen	Standard	Recommended
Specific Gravity	1.015, 25 ºC/25 ºC	AASHTO T43	-
Loss on Heating	0.004%	AASHTO T47	-
Penetration Test	65	AASHTO T49	<350
Softening Point Test	49 ºC	AASHTO T53	-
Ductility Test	100+	AASHTO T51	100+
Flash Point	310 ºC	AASHTO T48	-
Fire Point	360 ºC	AASHTO T48	-

9.2 Properties of Aggregate

Aggregate mechanical properties were derived for the coarse QEAF slag aggregates of size 1.5 inch downgrade to decide if they can be used as Sub-base or base section of flexible pavement. The details of the properties are discussed in Section 6.3. The results for the aggregate mechanical properties are given in Table 9.2 and details of the calculation is given in Appendix C. It is observed from the Table 9.2 that, Aggregate Crushing Value (ACV) is very high for the bigger size of QEAF slag aggregates. This means these aggregates are more prone to crush with applied strength than traditional stones used in sub base. For the Marshall test in the laboratory, QEAF slag aggregate of size 3/4-inch downgrade was used in the mix design. Aggregate mechanical properties for 3/4-inch downgrade QEAF aggregates were derived and given Section 7.1.

Table 9.2: Aggregate mechanical properties of QEAF slag of size 1.5” downgrade

	QEAF Slag	Standard	Recommended
Angularity Number Test	6	BS 812	0-12
Los Angeles Abrasion Test	23	ASTM C131-89	< 30
Unit Weight	4930 kg/m^3	ASTM C29	
AIV	22	BS 812	< 30
ACV	30	BS 812	< 30
TFV	110	BS 812	
Flakiness Index	17	BS 812	The lower the better
Elongation Index	7	BS 812	The lower the better
Absorption Capacity	2.1	ASTM C127	
Bulk Specific Gravity	3.28	ASTM C127	

9.3 Marshall Method of Mix Design

Composition of asphalt paving mixtures for Marshall method of mix design was determined according to ASTM D3515, for dense type of mix. For coarse aggregates, stone chips and QEAF coarse aggregate were used in different proportions. For fine aggregates and mineral filler, fine fractions of stones and fine fractions of QEAF slag were used in different proportions. The composition was selected for Medium Traffic Category (Compaction: 50 blows per face). Bitumen percentage of total mix were varied, 4%, 4.5%, 5%, 5.5% and 6%. Specific gravity was determined for coarse stone chips and coarse QEAF slag according to ASTM C-127, fine stone chips and fine QEAF slag according to ASTM C-128, both stone and QEAF mineral filler according to D-854 and Bitumen according to ASTM D-5. Sieve material of 1 inch downgrade to #8 retain is considered coarse fraction, #8 downgrade to #200 retain is considered fine fraction and #200 passing is considered as mineral filler. Mixing temperature was maintained 150 ºC, compaction temperature was maintained 140 ºC and oven temperature for bitumen and aggregates were maintained 155 ºC for 2 hours throughout the experiments. The composition of the asphalt mix is given in Section 8.5. Details of the calculation is given in Appendix C. The results are discussed in the following section.

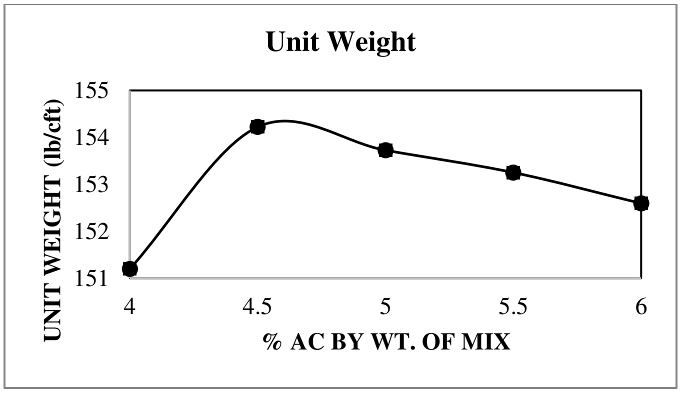
9.4 Results of Test Property Curve

By examining the test property curves, information can be learned about the sensitivity of the mixture to asphalt content. The test property curves have been found to follow a reasonably consistent pattern for dense-graded asphalt paving mixes, but variations will and do occur. Trends generally noted are:

(a) The stability value increases with increasing asphalt content up to a maximum after which the stability decreases.
(b) The flow value consistently increases with increasing asphalt content.
(c) The curve for unit weight of total mix follows the trend similar to the stability curve, except that the maximum unit weight normally (but not always) occurs at slightly higher asphalt content than the maximum stability.
(d) The percent of air voids, Va, steadily decreases with increasing asphalt content, ultimately approaching a minimum void content.
(e) The percent voids in the mineral aggregate, VMA, generally decreases, to a minimum value then increases with increasing asphalt content.
(f) The percent voids filled with asphalt, VFA, steadily increases with increasing asphalt content, because the VMA is being filled with asphalt.

9.4.1 Batch 1 (Standard)

The composition for Batch 1 was selected to according to ASTM D3515, and given in Section 8.4. Stone chips were used as coarse, fine and mineral filler. The characteristics curves for the Standard batch is shown in Figure 9.1. From observing the curves, it was found that the percent of air void, Va, curve and the percent voids filled with asphalt, VFA do not follow the trend. The percent of air void, Va, according to trend should be steadily decreases with increasing asphalt content. But in this case, the curve is first decreasing and then increasing. Again, the percent voids filled with asphalt, VFA, curve should be steadily increasing with the increasing asphalt, but in this case, it is first increasing and then decreasing. The maximum unit weight of 154.22 lb/cft and minimum air void of 1.92 was obtained at 4.5% of asphalt content, and maximum stability of 3100 lb was obtained at 4% asphalt content. The rest of the Marshal mix will be compared with the performance of Batch 1 Mashal mix. That is why, it is called standard batch in this section.



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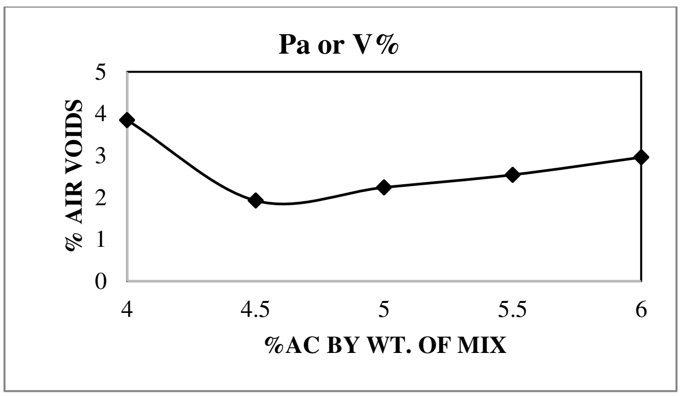

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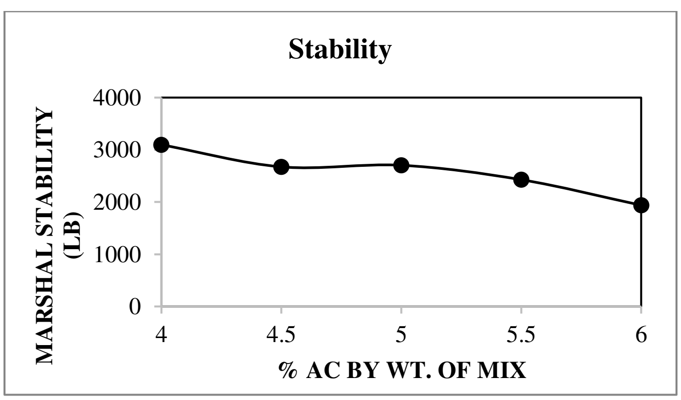


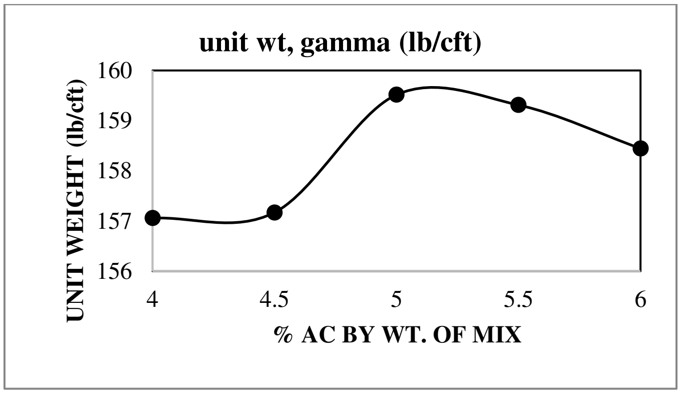
(c)

Figure 9.1: Test property curves for standard sample hot mix design data (a) unit weight vs. asphalt content (b) air void vs. asphalt content (c) stability vs. asphalt content

9.4.2 Batch 2 (20% Coarse Aggregate Replacement by QEAF Slag)

The composition of Batch 2 was determined by replacing 20% of the coarse, fine and mineral filler by weight by QEAF slag from GPH Ispat. The gradation details are given in Section 8.4

and the detail calculation is given in Appendix C. The test property curves for unit weight, air void and stability are plotted and shown in Figure 9.2. Rest of the property curves are given in Appendix C.



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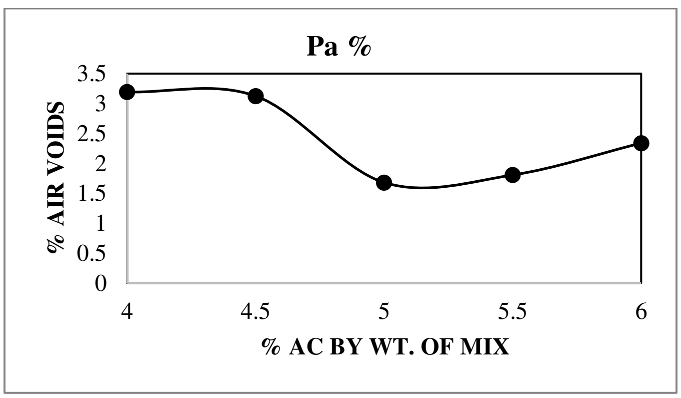

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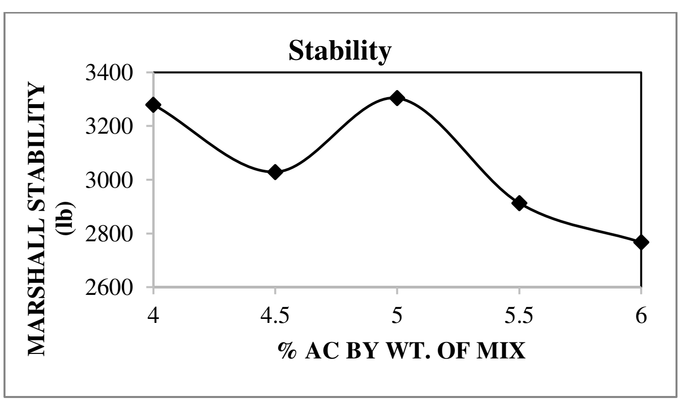


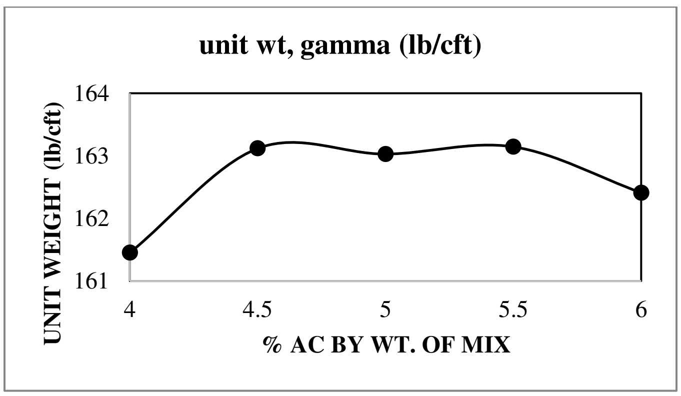
(c)

Figure 9.2: Test property curves for 20% replaced with slag sample hot mix design data (a) unit weight vs. asphalt content (b) air void vs. asphalt content (c) stability vs. asphalt content

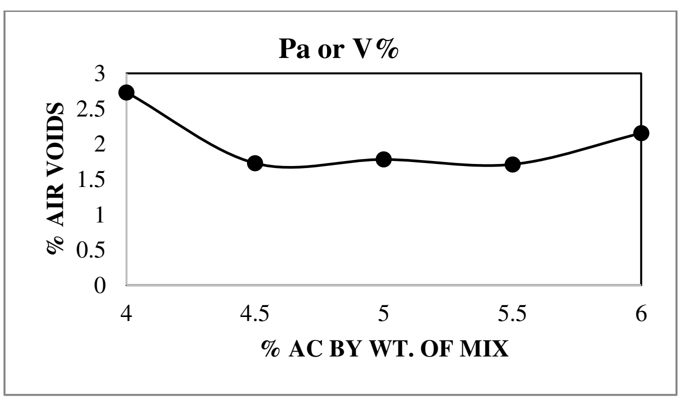
By observing the curves, it was found that curves strictly do not follow the trend. The maximum unit weight of 159.5 lb/cft, minimum air void of 1.68%, and stability of 3300 lb was found at 5% of Asphalt mixture. It can be concluded that 20% of aggregates can be replaced with better performance than the standard by QEAF slag aggregate for wearing coarse of flexible pavement.

9.4.3 Batch 3 (30% Coarse Aggregate Replacement by QEAF Slag)

The composition of Batch 3 was determined by replacing 30% of the coarse, fine and mineral filler by weight by QEAF slag from GPH Ispat. The gradation details are given in Section 8.4 and the detail calculation is given in Appendix C. The test property curves for unit weight, air void and stability are plotted and shown in Figure 9.3. Rest of the property curves are given in Appendix C.



(a)



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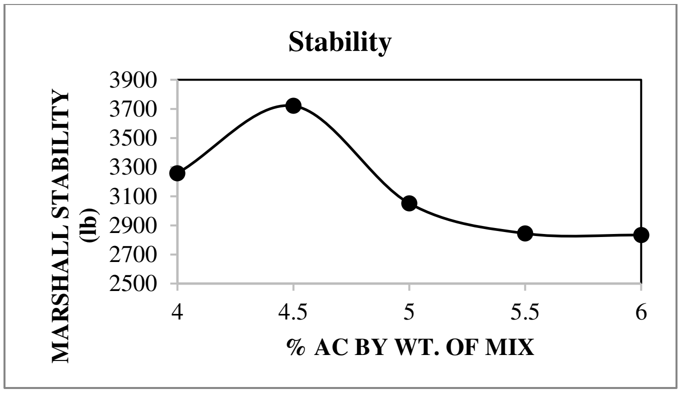


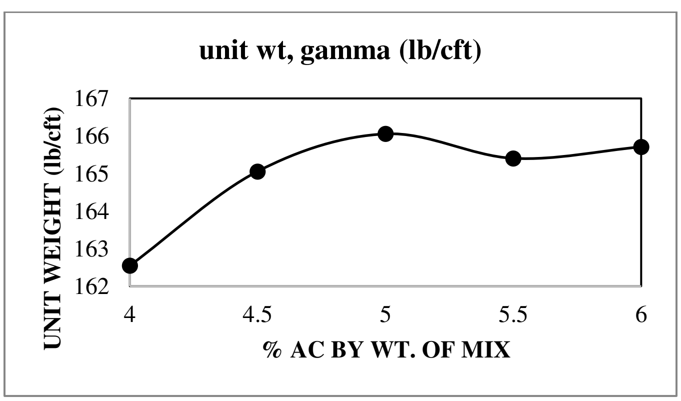
(c)

Figure 9.3: Test property curves for 30% replaced with slag sample hot mix design data (a) unit weight vs. asphalt content (b) air void vs. asphalt content (c) stability vs. asphalt content

By observing the curves, it was found that curves strictly do not follow the trend. The maximum unit weight of 163.11 lb/cft, minimum air void of 1.73%, and stability of 3720 lb was found at 4.5% of Asphalt mixture. It can be concluded that 30% of aggregates can be replaced with better performance than the standard by QEAF slag aggregate for wearing coarse of flexible pavement.

9.4.4 Batch 4 (40% Coarse Aggregate Replacement by QEAF Slag)

The composition of Batch 4 was determined by replacing 40% of the coarse, fine and mineral filler by weight by QEAF slag from GPH Ispat. The gradation details are given in Section 8.4 and the detail calculation is given in Appendix C. The test property curves for unit weight, air void and stability are plotted and shown in Figure 9.4. Rest of the property curves are given in Appendix C.



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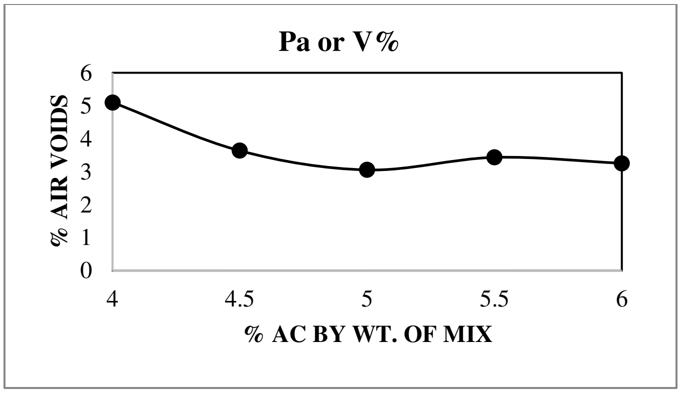

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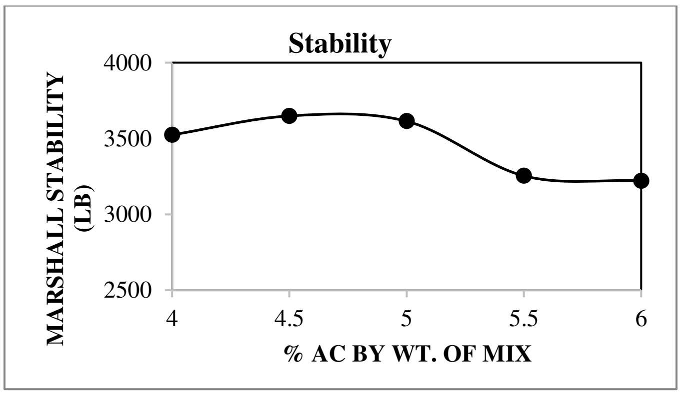


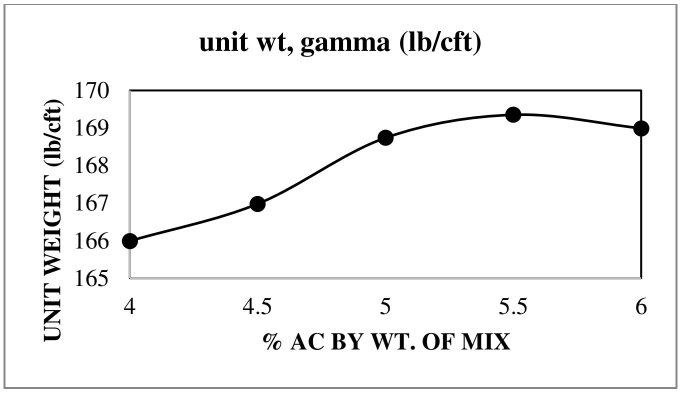
(c)

Figure 9.4: Test property curves for 40% replaced with slag sample hot mix design data (a) unit weight vs. asphalt content (b) air void vs. asphalt content (c) stability vs. asphalt content

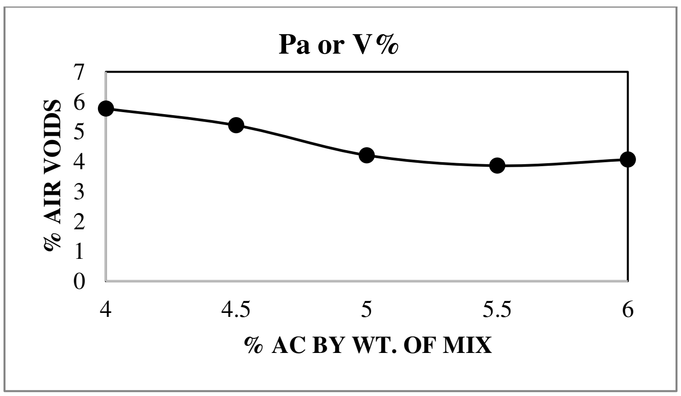
By observing the curves, it was found that the curves follow the general trend. The maximum unit weight of 166.1 lb/cft and minimum air void of 3% was found at 5% of Asphalt mixture. The maximum stability of 3650 lb was found at 4.5% of Asphalt mixture. It can be concluded that 40% of aggregates can be replaced with better performance than the standard by QEAF slag aggregate for wearing coarse of flexible pavement.

9.4.5 Batch 5 (50% Coarse Aggregate Replacement by QEAF Slag)

The composition of Batch 5 was determined by replacing 50% of the coarse, fine and mineral filler by weight by QEAF slag from GPH Ispat. The gradation details are given in Section 8.4 and the detail calculation is given in Appendix C. The test property curves for unit weight, air void and stability are plotted and shown in Figure 9.5. Rest of the property curves are given in Appendix C.



(a)



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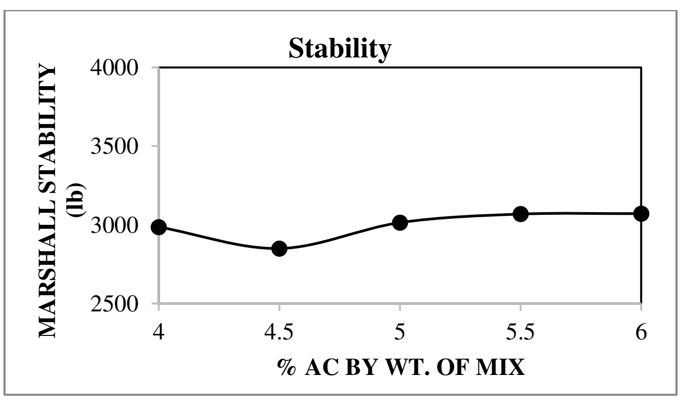


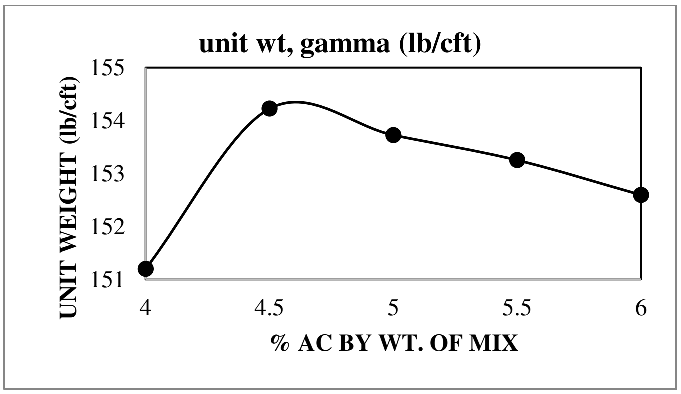
(c)

Figure 9.5: Test property curves for 50% replaced with slag sample hot mix design data (a) unit weight vs. asphalt content (b) air void vs. asphalt content (c) stability vs. asphalt content

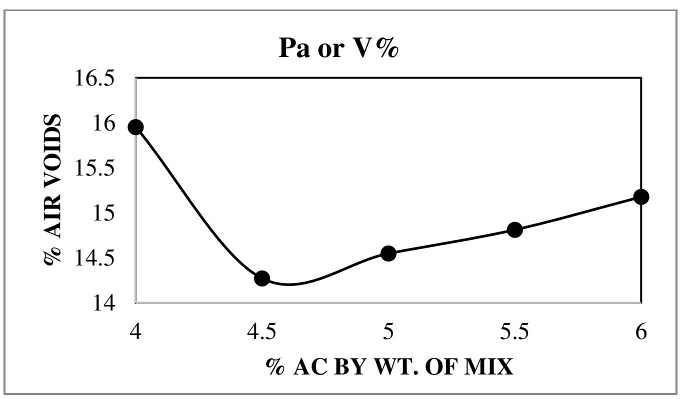
By observing the curves, it was found that curves strictly do not follow the trend. The maximum unit weight of 169.35 lb/cft, minimum air void of 3.86 % was found at 5.5% asphalt mix, and maximum stability of 3070 lb was found at 5.5% and 6% of Asphalt mixture. The stability value is lower than the stability value of the standard composition. Hence, it is not recommended to replace 50% of the aggregates by QEAF slag; as strength value decreases.

9.4.6 Batch 6 (60% Coarse Aggregate Replacement by QEAF Slag)

The composition of Batch 6 was determined by replacing 60% of the coarse, fine and mineral filler by weight by QEAF slag from GPH Ispat. The gradation details are given in Section 8.4 and the detail calculation is given in Appendix C. The test property curves for unit weight, air void and stability are plotted and shown in Figure 9.6. Rest of the property curves are given in Appendix C.



(a)



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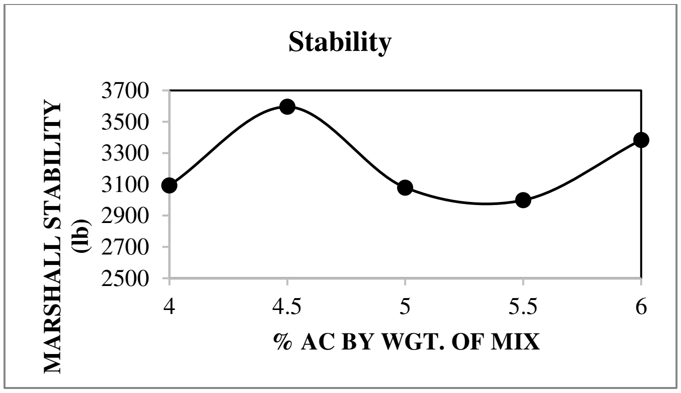

(c)

Figure 9.6: Test property curves for 60% replaced with slag sample hot mix design data (a) unit weight vs. asphalt content (b) air void vs. asphalt content (c) stability vs. asphalt content

By observing the curves, it was found that curves strictly do not follow the trend. The maximum unit weight of 154.22 lb/cft, minimum air void of 14.3% and maximum stability of 3600 lb was found at 4.5% asphalt mix. Though the strength increases with 60% replacement of aggregates by QEAF slag, but air void seems to exceed the tolerable limit which is below 5%. Hence, it is not recommended to replace 60% of the aggregates by QEAF slag; as void increases.

From the characteristic property curve, it can be concluded that QEAF slag from GPH Ispat can replace up to 40% of the aggregates in wearing coarse of flexible pavement in medium traffic roads; also, can give improvement in performances than the traditional aggregates.

Utilization of Quantum Electric Arc Furnace (QEAF) and Ladle Refining Furnace (LRF) Slag Generated in GPH ISPAT as CONCRETE BLOCK

CHAPTER 10

MATERIALS AND METHODS

10.1 Introduction

The objective of this study was to investigate the potential use of QEAF slag and LRF slag as a substitute for sand in concrete block through experimental research. The study involved conducting tests for compressive strength, water absorption, and density measurement for various replacement combinations of slag and sand to determine the optimal percentage of sand replacement.

This chapter provides a detailed discussion on the properties of the materials used in the study, the selected specimens, and the preparation technique employed for the specimens.

10.2 Materials Properties

The materials used in concrete block making were typically water, cement (OPC type), local sand and superplasticising admixture (Conplast SP337). The chemical composition of the OPC cement is provided in Table 6.1. The slag materials (QEAF and LRF) were collected from GPH ISPAT. QEAF slag was crushed into fine particles of less than 2.35mm, while LRF slag was sieved to achieve the same particle size.

10.3 Methodology

In this study, water, cement and sand were mixed in a volume ratio of 1:2:6. The slag materials were then added to the mix to replace 10%, 30%, and 50% of the sand. The resulting mixture was poured into a 2 in x 2 in x 2 in a metal mould, and pressure was applied by hand. After the blocks were ejected from the mould, they were cured by being kept underwater for 7 days, 14 days, and 28 days to attain the required strength. Figure 10.1 depicts the different stages of block manufacturing process. Table 10.1 shows the mix design used for this experiment.

Figure 10.1: Different stages of Block Manufacturing Process.

Table 10.1: Experimental design of utilization of slag in percentages for preparing block

		Sand Replaced by Volume of Slag (%)	**Cement Replaced by Volume of Admixture (%)**
With QEAF Slag	Batch 01	10	-
	Batch 02	30	-
	Batch 03	50	-
No Slag	Batch 04	0	-
With LRF Slag	Batch 05	10	-
	Batch 06	30	-
	Batch 07	50	-
With LRF Slag and Admixture	Batch 08	10	1
	Batch 09	30	1.5
	Batch 10	50	2

10.2 Experimental Tests

10.2.1 Compressive Strength

Compressive strength testing was done for each sample in accordance with the IS 2185 (Part 1). The load was applied to the specimen using the Universal Testing Machine. The load was applied until the specimen was broken. When the specimen was broken, a reading was collected from the digital meter. Table 10.2 shows the physical requirements of the concrete blocks according to the IS 2185 standard.

Table 10.2 Physical Requirements of Concrete Blocks (IS 2185)

<table>
<tr><th>Type</th><th>Grade</th><th>Density of Block (kg/m³)</th><th>Minimum average Compressive Strengths of Units (MPa)</th></tr>
<tr><td rowspan="8">Hollow (open and closed cavity) load bearing unit</td><td>A (3.5)</td><td rowspan="8">Not less than 1500</td><td>3.4</td></tr>
<tr><td>A (4.5)</td><td>4.5</td></tr>
<tr><td>A (5.5)</td><td>5.5</td></tr>
<tr><td>A (7.0)</td><td>7.0</td></tr>
<tr><td>A (8.5)</td><td>8.5</td></tr>
<tr><td>A (10.0)</td><td>10.0</td></tr>
<tr><td>A (12.5)</td><td>12.5</td></tr>
<tr><td>A (15.0)</td><td>15.0</td></tr>
<tr><td rowspan="4">Solid load bearing unit</td><td>B (3.5)</td><td rowspan="2">Less than 1500 but not less than 1100</td><td>3.5</td></tr>
<tr><td>B (5.0)</td><td>5.0</td></tr>
<tr><td>C (5.0)</td><td rowspan="2">Not less than 1800</td><td>5.0</td></tr>
<tr><td>C (4.0)</td><td>4.0</td></tr>
</table>

10.2.2 Water Absorption Test

According to the method described in IS 2185 (Part 1), after curing, the specimens were subjected to a drying process in a furnace for 24 hours at a temperature of 110°C, and their weights were then measured. After that, they were completely submerged in a bucket of water for 24 hours while suspended by a metal wire, as depicted in Figure 10.2. Following this, the specimens were removed from the water and left to drain for a minute on a 10 mm wire mesh before their weights were measured once again. The percentage of water absorption was then calculated based on the difference in weight before and after the immersion in water.

Figure 10.2 Water Absorption Test: Drying (Left) and Curing (Right).

10.2.3 Density

Apparent densities of the blocks were measured according to the method described in IS 2185 (Part 1). After curing, the specimens were oven heated to 100°C. Then they were cooled to room temperature. After that their weight was taken with a weight machine in kg. Their height, width, and length were measured using slide calipers in centimeters. Then their density or unit volume weight was measured using the formula (Mass/Volume) kg/m^3.

CHAPTER 11

RESULTS AND DISCUSSIONS

11.1 Compressive Strength Tests

11.1.1 Effects of Slag Composition

Table 11.1 and Table 11.2 show the variation of strength for 0%, 10%, 30% and 50% replacement of local sand by QEAF and LRF slag, respectively. In the case of replacing sand with QEAF slag, approximately 40-60% strength is increased at 28 days from that obtained at 7 days. With the gradual increase in QEAF slag content, the compressive strength increased, with the maximum strength at 26.23MPa for 50% sand replacement with QEAF slag. All the bricks, made from QEAF slag in this study, met the minimum compressive strength requirements for solid load bearing units (Grade C) (see Table 10.2), which fall within the range of 3.2 to 5.0 MPa as specified in the "IS 2815: Part 1 Hollow and Solid Concrete Blocks". In contrast to the previous observation, an inverse correlation is evident when considering the blocks manufactured using LRF slag. Specifically, the compressive strength of these blocks decreases as the amount of LRF slag in the mixture increases. From the explanation of Zago, S. C., Vernilli, F., & Cascudo, O. (2023), it is possible that the decrease in strength can be attributed to the presence of excessive free lime in the LRF slag, which may react with the cement and cause disintegration of the material, ultimately leading to a reduction in strength of the blocks.

Table 11.1 Compressive Strength Test Results for Concrete Blocks with QEAF slag

Compressive Strength of Blocks Made with QEAF Slag				
Days	B1 (MPa)	B2 (MPa)	B3 (MPa)	B4 (MPa)
7	10.83	14.13	21.28	12.89
14	12.95	17.92	22.72	14.92
28	16.23	18.11	26.23	17.23

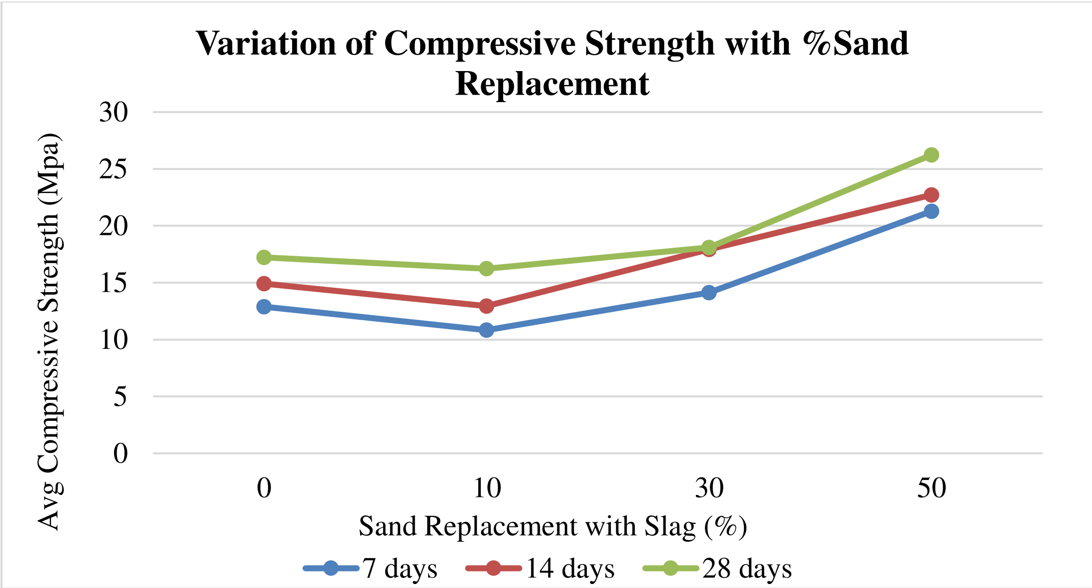

Figure 11.1 Compressive Strength Test Results for Concrete Blocks with QEAF slag

Table 11.2 Compressive Strength Test Results for Concrete Blocks with LRF slag

Compressive Strength of Blocks Made with LRF Slag			
Days	B5 (MPa)	B6 (MPa)	B7 (MPa)
7	7.53	3.83	2.60
14	13.18	4.67	3.53
28	15.58	7.46	3.97

11.1.2 Effect of Admixture

Superplasticizer admixtures were utilized to enhance the compressive strength of blocks made from LRF slag. As can be seen in the Table 11.3, an inverse relationship was observed between the magnitude of compressive strength and the weight percentage of admixture, indicating that higher doses of admixture lead to a decline in compressive strength. This is because the increased dosage of superplasticizer admixture results in a reduction of water content in the cement mixture, which can inhibit the formation of strong bonds among cement particles, and thus result in weaker blocks with lower compressive strength (Musbah et. al., 2019).

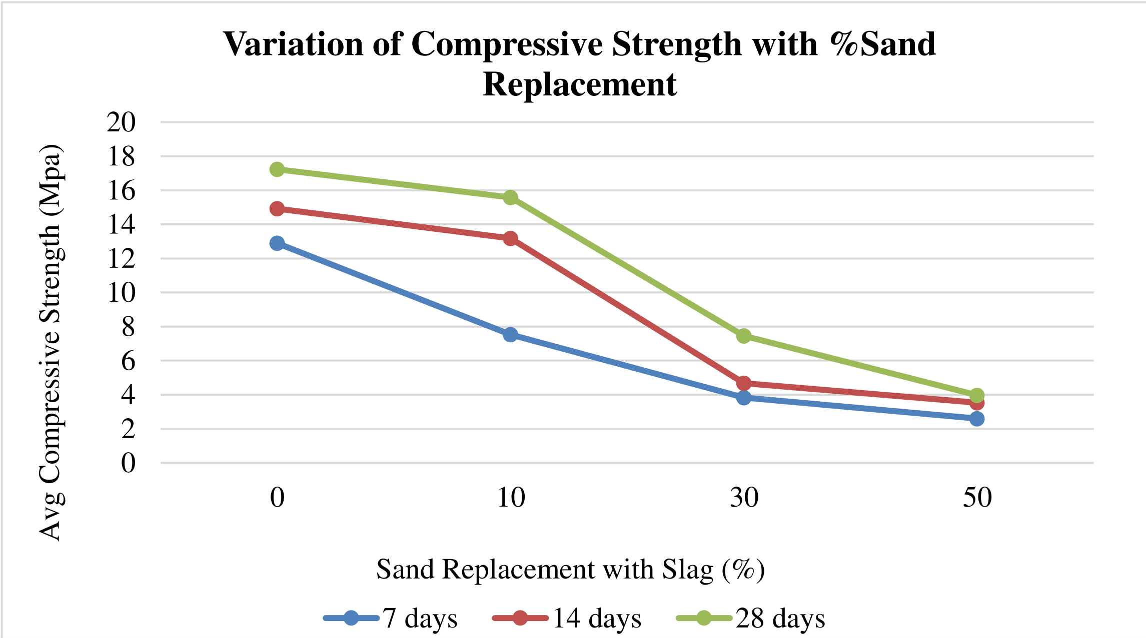

Figure 11.2 Compressive Strength Test Results for Concrete Blocks with LRF slag

Table 11.3 Compressive Strength Test Results for Concrete Blocks with LRF slag (Adding Admixture)

Compressive Strength of Blocks Made with LRF Slag and Admixture			
Days	B8 (MPa)	B9 (MPa)	B10 (MPa)
7	7.18	6.71	5.92
14	10.35	9.35	7.35
28	14.35	10.23	9.34

11.2 Percentage of Water Absorption

As per IS 2815, the maximum allowable water absorption of concrete blocks is 10% by mass. All the blocks produced from QEAF slag satisfy this requirement. . There is a slight increase in water absorption with an increase in slag percentage Based on the data trend, it is expected that blocks containing more than 50% QEAF slag as a sand replacement will not probably meet the standard. Blocks made from LRF slag do not meet the specified standard. Water absorption test results are shown in Table 11.4.

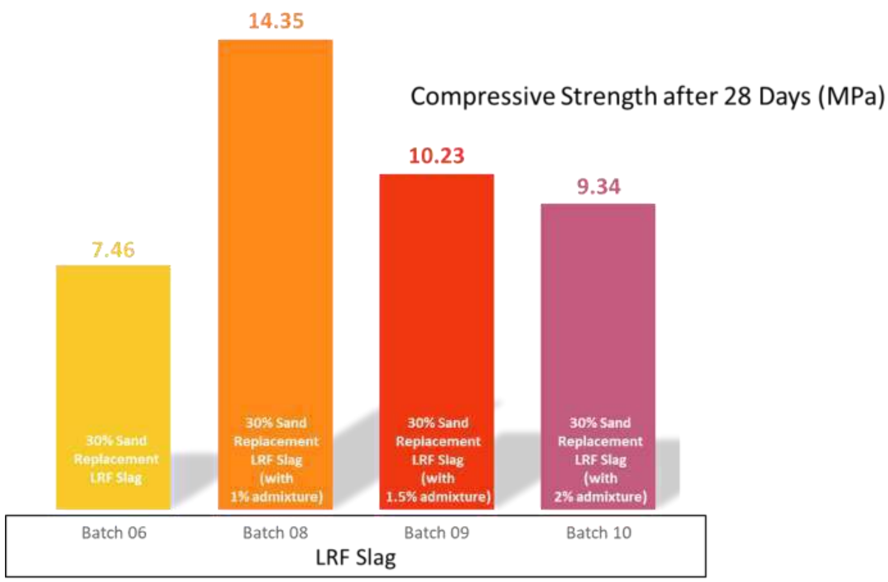

Figure 11.3: Effect of admixture on the compressive strength of concrete blocks (after 28 days)

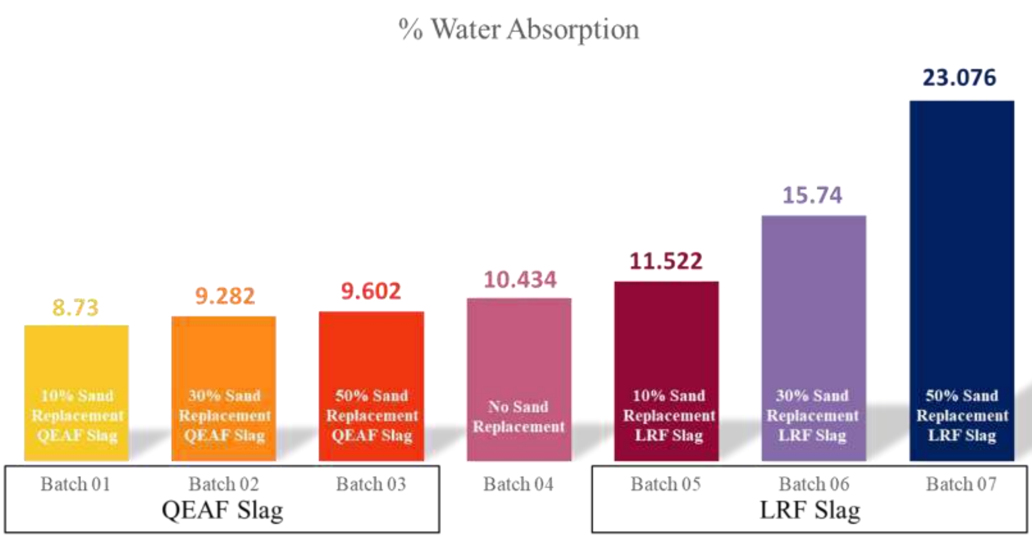

Figure 11.4 Water Absorption Test Results for Concrete Blocks

Table 11.4 Water Absorption Test Results for Concrete Blocks

	Sample	%Water Absorption
With QEAF	Batch 01	8.73
	Batch 02	9.28
	Batch 03	9.60
No slag	Batch 04	10.43
With LRF	Batch 05	11.52
	Batch 06	15.74
	Batch 07	23.07

11.3 Density Measurement Test

IS 2185 specifies that Grade B solid blocks should have a density between 1100 kg/m^3 and 1500 kg/m^3, while Grade C solid blocks should have a density of no less than 1800 kg/m^3 (see Table 10.2). Based on this standard, all blocks containing QEAF slag fall under the Grade C category. It is evident that increasing the percentage of QEAF slag results in an increase in block density. Conversely, the opposite trend is observed for blocks made with LRF slag. Table 11.5 displays the results of the density measurements.

Table 11.5 Apparent Density of Concrete Blocks

	Sample	App. Density (kg/m^3)
With QEAF	Batch 01	2035
	Batch 02	2186
	Batch 03	2412
No slag	Batch 04	1960
With LRF	Batch 05	2035
	Batch 06	1884
	Batch 07	1733

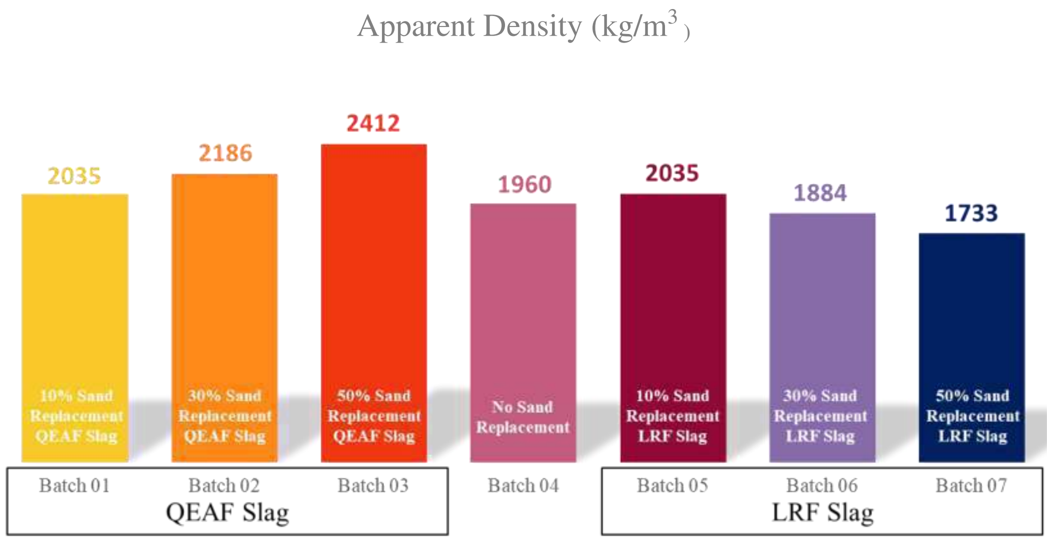

Figure 11.5 Apparent Density Results for Concrete Blocks

Based on the compressive strength test, density measurement test, and water absorption measurement test, it can be inferred that the use of QEAF slag from GPH ISPAT as a replacement for up to 30% of sand in the production of concrete blocks is feasible. However, exceeding this percentage can result in higher compressive strength of the blocks, but at the cost of increased block density and reduced workability of the concrete. On the other hand, substituting sand with LRF slag alone did not yield satisfactory outcomes, but incorporating a small amount of admixture (equivalent to 1wt% of the amount of cement) helped improve the compressive strength of the blocks. In summary, according to the IS 2185 (Part 1) standard, samples B1-6 clearly falls within the category of grade C blocks (see Table 10.2), whereas the B7 samples comply with the requirements for grade B blocks.

CHAPTER 12

CONCLUSIONS AND RECOMMENDATIONS

12.1 General

Steel slag is an industrial waste, a byproduct of the steel-making and refining process. In Bangladesh, more than 400 steel mills of various categories and sizes, currently produce 9 million metric tonnes of steel and 10-15% of them produce the steelmaking slag. With the economy's progress, the per capita consumption of steel, presently estimated as 45 kg, will increase leading to higher volumes of slag. There are no comprehensive industry statistics on slag produced versus slag utilized in Bangladesh. In most cases, landfill is the main solution for all the slag generated in Bangladesh. Therefore, improving the utilization of steel slag is a necessity to realize sustainable development in the steel sector.

This study examined the possible utilization of QEAF and LRF slags produced in GPH Ispat, in some useful products primarily used in the construction sector. Steelmaking slag, both QEAF and LRF slags, were collected from GPH steel plants. Experiments were carried out to evaluate the effects of replacing natural aggregates (coarse and fine) by slag (QEAF and LRF) on concrete, cement, flexible pavement, and concrete blocks and observing their strength and other required properties.

There was enough indication that steelmaking slag can be converted into or incorporated in construction/building materials. Such use of slag can help manage the ever-increasing volume of slag generated in GPH Ispat steel plant as well in other steel plants of Bangladesh. It will also help establish a cleaner environment in the steel sector and reduce CO_2 emission in Bangladesh.

12.2 Findings and Recommendations

12.2.1 Utilization of slag in cement production

a) From the characterizations of LRF slag and QEAF slag, it was found that, the chemical composition of the slags is very similar to the chemical compositions of clinker used in cement production; except that QEAF has higher percentages of Iron (Fe) oxide than the clinker and the LRF slag.

b) Normal consistency, initial and final setting time, and soundness properties of cement produced by replacing different percentages of clinker with both QEAF and LRF slags showed similar behavior as OPC cement meeting the respective standard.
c) The compressive strength of the mortar produced with cement replacing 5% clinker by LRF has the highest value of 40.86 MPa and cement replacing 5% clinker by QEAF has the highest value of 40.60 MPa. All samples meet the standard value according to ASTM C150-18.
d) 15% of the LRF slag can be added without hampering the traditional cement clinker performances. On the other hand, 10% of the QEAF slag can be added without hampering the traditional cement clinker performances.

Further investigation may be conducted regarding the addition of more gypsum to the existing formula. Additionally, the inclusion of granulated blast furnace slag in conjunction with the desired combination of samples warrants exploration with respect to the strength and other properties of slag cement. To optimize the utilization of slag in cement production, it is recommended to decrease the percentage of iron in QEAF slag to improve overall output. Comprehensive analyses may be conducted to evaluate the long-term impact and physical properties of the final product to determine the optimal combination and maximize environmental sustainability while ensuring longevity.

12.2.2 Utilization of slag as replacement of coarse and fine aggregates in concrete

a) The concrete produced by replacing coarse aggregate and fine aggregate by QEAF slag met the required compressive strength at 28 days. According to ASTM C39, minimum 28-day compressive strength should be 25 MPa (3626 psi).
b) The compressive strength of concrete replaced by 80% of coarse aggregate by QEAF slag showed the highest strength of 4900 psi, Compressive strength of concrete replaced by 10% of fine aggregate by QEAF slag showed the highest strength of 4030 psi at 28 days of curing.
c) Finally compressive strength for 80% coarse and 10% fine aggregate combinedly replaced by QEAF slag showed the highest strength of 5500 psi.

d) Compressive strength of concrete by partially replace fine aggregates by LRF slag was all lesser than the standard concrete strength; hence, LRF slag is not recommended to use as fine aggregate replacement in concrete.

A much more extensive field study on a concrete structure made with QEAF slag aggregates used in the mixture may be conducted and changes in mechanical properties may be investigated and correlated to laboratory results. Effect of atmosphere or the environment on concrete structure using partial replacement of QEAF slag aggregate can be studied. Corrosion test on raw QEAF slag can be done by simulating different temperature and environmental conditions in the laboratory. Life Cycle Assessment (LCA) of using as coarse aggregate is recommended.

12.2.3 Utilization of slag as coarse aggregate replacement in flexible pavement

a) Unit weight increased for up to 50% coarse aggregate replacement by slag; then from 60% coarse aggregate replacement the unit weight starts to decrease.
b) Air void in the samples remained within the range of 3 to 5% for up to 50% coarse aggregate replacement by slag; but for 60% aggregate replacement, the air void increased to 15% exceeding the limit of 3-5%.
c) Stability value indicates the strength of the wearing coarse. For 20 to 40% replacement, the stability values were higher than the standard batch. For 30% replacement of coarse aggregate by QEAF slag, the stability value was highest. For 50% replacement of coarse aggregate stability was lowest.
d) From the Marshall testing on sample for flexible pavement, it was found that 20 to 40% of the stone chips of wearing courses can be replaced by the QEAF slag, also improvement in road performances was noted.

Extended field performance may be observed for a longer period. Drainage quality through the slag may be observed. Leachate test can be done to know if they are safe to use in the environment Investigations of LRF slag as base and sub-base material is highly recommended.

12.2.4 Utilization of slag as concrete block

a) The concrete blocks produced with QEAF slag met the required standards outlined in IS 2185:1 for block densities, compressive strength values, and water absorption.

b) The use of QEAF slag as a substitute for sand up to 30% in the production of concrete blocks resulted in higher compressive strength values, whereas LRF slag yielded unsatisfactory outcomes. However, the properties of blocks made with LRF slag can be improved by adding a small amount of admixture (1% of cement amount).

QEAF slag has shown promising results as a replacement for sand in concrete block production, more research is needed to fully understand its long-term properties and potential drawbacks. Adding other materials, such as fly ash, silica fume or fibers, could lead to even more sustainable and cost-effective solutions for concrete block production. Advances in technology are constantly opening new production techniques for concrete blocks. For example, using 3D printing technology to produce concrete blocks could offer significant advantages in terms of speed, precision, and material efficiency. Investigating new production techniques could thus help to optimize the production process and improve the quality of the blocks. A way to address the increased block density issue when using QEAF slag is to produce hollow blocks. This entails utilizing molds that generate an empty space in the block's center, which lowers the quantity of material required and thus lessens the block's overall density. Besides, this technique has the potential to decrease weight and enhance insulation properties.

12.3 Limitations of the Study

Most of the tests were conducted in laboratory environment. Field tests to examine the validity of the laboratory test results in actual application will yield more reliable data. The tests for hardened concrete are susceptible to variation with time due to possible ageing effects. This is particularly true for QEAF slag that contains CaO. Lime is hygroscopic in nature. Any indication of long-time behavior of incorporation in building materials could not be ascertained. There was a serious time constraint.

12.4 Cost Savings Per Cubic Feet of Construction by Using Slag

The endeavor to utilize slag in construction is an important part of using by-products or nontraditional materials to realize the sustainability principles in natural resources, the environment, and the economy.

In general, the weight of a cement bag is 50 kg, accompanied by a corresponding volume of 1.23 cubic feet. Presently, the cost of a 50 kg cement bag ranges from 500 to 600 takas. Utilizing this information, the approximate price of one cubic foot of cement can be estimated to be within the range of 400 to 500 takas. Notably, when slag is employed as a partial substitute for clinker in cement production, savings of approximately 60 to 75 takas per cubic foot can be realized, owing to the replacement of 10% to 15% clinker with slag.

Current price of one cubic feet concrete is 300 to 350 takas. When slag is used as partial replacement of coarse aggregates in concrete, according to current price of stones, 210 to 250 takas can be saved in per cubic feet concrete, as 80% to 100% coarse aggregates can be replaced by QEAF slag.

40% of the stones can be replaced by QEAF slag in flexible pavement. This means a saving of 100 takas can be expected from one cubic feet of flexible pavement.

12.5 Application Priority

Investigators have suggested the utilization of slags produced in GPH Ispat in four different fields of construction sectors. However, before the implementation of the slags in these fields, some measures should be taken by the manufacturer. Also, an application priority list has been prepared among these four fields which tells the manufacturer the sequence of implementation in terms of priority.

1. According to this research, QEAF slag can be a possible replacement for coarse and fine aggregate replacement in concrete. To use slag aggregates in concrete, the size must be ¾ inch downgrade for coarse aggregate replacement and a 1/5-inch (4.75 mm) downgrade for fine aggregates.
2. QEAF slag can be used as partial replacement of coarse aggregate in wearing course in flexible pavement. For application in roads, slag particle size should be 1.5-inch downgrade.
3. Both QEAF and LRF slag can be used in concrete block production.
4. Slag performance as partial replacement of clinker in cement is recommended according to the findings of this research.

12.6 Environmental Aspects of Utilization of Slag According to this Research

12.6.1 Cement

The production of cement is associated with significant environmental impacts at every stage, including the emission of dust and gases, noise and vibration from machinery operations and quarry blasting, and the disfigurement of local environments resulting from limestone quarrying. The cement industry contributes approximately 5% of global man-made CO_2 emissions, with 50% originating from the chemical process and 40% from fuel combustion. On average, the production of 1000 kg of cement emits nearly 900 kg of CO_2. For Portland cement, nearly one ton of CO_2 is generated for every ton of cement manufactured.

If 15% clinker is replaced by slag in cement production without hampering the physical and chemical properties of cement, then nearly 13.5% less CO_2 will be produced. So, approximately, the production of 1000 kg of cement will emit 865 kg of CO_2, which is 35 kg less than the conventional process. Therefore, in large-scale cement production, the use of slag can reduce the production of greenhouse gases.

12.6.2 Concrete

Brick kilns release over 1,072 million tonnes of carbon dioxide emissions into the atmosphere every year which is 2.7% of total emissions. Globally brick kilns burn 375,000,000 tonnes of coal per year. They are major contributors to climate change and a significant source of CO_2 emissions, greenhouse gas emissions and short-lived climate pollutants (SCLP's). Brick kilns damage air quality and human health and in toxic pollutants seriously affect the lives of billions. They also impact agricultural progress by damaging soil, crop production and food security. Rice and wheat crops being particularly susceptible. Hence, they are detrimental to biodiversity. On the other hand, natural resources like stones, gravels are becoming scarce in nature due to rapid urbanization and high demand of stones globally.

By replacing 80% to 100% of the coarse aggregate and 10% fine aggregate by QEAF slag can save the environment from potential damage from brick kiln and large number of CO_2 emission.

12.6.3 Flexible Pavement

Using QEAF slag as partial replacement of coarse aggregate in flexible pavement also serves the same environmental gain as it serves in concrete. In addition, extensive literatures are available which depicts result of environmental tests comprising total and leachable heavy metal tests undertaken on both EAF and LRF steel slag aggregates (Maghool et. al., 2017). From an environmental perspective, EAFS and LFS were found to pose no environmental risks for use as aggregates in roadwork applications.

12.6.4 Concrete Block

Coal is used as the principal fuel for brick production resulting in the release of several air pollutants in the atmosphere which include carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO), and particulate matter. Acid deposition from the sulfur dioxide (SO_2) and NO emitted by the brick kilns' flue gas also has an adverse effect on agricultural productivity. In the Dhaka region, every year the total emissions from the manufacturing of 3.5 billion bricks are estimated about 23,300 tons of particulate matter, 15500 tons of sulfur dioxide (SO_2), and 302,000 tons of carbon monoxide (CO). Figure 12.1 shows the environmental pollution from typical brick industries.

Figure 12.1 Environmental Pollution from Brick Making Operations

Another concerned matter about conventional burnt clay brick is the consumption of top agricultural soil. The major ingredient of conventional burnt clay is soil and the source of soil is agricultural and river land that consumes clay per year converting acres of land into barren land. Per year 140 billion brick production needs around 540 million tonnes of soil. Every year the average excavation depth of 0.75m, around 500sq. km of agricultural land is adversely affected by brick production. Figure 12.2 depicts an example of consumption of agricultural soil for brick production The utilization rate of slag is 22% in China which is far behind for a developed country. Thus, the weight of unutilized slag is 30Mt. This huge slag is stored in the arid and occupied the farmland. However, developed countries like Japan, Germany, and France, have a 50% slag consumption rate. They use slag for road projects and mainly; use the remaining slag for sintering and iron-making recycling in plants. Moreover, being possessed the same physical properties as sand, slag is used as a replacement for sand and produces mortar cubes, bricks, and pavers. Therefore, in this study, an attempt has been made to produce non-fired brick using steel slag and other ingredients for structural purposes.

Figure 12.2 Consumption of Agricultural Soil for Brick Production

In recent years, the world has seen a significant shift from the traditional method of making fired bricks to the use of concrete blocks. This shift has been driven by a number of factors, including environmental and economic concerns, as well as advances in technology. The most obvious reason for the shift to non-fired bricks is the environmental impact of the production of fired bricks. The production of fired bricks requires large amounts of energy, which is often generated using fossil fuels. This leads to high emissions of carbon dioxide and other greenhouse gases, as well as air pollution. In addition, the process of firing bricks also produces a large amount of dust, ash, and other hazardous waste that can be damaging to local ecosystems. By contrast, concrete blocks production does not require the same level of energy or resources and produces significantly fewer emissions and waste.

In terms of economic concerns, concrete blocks production is often more cost-efficient than fired brick production. This is due to a number of factors, including the lower energy costs associated with concrete blocks production and the fact that non-fired bricks can be made from a range of readily available materials, including clay, cement, fly ash, and sand. Moreover, concrete blocks typically require less labor and fewer specialized skills than fired bricks, which can help to keep costs down.

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APPENDIX A

CHAPTER 5

Table A1: Chemical Composition of Raw materials for Cement

Element	Clinker		Gypsum		LRF slag		QEAF slag	
	XRF (BUET Lab.)	Lit.[2]	XRF (BUET Lab.)	Lit.[5]	XRF (BUET Lab.)	Lit.[4]	XRF (BUET Lab.)	Lit.[1]
Fe_2O_3	3.65	2.66	-	0.51	4.21	3-4.4	31.96	26.36
SiO_2	21.73	22.18	-	4.94	23.76	26.4-26.8	17.69	17.53
Al_2O_3	5.04	3.97	-	0.84	2.84	4.7-5.2	5.32	6.25
CaO	65.69	68.67	33.73	33.51	59.58	55.9-57.0	31.71	35.70
MgO	1.46	-	0.97	-	5.87	3.2-4.2	6.05	6.45
MnO	-	-	-	-	1.59	0.5-1.0	4.60	2.50
SO_3	0.34	0.30	42.27	24.54	1.14	-	0.45	-
TiO_2	-	-	-	-	0.65	-	0.82	-
P_2O_5	-	-	-	-	0.04	-	0.46	-
Na_2O	-	-	-	-	0.17	-	0.32	-

Table A2: Initial and final setting time of cement samples

Serial No.	**Clinker wt%**	**Gypsum wt%**	**LRF Slag wt%**	**QEAF Slag wt%**	**Initial setting time (minutes)**	**Final setting time (minutes)**
1	97	3	-	-	141	245
2	92	3	5	-	125	252
3	87	3	10	-	132	270
4	82	3	15	-	153	300
5	77	3	20	-	149	293
6	72	3	25	-	118	273
7	67	3	30	-	143	308
8	92	3	-	5	118	247
9	87	3	-	10	122	282
10	82	3	-	15	129	286
11	77	3	-	20	114	266
12	72	3	-	25	103	249

Table A3: Soundness of cement by expansion of cement mortar bars

Serial No.	Clinker wt%	Gypsum wt%	LRF Slag wt%	Dial reading of the length comparator at age 1 day			Dial reading of the length comparator at age 14 day			Mortar bar expansion E=(B-A)*G mm	Mortar bar expansion,=E/L*100%	Average Mortar bar expansion, %
				Reference steel bar,a	Mortar bar,b	Reading difference, A=a-b	Reference steel bar,c	Mortar bar,d	Dial reading difference ,B=c-d			
1	97	3	-	**966**	**481**	**485**	**966**	**485**	**481**	**-0.04**	**-0.016**	**-0.014**
				966	**590**	**376**	**966**	**593**	**373**	**-0.03**	**-0.012**	
2	92	3	5	**966**	**318**	**648**	**966**	**321**	**645**	**-0.03**	**-0.012**	**-0.012**
				966	**481**	**485**	**966**	**484**	**482**	**-0.03**	**-0.012**	
3	87	3	10	**966**	**619**	**347**	**966**	**621**	**345**	**-0.02**	**-0.008**	**-0.006**
				966	**653**	**313**	**966**	**654**	**312**	**-0.01**	**-0.004**	
4	82	3	15	**966**	**665**	**301**	**966**	**667**	**299**	**-0.02**	**-0.008**	**-0.008**
					-	-	-	-	-		-	
5	77	3	20	**966**	**617**	**349**	**966**	620	**346**	**-0.03**	**-0.012**	**-0.012**
				966	**529**	**437**	**966**	-	-	-	-	
6	72	3	25	**966**	**592**	**374**	**966**	**598**	**368**	**-0.06**	**-0.024**	**-0.012**
				966	**740**	**226**	**966**	**740**	**226**	**0**	**0**	
7	67	3	30	**966**	**610**	**356**	**969**	**620**	**349**	**-0.07**	**-0.028**	**-0.008**
				966	**267**	**699**	**969**	**267**	**702**	**0.03**	**0.012**	

Table A3: Soundness of cement by expansion of cement mortar bars (continue)

Serial No.	Clinker	Gypsum	QEAF Slag	Dial reading of the length comparator at age 1 day			Dial reading of the length comparator at age 14 day			Mortar bar expansion E=(B-A)*G mm	Mortar bar expansion, =E/L*100 %	Average Mortar bar expansion, %
				Reference steel bar,a	Mortar bar,b	Reading difference, A=a-b	Reference steel bar,c	Mortar bar,d	Dial reading difference, B=c-d			
1	97	3	-	966	481	485	966	485	481	-0.04	-0.016	-0.014
				966	590	376	966	593	373	-0.03	-0.012	
8	92	3	5	966	575	391	969	570	399	0.08	0.032	0.02
				966	573	393	969	574	395	0.02	0.008	
9	87	3	10	966	636	330	969	628	341	0.11	0.044	0.03
				966	542	424	969	541	428	0.04	0.016	
10	82	3	15	969	570	399	968	568	400	0.01	0.004	0
				969	700	269	968	700	268	-0.01	-0.004	
11	77	3	20	969	377	592	968	379	589	-0.03	-0.012	-0.01
				969	505	464	968	506	462	-0.02	-0.008	
12	72	3	25	969	416	553	968	416	552	-0.01	-0.004	-0.004
				969	265	704	968	265	703	-0.01	-0.004	

Table A4: Compressive Strength of cement samples

Serial No.	Clinker wt%	Gypsum wt%	LRF Slag wt%	QEAF Slag wt%	3 days	7 days	28 days
1	97	3	-	-	21.07	28.53	39.20
2	92	3	5	-	24.65	27.25	40.86
3	87	3	10	-	20.66	28.65	38.81
4	82	3	15	-	20.40	27.73	39.64
5	77	3	20	-	17.95	24.50	34.78
6	72	3	25	-	18.91	24.68	34.81
7	67	3	30	-	14.15	19.40	28.45
8	92	3	-	5	23.40	28.87	40.60
9	87	3	-	10	23.47	30.13	40.21
10	82	3	-	15	19.91	26.92	34.54
11	77	3	-	20	17.61	24.58	31.86
12	72	3	-	25	17.74	23.07	31.65

APPENDIX B

CHAPTER 6

Table B1: Gradation of Sylhet Sand

material Taken: 500 gm

Sieve Analysis of Sylhet Sand						
Sieve Designation	Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Fineness Modulus
	mm	gm	%	%	%	FM = 3.13
No.4	4.75	0	0.00	0	100.00	
No.8	2.36	25.8	5.16	5.16	94.84	
No.16	1.18	108	21.62	26.78	73.22	
No.30	0.6	224.8	45.00	71.78	28.22	
No.50	0.3	111.8	22.38	94.16	5.84	
No.100	0.15	25.4	5.08	99.24	0.76	
PAN	0	3.8	0.76	100.00	0.00	
	Total	499.6				

Table B2: Gradation of Fine (5 mm Downgrade) QEAF slag

material Taken: 120 gm

Sieve Analysis of local Sand						
Sieve Designation	Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Fineness Modulus = 1.32
	mm	gm	%	%	%	
No.4	4.75	0	0.00	0	100.00	
No.8	2.36	0	0.00	0.00	100.00	
No.16	1.18	0.2	0.17	0.17	99.83	
No.30	0.6	5.4	4.51	4.67	95.33	
No.50	0.3	40.85	34.10	38.77	61.23	
No.100	0.15	59.35	49.54	88.31	11.69	
PAN	0	14	11.69	100.00	0.00	
	Total	119.8				

Table B3: Gradation of LRF slag

Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Remarks
mm	gm	%	%	%	
4.75	0.50	0.26	0.26	99.74	FM: 1.47
2.36	0.90	0.46	0.71	99.29	
1.18	1.30	0.66	1.38	98.62	
0.60	9.60	4.90	6.28	93.72	
0.30	106.40	54.29	60.56	39.44	
0.15	33.90	17.30	77.86	22.14	
0.075	14.10	7.19	85.05	14.95	
Pan	29.30	14.95			
Total	196				

Table B4: Gradation of Stone chips

Sieve Analysis of Stone						
Sieve Designation	Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Fineness Modulus
	mm	gm	%	%	%	
1.5	37.5	0	0	0	100	6.78325
1	25	0	0	0	100	
0.75	19	1556.5	15.565	15.565	84.44	
0.5	12.5	3563.5	35.635	51.2	48.8	
0.375	9.5	2020	20.2	71.4	28.6	
No.4	4.75	2716	27.16	98.56	1.44	
No.8	2.36	0	0	98.56	1.44	
No.16	1.18	0	0	98.56	1.44	
No.30	0.6	0	0	98.56	1.44	
No.50	0.3	0	0	98.56	1.44	
No.100	0.15	0	0	98.56	1.44	
PAN	0	144	1.44	100	0	
	Total	10000				

Table B5: Gradation of Coarse QEAF slag (3/4" downgrade)

Sieve Analysis of coarse QEAF slag						
Sieve Designation	Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Fineness Modulus
	mm	gm	%	%	%	
1.5	37.5	0	0	0	100.00	6.85425
1	25	150	1.5	1.5	98.50	
0.75	19	2350.5	23.505	25.005	75.00	
0.5	12.5	3254.5	32.545	57.55	42.45	
0.375	9.5	1946	19.46	77.01	22.99	
No.4	4.75	2022.5	20.225	97.235	2.76	
No.8	2.36	0	0	97.235	2.76	
No.16	1.18	0	0	97.235	2.76	
No.30	0.6	0	0	97.235	2.76	
No.50	0.3	0	0	97.235	2.76	
No.100	0.15	0	0	97.235	2.76	
PAN	0	276.5	2.765	100	0	
	Total	10000				

Chapter 7

Table B6: Cylinder test results for Standard

Cylinder ID	**Curing Days**	**Diameter (mm)**	**Area (mm2)**	**Load (KN)**	**Calibrated Load (KN)**	**f'c (psi)**	**Avg f'c (psi)**
C-01		101	8011.865	163.48	160.395164	2902.857	
C-03		101	8011.865	139.62	136.909766	2477.814	
C-10	7	100.5	7932.736	142.33	139.577219	2551.288	2644
C-05		101	8011.865	177	173.7029	3143.702	
C-07		101	8011.865	201	197.3261	3571.239	
C-11	14	101.5	8091.387	169.5	166.32065	2980.514	3232
C-08		101	8011.865	240.18	235.890974	4269.192	
C-09		101	8011.865	183.17	179.776031	3253.615	
C-12	28	101	8011.865	195	191.4203	3464.355	3662

Table B7: Cylinder test results for 60% CA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-05		101	8011.865	169.37	166.192691	3007.781	
C-09		101	8011.865	178.87	175.543541	3177.015	
C-12	7	100	7854	145.03	142.234829	2625.929	2937
C-03		101	8011.865	200	192.8554	3490.327	
C-06		101	8011.865	194	187.1266	3386.647	
C-10	14	101	8011.865	190	183.3074	3317.526	3398
C-07		101	8011.865	227	222.9179	4034.403	
C-08		101	8011.865	204	200.279	3624.681	
C-11	28	101	8011.865	215	211.1063	3820.635	3827

Table B8: Cylinder test results for 80% CA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-01		101	8011.865	233.04	228.863072	4142	
C-05		101	8011.865	226.35	222.278105	4022.824	
C-12	7	101	8011.865	211.86	208.015598	3764.699	3977
C-07		101	8011.865	200	196.3418	3553.425	
C-08		101	8011.865	194	190.436	3446.541	
C-11	14	101	8011.865	190	186.4988	3375.285	3458
C-03		101	8011.865	291	285.9131	5174.5	
C-09	28	101	8011.865	261	256.3841	4640.08	4907

Table B9: Cylinder test results for 100% CA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-05		101	8011.865	226.75	222.671825	4029.95	
C-07		101	8011.865	207.29	203.517347	3683.289	
C-08	7	100.5	7932.736	214.04	210.161372	3841.474	3852
C-10		101.5	8091.387	292	286.8974	5141.284	
C-11		101	8011.865	242	237.6824	4301.613	
C-12	14	101.5	8091.387	189	185.5145	3324.474	4256
C-03		101	8011.865	291	285.9131	5174.5	
C-04		101	8011.865	260	255.3998	4622.266	
C-09	28	101	8011.865	245	240.6353	4355.056	4717

Table B10: Cylinder test results for 10% FA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-03		101.5	8091.387	191.85	188.319755	3374.745	
C-05		101.5	8091.387	171.99	168.771557	3024.435	
C-08	7	101	8011.865	179.24	175.907732	3183.606	3194
C-01		101	8011.865	201	197.3261	3571.239	
C-02		101	8011.865	147	144.1739	2609.282	
C-12	14	100.5	7932.736	184	180.593	3301.003	3436
C-07		101	8011.865	196	192.4046	3482.169	
C-09		101	8011.865	211	207.1691	3749.379	
C-10	28	101	8011.865	274	269.18	4871.662	4034

Table B11: Cylinder test results for 20% FA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-08		100	7854	185.62	182.187566	3363.534	
C-10		101	8011.865	162.43	159.361649	2884.152	
C-11	7	101.5	8091.387	174.94	171.675242	3076.47	3108
C-01		101	8011.865	136	131.7482	2384.4	
C-03		101	8011.865	150	145.1154	2626.321	
C-04	14	101	8011.865	102	99.285	1796.876	2269
C-06		101	8011.865	172	168.7814	3054.632	
C-09		101	8011.865	185	181.5773	3286.215	
C-10	28	101	8011.865	164	160.907	2912.12	3084

Table B12: Cylinder test results for 30% FA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-04		100.5	7932.736	145.26	142.461218	2604.004	
C-07		100	7854	138.8	136.10264	2512.717	
C-12	7	100	7854	134.2	131.57486	2429.126	2515
C-01		101	8011.865	188	181.3978	3282.966	
C-08		102	8171.302	148	143.2058	2541.191	
C-09	14	101.5	8091.387	144	139.3866	2497.848	2774
C-02		101	8011.865	194	190.436	3446.541	
C-06		101	8011.865	150	147.1268	2662.724	
C-10	28	101	8011.865	162	158.9384	2876.492	2995

Table B13: Cylinder test results for 40% FA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-07		100	7854	148.98	146.122814	2697.709	
C-08		101	8011.865	172.83	169.598369	3069.418	
C-12	7	100	7854	170.81	167.610083	3094.406	2954
C-02		101.5	8091.387	196	189.0362	3387.583	
C-09		101	8011.865	230	221.4994	4008.731	
C-11	14	101	8011.865	220	211.9514	3835.93	3744
C-04		101	8011.865	232	227.8394	4123.473	
C-05		101	8011.865	228	223.9022	4052.217	
C-06	28	101	8011.865	210	206.1848	3731.565	3969

Table B14: Cylinder test results for 50% FA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-04		101.25	8051.577	97.81	95.756183	1724.463	
C-09		101.5	8091.387	124.84	122.361812	2192.759	
C-10	7	101.5	8091.387	88.92	87.005756	1559.168	1825
C-02		101	8011.865	150	147.1268	2662.724	
C-05		101	8011.865	154	151.064	2733.98	
C-08	14	101	8011.865	138.11	135.423473	2450.915	2616
C-11		101	8011.865	155	152.0483	2751.794	
C-03		101	8011.865	195	191.4203	3464.355	
C-09	28	101	8011.865	181	177.6401	3214.958	3144

Table B15: Cylinder test results for 10% FA replacement by LRF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-03		101	8011.865	98.71	96.642053	1749.043	
C-05		101	8011.865	112.84	110.550212	2000.755	
C-09	7	101	8011.865	85.91	84.043013	1521.024	1757
C-06		101	8011.865	146.3	143.48489	2596.812	
C-08		101	8011.865	134	131.378	2377.7	
C-11	14	101	8011.865	92.38	90.411434	1636.28	2204
C-01		101	8011.865	152	149.0954	2698.352	
C-07		101	8011.865	139	136.2995	2466.77	
C-02	28	101	8011.865	152	149.0954	2698.352	2621

Table B16: Cylinder test results for 20% FA replacement by LRF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-08		100.5	7932.736	122.22	119.782946	2189.475	
C-10		101	8011.865	156.04	153.071972	2770.321	
C-11	7	101	8011.865	117.03	114.674429	2075.396	2345
C-01		101	8011.865	151	148.1111	2680.538	
C-07		101	8011.865	164	160.907	2912.12	
C-12	14	101	8011.865	174.26	171.005918	3094.892	2896
C-6		101	8011.865	197	193.3889	3499.983	
C-04		101	8011.865	214	210.122	3802.821	
C-02	28	101	8011.865	190	186.4988	3375.285	3559

Table B17: Cylinder test results for 30% FA replacement by LRF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-03		101	8011.865	136.62	133.956866	2424.372	
C-05		101	8011.865	154.38	151.438034	2740.749	
C-10	7	102	8171.302	129.93	127.371899	2260.218	2475
C-0		101	8011.865	187	183.5459	3321.843	
C-11		101	8011.865	171	167.7971	3036.818	
C-12	14	101	8011.865	184	180.593	3268.401	3209
C-02		101	8011.865	218	214.0592	3874.077	
C-08		101	8011.865	197	193.3889	3499.983	
C-01	28	101	8011.865	199	195.3575	3535.611	3637

Table B18: Cylinder test results for 40% FA replacement by LRF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-01		101.5	8091.387	133.45	130.836635	2344.63	
C-08		101.5	8091.387	124.67	122.194481	2189.76	
C-12	7	101.5	8091.387	125.39	122.903177	2202.461	2246
C-03		101	8011.865	170	166.8128	3019.004	
C-06		101	8011.865	195	191.4203	3464.355	
C-09	14	101	8011.865	165	161.8913	2929.934	3138
C-05		101	8011.865	188	184.5302	3339.657	
C-10		101	8011.865	214	210.122	3802.821	
C-11	28	101	8011.865	175	171.7343	3108.074	3417

Table B19: Cylinder test results for 50% FA replacement by LRF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-03		102	8171.302	141.02	138.287786	2453.921	
C-08		101	8011.865	122.62	120.176666	2174.976	
C-10	7	101	8011.865	116.5	114.15275	2065.954	2232
C-01		101	8011.865	148	145.1582	2627.096	
C-02		101	8011.865	140	137.2838	2484.584	
C-05	14	101	8011.865	167	163.8599	2965.562	2692
C-06		101	8011.865	205	201.2633	3642.495	
C-11		101	8011.865	217	213.0749	3856.263	
C-12	28	101	8011.865	191	187.4831	3393.099	3631

Table B20: Cylinder test results for 80% CA and 5% FA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-07		101	8011.865	142.3	139.54769	2525.556	
C-06		101	8011.865	136.31	133.651733	2418.85	
C-12	7	101	8011.865	131.44	128.858192	2332.096	2426
C-05		101	8011.865	193.14	189.589502	3431.221	
C-10		101	8011.865	193.5	189.94385	3437.634	
C-04	14	101	8011.865	188.03	184.559729	3340.191	3403
C-08		101	8011.865	225	229.1294	4146.82	
C-01		101	8011.865	190	193.9019	3509.267	
C-03	28	101	8011.865	250	254.2919	4602.215	4086

Table B21: Cylinder test results for 80% CA and 10% FA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-06		101	8011.865	209.68	205.869824	3725.864	
C-05		101	8011.865	209.53	205.722179	3723.192	
C-04	7	101	8011.865	223.25	219.226775	3967.601	3806
C-11		101	8011.865	240.85	236.550455	4281.127	
C-09		101	8011.865	246.11	241.727873	4374.829	
C-10	14	101	8011.865	237.74	233.489282	4225.726	4294
C-07		101	8011.865	300	304.6169	5513.005	
C-01		101	8011.865	285	289.5194	5239.768	
C-03	28	101	8011.865	305	309.6494	5604.084	5452

Table B22: Cylinder test results for 80% CA and 15% FA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-09		101	8011.865	148.05	145.207415	2627.987	
C-03		101	8011.865	148.83	145.975169	2641.882	
C-07	7	101	8011.865	154.09	151.152587	2735.583	2668
C-12		101	8011.865	196.53	192.926279	3491.61	
C-06		101	8011.865	198.4	194.76692	3524.922	
C-08	14	101	8011.865	195.87	192.276641	3479.853	3499
C-01		101	8011.865	250	254.2919	4602.215	
C-02		101	8011.865	245	249.2594	4511.136	
C-04	28	101	8011.865	240	244.2269	4420.057	4511

Table B23: Cylinder test results for 100% CA and 5% FA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-03		101	8011.865	98.64	96.573152	1747.796	
C-10		101	8011.865	107.78	105.569654	1910.616	
C-11	7	101	8011.865	102.89	100.756427	1823.506	1827
C-08		101	8011.865	159.27	156.251261	2827.86	
C-07		101	8011.865	142.5	139.74455	2529.119	
C-09	14	101	8011.865	154.12	151.182116	2736.118	2698
C-01		101	8011.865	170	173.7719	3144.951	
C-02		101	8011.865	200	203.9669	3691.425	
C-05	28	101	8011.865	195	198.9344	3600.346	3479

Table B24: Cylinder test results for 100% CA and 10% FA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-09		101	8011.865	117.69	115.324067	2087.153	
C-03		101	8011.865	105.96	103.778228	1878.195	
C-06	7	101	8011.865	104.64	102.478952	1854.68	1940
C-08		101	8011.865	150.06	147.185858	2663.793	
C-07		101	8011.865	146.82	143.996726	2606.075	
C-02	14	101	8011.865	149	146.1425	2644.91	2638
C-01		101	8011.865	190	193.9019	3509.267	
C-04		101	8011.865	185	188.8694	3418.188	
C-05	28	101	8011.865	180	183.8369	3327.109	3418

Table B25: Cylinder test results for 100% CA and 15% FA replacement by QEAF

Cylinder ID	Curing Days	Diameter (mm)	Area (mm2)	Load (KN)	Calibrated Load (KN)	f'c (psi)	Avg f'c (psi)
C-07		101	8011.865	121.1	118.68053	2147.899	
C-10		101	8011.865	122.55	120.107765	2173.729	
C-12	7	101	8011.865	120.24	117.834032	2132.579	2151
C-11		101	8011.865	171.96	168.742028	3053.92	
C-02		101	8011.865	188.34	184.864862	3345.713	
C-03	14	101	8011.865	176.1	172.81703	3127.67	3176
C-01		101	8011.865	220	224.0969	4055.741	
C-04		101	8011.865	225	229.1294	4146.82	
C-08	28	101	8011.865	230	234.1619	4237.899	4147

APPENDIX C

Chapter 9

Related Formulas of Marshall Test

Bulk Specific Gravity of compacted mixture, $G_{mb} = \frac{W_a}{W_s - W_w}$

Maximum Specific Gravity of paving mixture, $G_{mm} = \frac{P_{mm}}{\frac{P_s}{G_{se}} + \frac{P_b}{G_b}}$

Aggregate content by percent, $P_s = 100 - P_b$

Effective Specific Gravity, $G_{se} = \frac{P_{mm} - P_b}{\frac{P_{mm}}{G_{mm}} - \frac{P_b}{G_b}}$

Bulk Specific Gravity of aggregates, $G_{sb} = \frac{P_1 + P_2 + P_3}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \frac{P_3}{G_3}}$

Air void in compacted mixture, $\%V_a = 100 \frac{G_{mm} - G_{mb}}{G_{mm}}$

Voids in mineral aggregates, $\%VMA = 100 - \frac{G_{sb} * P_s}{G_{sb}}$

Voids filled with asphalt, $\%VFA = \frac{\%VMA - \%V_a}{\%VMA} * 100$

Table C1: Marshall Test data of Batch 1 (Standard)

P_b (in %)	wt. in air, w_a (gm)	wt. in water, w_w (gm)	SSD wt. in air, W_s (gm)	G_{mb}	unit wt, gamma (lb/cft)	G_{mm}	P_s (in %)	G_{se}	G_{sb}	Pa or V %	VMA %	VFA%	height, inch	correlation factor	stability reading	corrected stability (lb)	flow value (1/100 in)
4	1182.9	701.7	1189	2.43	151.47	2.52	96	2.69	2.67	4	13	71	2.36	1.14	468	3118	20
4	1184.8	702	1190.5	2.43	151.34	2.52	96	2.69	2.67	4	13	71	2.40	1.09	565	3607	10
4	1193.7	705.3	1199.3	2.42	150.78	2.52	96	2.69	2.67	4	13	69	2.39	1.09	403	2562	16
4	1187.1	703	1192.9	2.42	151.2	2.52	96	2.69	2.67	4	13	70	2.38	1.11	479	3097	15
4.5	1197.5	714	1199.8	2.47	153.82	2.52	95.5	2.71	2.67	2	12	82	2.36	1.14	382	2538	17
4.5	1188	707.9	1192.1	2.45	153.1	2.52	95.5	2.71	2.67	3	12	79	2.35	1.14	392	2606	17
4.5	1196.7	713.6	1193	2.5	155.77	2.52	95.5	2.71	2.67	1	11	91	2.39	1.09	450	2865	16
4.5	1194.1	711.8	1195	2.47	154.22	2.52	95.5	2.71	2.67	2	12	84	2.37	1.12	408	2674	16
5	1202.4	718.4	1204.3	2.47	154.41	2.52	95	2.73	2.67	2	12	85	2.35	1.14	425	2828	22
5	1207.4	718.2	1210.6	2.45	153.01	2.52	95	2.73	2.67	3	13	79	2.40	1.09	448	2852	18
5	1199.8	715.3	1202.2	2.46	153.76	2.52	95	2.73	2.67	2	12	82	2.39	1.09	383	2433	16
5	1203.2	717.3	1205.7	2.46	153.73	2.52	95	2.73	2.67	2	12	82	2.38	1.11	419	2704	18
5.5	1212.7	724.3	1219	2.45	152.97	2.52	94.5	2.76	2.67	3	13	80	2.36	1.14	380	2525	22
5.5	1206.4	717.7	1208.6	2.46	153.35	2.52	94.5	2.76	2.67	2	13	81	2.36	1.14	385	2558	20
5.5	1208.6	719	1210.5	2.46	153.44	2.52	94.5	2.76	2.67	2	13	81	2.37	1.14	332	2201	20
5.5	1209.2	720.3	1212.7	2.46	153.25	2.52	94.5	2.76	2.67	3	13	81	2.36	1.14	366	2428	21
6	1207.8	717	1209.8	2.45	152.94	2.52	94	2.78	2.67	3	14	80	2.41	1.09	349	2214	20
6	1201.6	712.2	1203.8	2.44	152.52	2.52	94	2.78	2.67	3	14	79	2.40	1.09	285	1801	23
6	1206.9	714.8	1209.2	2.44	152.33	2.52	94	2.78	2.67	3	14	78	2.40	1.09	285	1801	18
6	1205.4	714.7	1207.6	2.45	152.59	2.52	94	2.78	2.67	3	14	79	2.40	1.09	306	1939	20

Table C2: Marshall Test data of Batch 2 (20% aggregates replaced by QEAF)

P_b (in %)	wt. in air, w_a (gm)	wt. in water, w_w (gm)	SSD wt. in air, W_s (gm)	G_{mb}	unit wt, gamma (lb/cft)	G_{mm}	P_s (in %)	G_{se}	G_{sb}	Pa or V %	VMA %	VFA%	height, inch	correlation factor	stability reading	corrected stability (lb)	flow value (1/100 in)
4	1182.5	714.8	1187.9	2.5	155.97	2.6	96	2.78	2.87	4	16	76	2.30	1.19	425	2952	18
4	1211.3	738.4	1215.2	2.54	158.53	2.6	96	2.78	2.87	2	15	85	2.39	1.09	615	3929	14
4	1199.4	727	1204.7	2.51	156.67	2.6	96	2.78	2.87	3	16	78	2.30	1.19	415	2882	15
4	1197.7	726.7	1202.6	2.52	157.06	2.6	96	2.78	2.87	3	16	80	2.33	1.16	485	3280	16
4.5	1200.9	726.9	1206.5	2.5	156.25	2.6	95.5	2.81	2.87	4	17	78	2.32	1.14	435	2895	16
4.5	1202.6	728.4	1208.1	2.51	156.44	2.6	95.5	2.81	2.87	4	16	78	2.34	1.14	415	2761	19
4.5	1200.6	731.3	1202.9	2.55	158.86	2.6	95.5	2.81	2.87	2	15	86	2.30	1.19	495	3445	17
4.5	1201.4	728.9	1205.8	2.52	157.17	2.6	95.5	2.81	2.87	3	16	81	2.32	1.16	448	3029	17
5	1196.2	732	1198.1	2.57	160.14	2.6	95	2.83	2.87	1	15	91	2.28	1.19	525	3656	15
5	1200.3	732.3	1202.3	2.55	159.36	2.6	95	2.83	2.87	2	15	88	2.30	1.19	475	3304	20
5	1197.2	729.8	1199.5	2.55	159.05	2.6	95	2.83	2.87	2	15	87	2.26	1.19	425	2952	14
5	1197.9	731.4	1200.0	2.56	159.52	2.6	95	2.83	2.87	2	15	89	2.28	1.19	475	3304	16
5.5	1213.5	739.2	1214.9	2.55	159.18	2.6	94.5	2.86	2.87	2	16	88	2.35	1.14	424	2821	15
5.5	1206.4	736.1	1208.2	2.56	159.46	2.6	94.5	2.86	2.87	2	16	89	2.28	1.19	425	2952	18
5.5	1205.2	734.6	1206.7	2.55	159.3	2.6	94.5	2.86	2.87	2	16	89	2.22	1.25	406	2960	20
5.5	1208.4	736.6	1209.9	2.55	159.31	2.6	94.5	2.86	2.87	2	16	89	2.29	1.19	418	2913	17
6	1206.4	732.9	1208.4	2.54	158.32	2.6	94	2.89	2.87	2	17	86	2.31	1.19	410	2846	18
6	1220.8	741.5	1221.9	2.54	158.57	2.6	94	2.89	2.87	2	17	86	2.34	1.14	445	2963	23
6	1222.4	742.2	1223.6	2.54	158.45	2.6	94	2.89	2.87	2	17	86	2.31	1.14	375	2491	22
6	1216.5	738.9	1218	2.54	158.45	2.6	94	2.89	2.87	2	17	86	2.32	1.16	410	2767	21

Table C3: Marshall Test data of Batch 3 (30% aggregates replaced by QEAF)

P_b (in %)	wt. in air, w_a (gm)	wt. in water, w_w (gm)	SSD wt. in air, W_s (gm)	G_{mb}	unit wt, gamma (lb/cft)	G_{mm}	P_s (in %)	G_{se}	G_{sb}	Pa or V %	VMA %	VFA%	height, inch	correlation factor	stability reading	corrected stability (lb)	flow value (1/100 in)
4	1193.1	738.5	1196.9	2.6	162.41	2.66	96	2.85	2.91	2	14	85	2.26	1.19	532	3705	15
4	1201.5	738.5	1206.1	2.57	160.34	2.66	96	2.85	2.91	3	15	78	2.32	1.14	428	2848	17
4	1198.2	738.6	1201.2	2.59	161.62	2.66	96	2.85	2.91	3	15	82	2.26	1.19	465	3234	16
4	1197.6	738.5	1201.4	2.59	161.45	2.66	96	2.85	2.91	3	15	81	2.28	1.17	475	3258	16
4.5	1204.5	747.1	1207.2	2.62	163.36	2.66	95.5	2.88	2.91	2	14	89	2.24	1.25	489	3574	18
4.5	1205	744.4	1207.7	2.6	162.3	2.66	95.5	2.88	2.91	2	15	85	2.30	1.19	520	3621	24
4.5	1196.6	742.2	1198.3	2.62	163.71	2.66	95.5	2.88	2.91	1	14	90	2.24	1.25	542	3966	14
4.5	1202.0	744.6	1204.4	2.61	163.12	2.66	95.5	2.88	2.91	2	14	88	2.26	1.23	517	3721	19
5	1186.7	736	1188.8	2.62	163.54	2.66	95	2.91	2.91	1	14	90	2.20	1.25	410	2990	16
5	1198.8	740.5	1200.7	2.6	162.55	2.66	95	2.91	2.91	2	15	86	2.25	1.25	450	3286	17
5	1199.3	742.1	1201.2	2.61	163.01	2.66	95	2.91	2.91	2	15	88	2.28	1.19	415	2882	14
5	1195	739.5	1196.9	2.61	163.03	2.66	95	2.91	2.91	2	15	88	2.25	1.23	425	3051	16
5.5	1211	752.7	1213.1	2.63	164.13	2.66	94.5	2.94	2.91	1	15	92	2.26	1.19	385	2671	21
5.5	1196.4	739.3	1198.6	2.6	162.54	2.66	94.5	2.94	2.91	2	15	87	2.24	1.25	389	2835	24
5.5	1223.6	756.1	1225.2	2.61	162.76	2.66	94.5	2.94	2.91	2	15	87	2.30	1.19	435	3022	14
5.5	1210.3	749.4	1212.3	2.61	163.14	2.66	94.5	2.94	2.91	2	15	89	2.27	1.21	403	2844	20
6	1220.4	753.3	1221.8	2.6	162.55	2.66	94	2.97	2.91	2	16	87	2.26	1.19	425	2952	19
6	1197.5	740	1199	2.61	162.8	2.66	94	2.97	2.91	2	16	88	2.24	1.25	385	2805	21
6	1190.8	733.3	1192.3	2.59	161.89	2.66	94	2.97	2.91	2	16	85	2.23	1.25	375	2731	21
6	1203	742.2	1204.4	2.6	162.41	2.66	94	2.97	2.91	2	16	87	2.24	1.23	395	2833	20

Table C4: Marshall Test data of Batch 4 (40% aggregates replaced by QEAF)

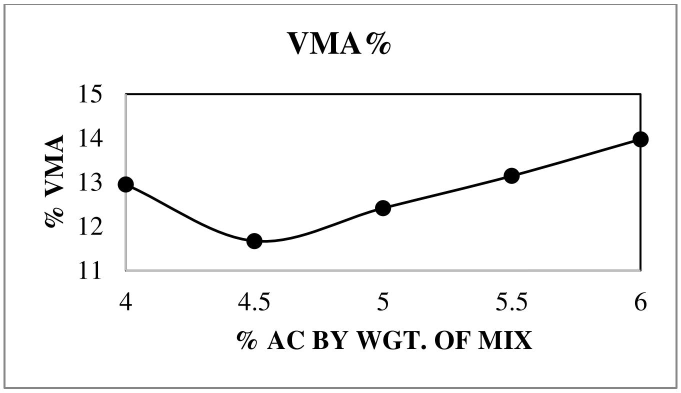
P_b (in %)	wt. in air, w_a (gm)	wt. in water, w_w (gm)	SSD wt. in air, W_s (gm)	G_{mb}	unit wt, gamma (lb/cft)	G_{mm}	P_s (in %)	G_{se}	G_{sb}	Pa or V %	VMA %	VFA%	height, inch	correlation factor	stability reading	corrected stability (lb)	flow value (1/100 in)
4	1192.8	739.6	1197.9	2.6	162.41	2.75	96	2.95	3.03	5	17	70	2.36	1.25	470	3434	16
4	1194.9	742.5	1199.6	2.61	163.12	2.75	96	2.95	3.03	5	17	72	2.40	1.19	550	3832	14
4	1198.8	743.4	1204.8	2.6	162.13	2.75	96	2.95	3.03	5	18	70	2.39	1.25	450	3286	15
4	1195.5	741.8	1200.8	2.6	162.55	2.75	96	2.95	3.03	5	17	71	2.38	1.23	490	3524	15
4.5	1196.2	750.6	1199.2	2.67	166.39	2.75	95.5	2.98	3.03	3	16	82	2.36	1.32	499	3852	19
4.5	1184.4	738.1	1187.9	2.63	164.31	2.75	95.5	2.98	3.03	4	17	76	2.35	1.32	420	3236	17
4.5	1199.9	748.0	1203.2	2.64	164.49	2.75	95.5	2.98	3.03	4	17	76	2.39	1.25	525	3840	14
4.5	1193.5	745.6	1196.8	2.65	165.06	2.75	95.5	2.98	3.03	4	17	78	2.37	1.30	481	3649	17
5	1204.4	753.5	1206.5	2.66	165.9	2.75	95	3.02	3.03	3	17	81	2.35	1.25	497	3633	14
5	1203.4	753.7	1205.7	2.66	166.13	2.75	95	3.02	3.03	3	16	82	2.40	1.19	485	3374	12
5	1209.5	757.2	1211.5	2.66	166.13	2.75	95	3.02	3.03	3	16	82	2.39	1.25	525	3840	17
5	1205.8	754.8	1207.9	2.66	166.06	2.75	95	3.02	3.03	3	16	81	2.38	1.23	502	3614	14
5.5	1208.4	755.3	1210.6	2.65	165.61	2.75	94.5	3.05	3.03	3	17	81	2.36	1.32	410	3157	19
5.5	1195.6	746.5	1198.3	2.65	165.13	2.75	94.5	3.05	3.03	4	17	79	2.36	1.32	395	3040	16
5.5	1199.4	749.4	1201.7	2.65	165.47	2.75	94.5	3.05	3.03	3	17	80	2.37	1.32	462	3563	22
5.5	1201.1	750.4	1203.5	2.65	165.41	2.75	94.5	3.05	3.03	3	17	80	2.36	1.32	422	3254	19
6	1207.9	753.6	1209.7	2.65	165.26	2.75	94	3.08	3.03	4	18	80	2.41	1.25	465	3397	16
6	1204.8	752.6	1206.6	2.65	165.59	2.75	94	3.08	3.03	3	18	81	2.40	1.25	390	2842	15
6	1204.5	754.3	1206.3	2.66	166.28	2.75	94	3.08	3.03	3	17	83	2.40	1.32	445	3431	17
6	1205.7	753.5	1207.5	2.66	165.71	2.75	94	3.08	3.03	3	18	81	2.40	1.27	433	3222	16

Table C5: Marshall Test data of Batch 5 (50% aggregates replaced by QEAF)

P_b (in %)	wt. in air, w_a (gm)	wt. in water, w_w (gm)	SSD wt. in air, W_s (gm)	G_{mb}	unit wt, gamma (lb/cft)	G_{mm}	P_s (in %)	G_{se}	G_{sb}	Pa or V %	VMA %	VFA%	height, inch	correlation factor	stability reading	corrected stability (lb)	flow value (1/100 in)
4	1152.1	725.8	1158.3	2.66	166.22	2.82	96	3.05	3.11	6	18	68	2.14	1.32	265	2025	17
4	1207.8	759.8	1213.8	2.66	166.01	2.82	96	3.05	3.11	6	18	68	2.18	1.32	440	3392	18
4	1205.2	757.0	1210.7	2.66	165.76	2.82	96	3.05	3.11	6	18	67	2.21	1.25	480	3508	15
4	1188.4	747.5	1194.3	2.66	165.99	2.82	96	3.05	3.11	6	18	68	2.18	1.30	395	2987	17
4.5	1193.2	752.2	1196.2	2.69	167.69	2.82	95.5	3.08	3.11	5	17	72	2.20	1.25	435	3175	15
4.5	1191.8	752.4	1195.3	2.69	167.91	2.82	95.5	3.08	3.11	5	17	73	2.14	1.32	365	2806	16
4.5	1190.1	745.5	1194.6	2.65	165.36	2.82	95.5	3.08	3.11	6	19	67	2.19	1.25	352	2561	17
4.5	1191.7	750.0	1195.4	2.68	166.98	2.82	95.5	3.08	3.11	5	18	71	2.18	1.27	384	2850	16
5	1202.6	758.9	1204.9	2.7	168.26	2.82	95	3.12	3.11	4	18	74	2.18	1.32	365	2806	16
5	1196.9	758.5	1197.2	2.73	170.25	2.82	95	3.12	3.11	3	17	80	2.13	1.32	435	3353	17
5	1201.6	757.2	1204.2	2.69	167.74	2.82	95	3.12	3.11	5	18	73	2.17	1.32	375	2884	17
5	1200.4	758.2	1202.1	2.7	168.74	2.82	95	3.12	3.11	4	17	76	2.16	1.32	392	3014	17
5.5	1202.4	763.4	1204.2	2.73	170.21	2.82	94.5	3.15	3.11	3	17	80	2.16	1.32	475	3665	17
5.5	1207.6	764.1	1209.9	2.71	169.03	2.82	94.5	3.15	3.11	4	18	77	2.21	1.25	365	2657	15
5.5	1202.3	760.2	1204.6	2.71	168.82	2.82	94.5	3.15	3.11	4	18	77	2.16	1.25	399	2909	19
5.5	1204.1	762.6	1206.2	2.71	169.35	2.82	94.5	3.15	3.11	4	17	78	2.18	1.27	413	3068	17
6	1201.2	760.8	1203.2	2.72	169.43	2.82	94	3.19	3.11	4	18	79	2.19	1.25	380	2768	15
6	1219.6	770.5	1221.4	2.7	168.78	2.82	94	3.19	3.11	4	18	77	2.21	1.25	428	3123	18
6	1235.0	779.6	1236.2	2.7	168.78	2.82	94	3.19	3.11	4	18	77	2.20	1.25	455	3323	20
6	1218.6	770.3	1220.3	2.71	168.99	2.75	94	3.19	3.11	4	18	78	2.20	1.25	421	3071	18

Table C6: Marshall Test data of Batch 6 (60% aggregates replaced by QEAF)

P_b (in %)	wt. in air, w_a (gm)	wt. in water, w_w (gm)	SSD wt. in air, W_s (gm)	G_{mb}	unit wt, gamma (lb/cft)	G_{mm}	P_s (in %)	G_{se}	G_{sb}	Pa or V %	VMA %	VFA%	height, inch	correlation factor	stability reading	corrected stability (lb)	flow value (1/100 in)
4	1182.9	701.7	1189.0	2.43	151.47	2.88	96	3.12	3.16	16	26	40	2.20	1.25	325	2362	14
4	1184.8	702.0	1190.5	2.43	151.34	2.88	96	3.12	3.16	16	26	40	2.23	1.25	475	3471	14
4	1193.7	705.3	1199.3	2.42	150.78	2.88	96	3.12	3.16	16	27	39	2.19	1.25	472	3448	19
4	1187.1	703.0	1192.9	2.42	151.2	2.88	96	3.12	3.16	16	26	39	2.20	1.25	424	3094	16
4.5	1197.5	714.0	1199.8	2.47	153.82	2.88	95.5	3.16	3.16	14	25	43	2.16	1.32	428	3298	18
4.5	1188.0	707.9	1192.1	2.45	153.1	2.88	95.5	3.16	3.16	15	26	42	2.23	1.25	502	3670	17
4.5	1196.7	713.6	1193.0	2.5	155.77	2.88	95.5	3.16	3.16	13	25	45	2.17	1.32	493	3805	12
4.5	1194.1	711.8	1195.0	2.47	154.22	2.88	95.5	3.16	3.16	14	25	43	2.19	1.30	474	3595	16
5	1202.4	718.4	1204.3	2.47	154.41	2.88	95	3.19	3.16	14	26	45	2.16	1.32	360	2767	16
5	1207.4	718.2	1210.6	2.45	153.01	2.88	95	3.19	3.16	15	26	43	2.19	1.32	455	3509	16
5	1199.8	715.3	1202.2	2.46	153.76	2.88	95	3.19	3.16	15	26	44	2.17	1.32	385	2962	14
5	1203.2	717.3	1205.7	2.46	153.73	2.88	95	3.19	3.16	15	26	44	2.17	1.32	400	3079	15
5.5	1212.7	724.3	1219.0	2.45	152.97	2.88	94.5	3.23	3.16	15	27	44	2.17	1.32	416	3204	15
5.5	1206.4	717.7	1208.6	2.46	153.35	2.88	94.5	3.23	3.16	15	26	44	2.17	1.32	428	3298	15
5.5	1208.6	719.0	1210.5	2.46	153.44	2.88	94.5	3.23	3.16	15	26	44	2.16	1.32	325	2494	15
5.5	1209.2	720.3	1212.7	2.46	153.25	2.88	94.5	3.23	3.16	15	27	44	2.16	1.32	390	2999	15
6	1207.8	717.0	1209.8	2.45	152.94	2.88	94	3.27	3.16	15	27	45	2.13	1.32	415	3196	18
6	1201.6	712.2	1203.8	2.44	152.52	2.88	94	3.27	3.16	15	27	44	2.16	1.32	435	3353	18
6	1206.9	714.8	1209.2	2.44	152.33	2.88	94	3.27	3.16	15	27	44	2.16	1.32	467	3602	17
6	1205.4	714.7	1207.6	2.45	152.59	2.88	94	3.27	3.16	15	27	44	2.15	1.32	439	3384	18



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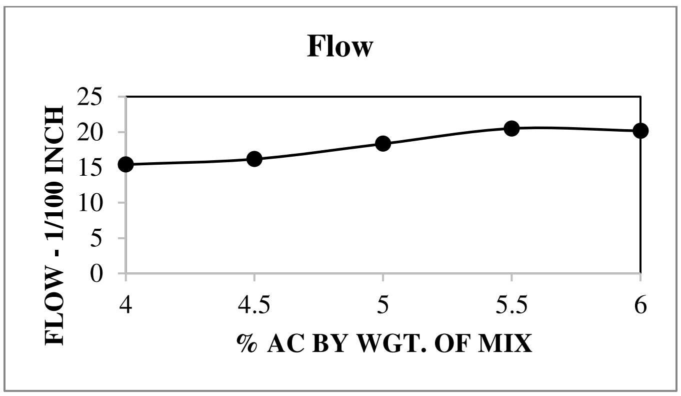

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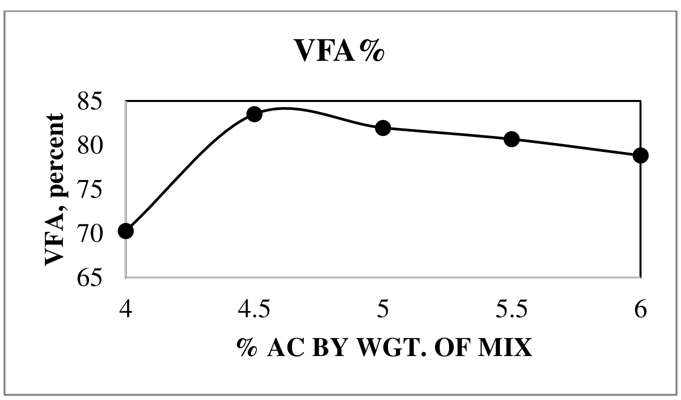
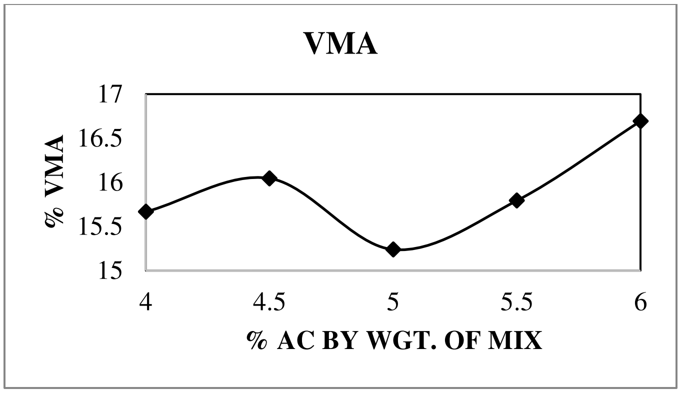


(c)

Figure C1: Test property curves for standard sample hot mix design data (a) VMA vs. asphalt content (b) Flow vs. asphalt content (c) VFA vs. asphalt content



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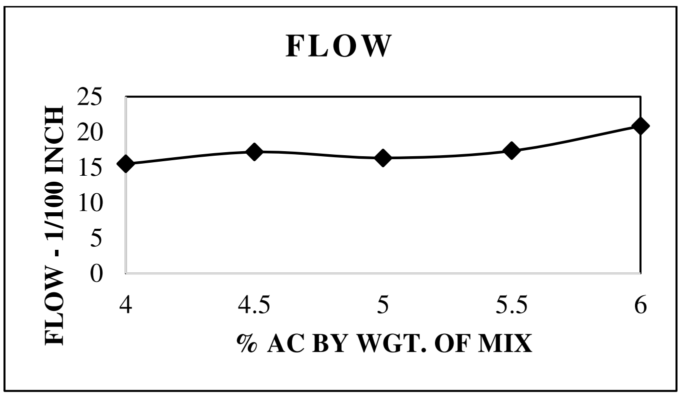

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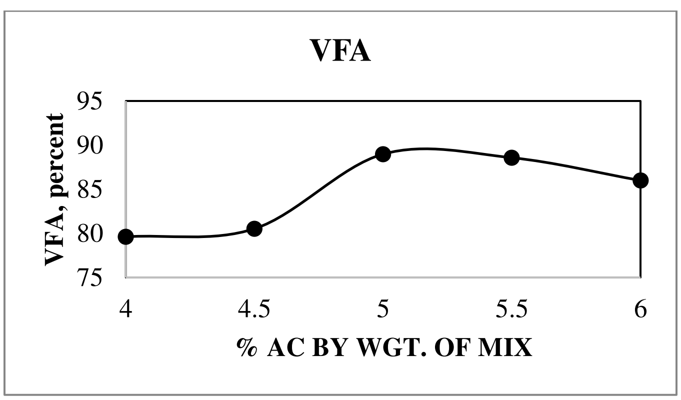
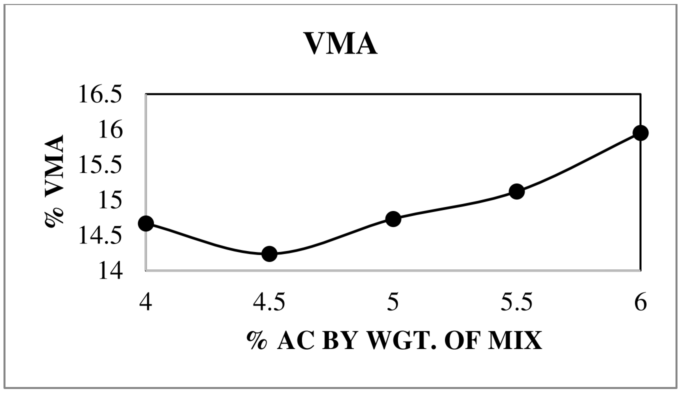


(c)

Figure C.2: Test property curves for 20% replaced with slag sample hot mix design data (a) VMA vs. asphalt content (b) Flow vs. asphalt content (c) VFA vs. asphalt content



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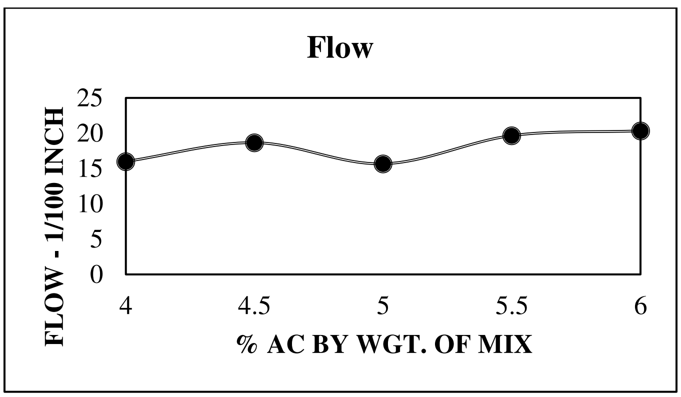

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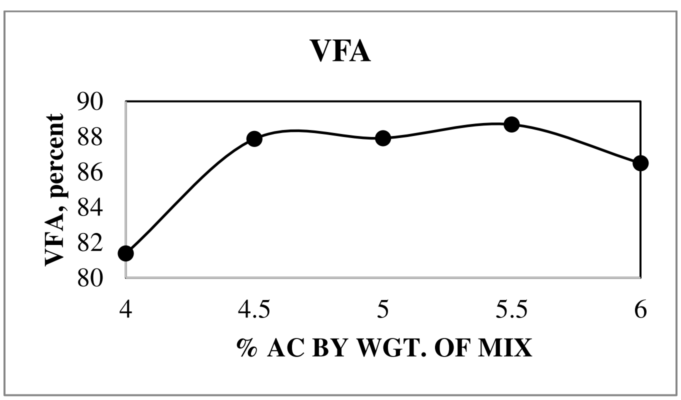
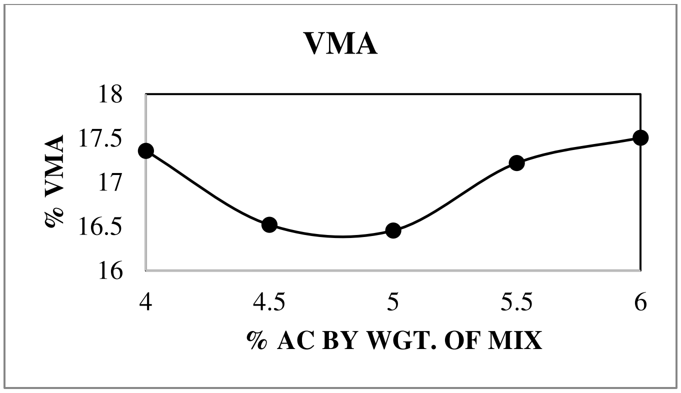


(c)

Figure C.3: Test property curves for 30% replaced with slag sample hot mix design data (a) VMA vs. asphalt content (b) Flow vs. asphalt content (c) VFA vs. asphalt content



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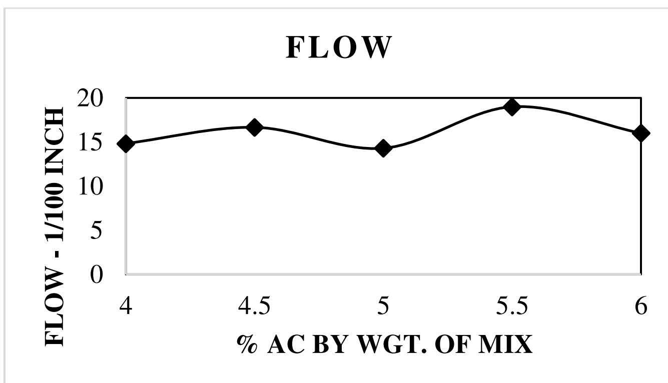

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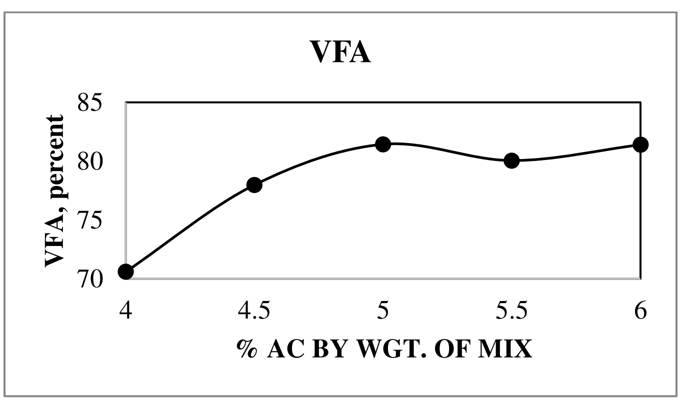
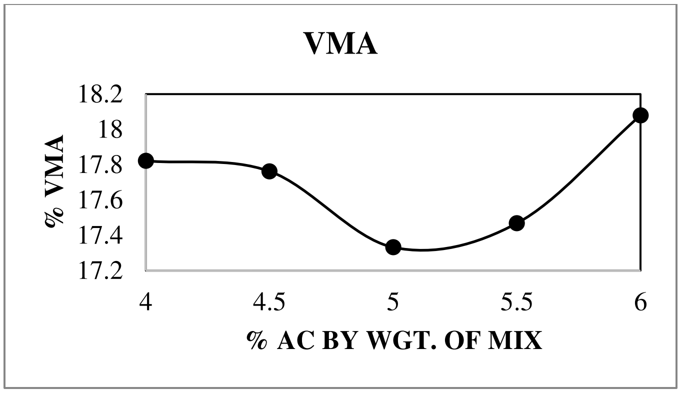
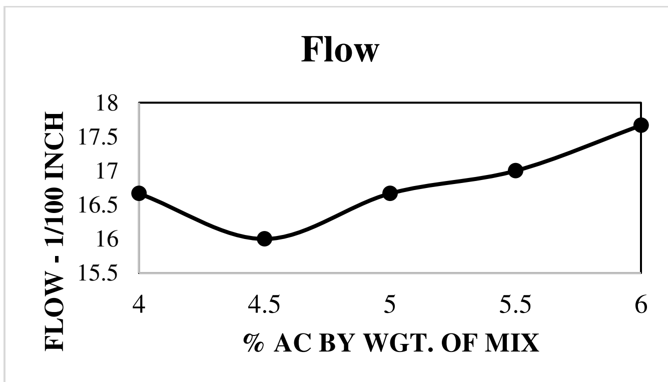


(c)

Figure C.4: Test property curves for 40% replaced with slag sample hot mix design data (a) VMA vs. asphalt content (b) Flow vs. asphalt content (c) VFA vs. asphalt content



(a)



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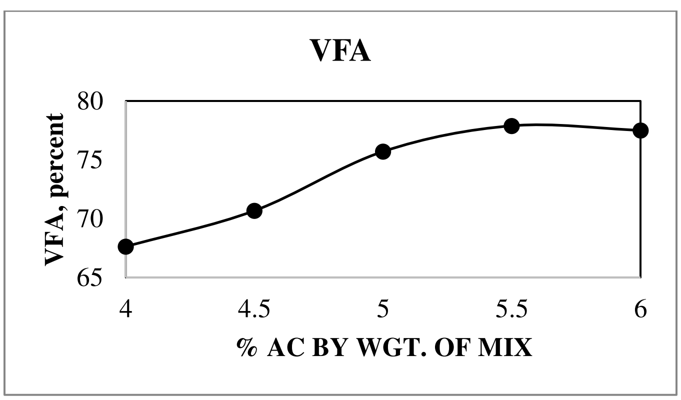
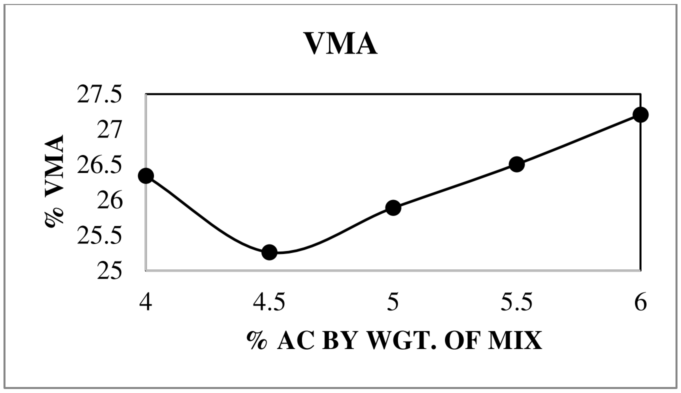
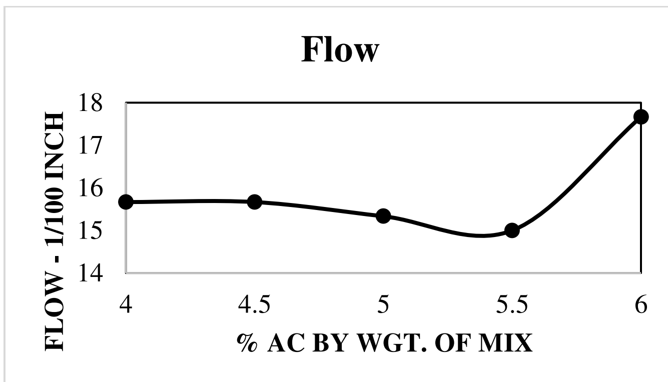


(c)

Figure C.5: Test property curves for 50% replaced with slag sample hot mix design data (a) VMA vs. asphalt content (b) Flow vs. asphalt content (c) VFA vs. asphalt content



(a)



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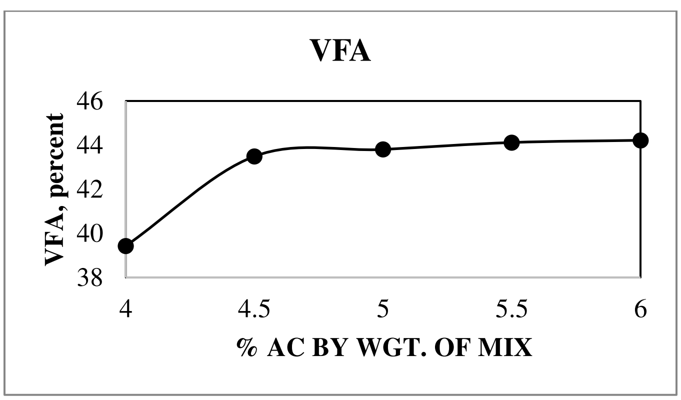


(c)

Figure C.6: Test property curves for 60% replaced with slag sample hot mix design data (a) VMA vs. asphalt content (b) Flow vs. asphalt content (c) VFA vs. asphalt content

Utilization of Quantum Electric Arc Furnace (QEAF) and Ladle Refining Furnace (LRF) slag Generated in GPH ISPAT

GPH ispat

Funded By
GPH ISPAT
Implemented By
Materials Research Center (MRC)
Bangladesh University of Engineering and Technology (BUET).

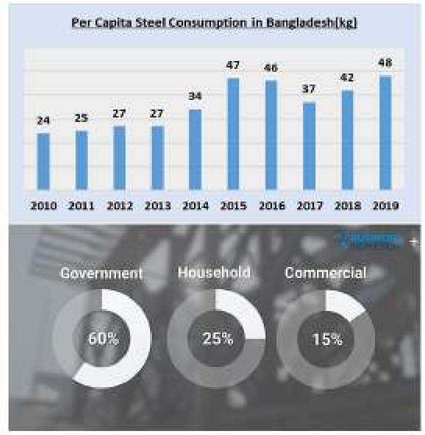
Preamble

- This research was conducted under the "**Memorandum of Agreement**" signed between **GPH Ispat and the Materials Research Centre (MRC), Bangladesh University of Engineering and Technology (BUET)**.
- The project proposed to study the nature of the **Quantum Electric Arc Furnace (QEAF) and Ladle Refining Furnace (LRF) Slag** generated in GPH Ispat in the process of its utilization in the construction sector.
- **Reuse of this industrial waste** that is being generated in an ever-increasing volume will be **financially rewarding** for the industry. The utilization of this slag would also help maintain a **healthy environment**.
- The project was proposed for **one year (April 2022-March 2023).**

The project was implemented by an expert team of Faculty members and researchers of BUET and the team members delicately performed their well-defined responsibilities with active cooperation of GPH ISPAT throughout the project implementation period.

Background: Steel consumption in Bangladesh

- Bangladesh's steel consumption is significantly lower than the global average.
- Currently (Oct 30, 2022), per capita consumption is **45 kg** whereas the global average is **208 kg**. [1]
- The country consumes **more than 7 million metric tons** of steel. [2]
- The steel sector employs around **1 million people** directly or indirectly. [2]
- Of the total production, **60%** of steel is used in Bangladesh's public sector, **25%** is used in households, and **15%** is used in commercial construction.



1. https://www.thedailystar.net/business/economy/news/steel-industry-heat-new-players-joining-race-3155591
2. https://www.tbsnews.net/supplement/once-booming-steel-industry-now-deep-stress-574518

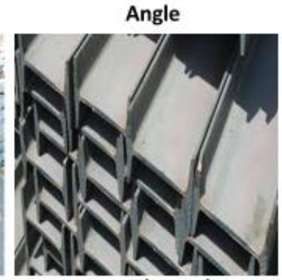
Background: Steel Industries in Bangladesh

- **Steel Products:**
  The steel industry in Bangladesh produces mainly
  - Billet-MS Angle-MS Channel-Flat Bar-Round Bar
  - 40 grade/60 grade/75 grade deformed bar

Angle

Billet

Deformed bar



Channel

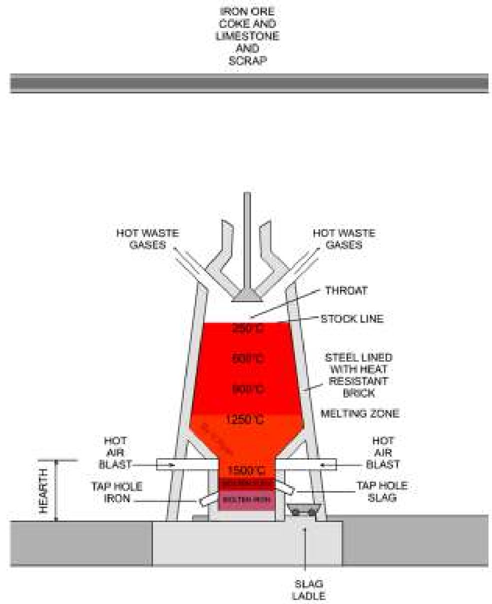
Background: Steel Making routes

Plain carbon steels are produced principally by the following routes:

1) Primary steelmaking uses mostly new iron as the feedstock, usually from a blast furnace.

Blast furnace→ Basic oxygen furnace →Ladle treatments→continuous casting→ Rolling →flat or long products.

Adopted by Integrated Steel Plants



Background: Steel Making routes

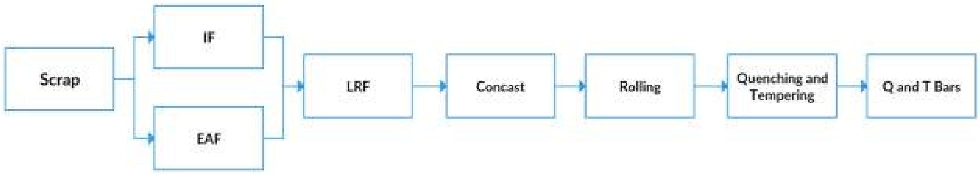
2) Secondary steelmaking uses scrap steel as the primary raw material.

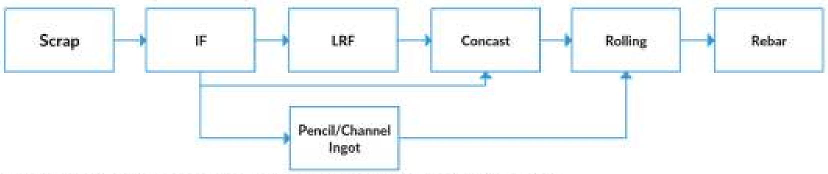
Electric Furnace→ Ladle treatments→ Continuous casting→Rolling →Mostly long products but occasionally flat products.

Adopted by Mini Steel Plants

Background: Steel Making in Bangladesh

- According to Bangladesh Steel Mills Owners Association, there are about **400 steel mills** in the country, with a total production capacity of about **9 million metric tons.** [1]





1. https://www.tbsnews.net/supplement/once-booming-steel-industry-now-deep-stress-574518

Background: Steel Production in GPH Ispat

New Technology: Quantum EAF

The plant has the capacity to produce **8.4 lakh tonnes of MS billet** and **6.4 lakh tonnes of MS rod** and medium section products such as steel beam, angle, channel and flat bar[1].

Scrap Processing

Scrap Charging & Preheating

1. https://www.thedailystar.net/business/news/gph-ispat-begins-commercial-production-tk-2390cr-plant-2115261 (2021)

Background: Steel Production in GPH Ispat

Types of Products

Rebar

B600C-R-Rebar
YS ≥ 600 MPa or 87000 PSI
Ductility Class C: TS/YS = 1.15

B500DWR
YS ≥ 500 MPa or 72,500 PSI
Ductility Class D: TS / YS = 1.25

B500CWR
YS ≥ 500 MPa or 72,500 PSI
Ductility Class C: TS /YS = 1.15

B420DWR
YS ≥ 420 MPa or 60,900 PSI
Ductility Class D: TS/YS = 1.25

Billet

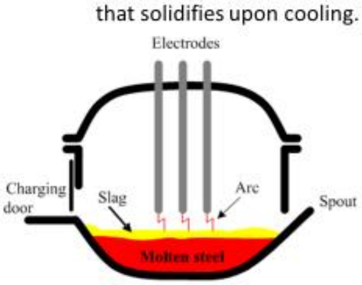
AVAILABLE SIZES

160X160 mm2 size, length 12000 mm	160X160 mm2 size, length 6000 mm
130X130 mm2 size, length 12000 mm	130X130 mm2 size, length 6000 mm

Background: What is SLAG?

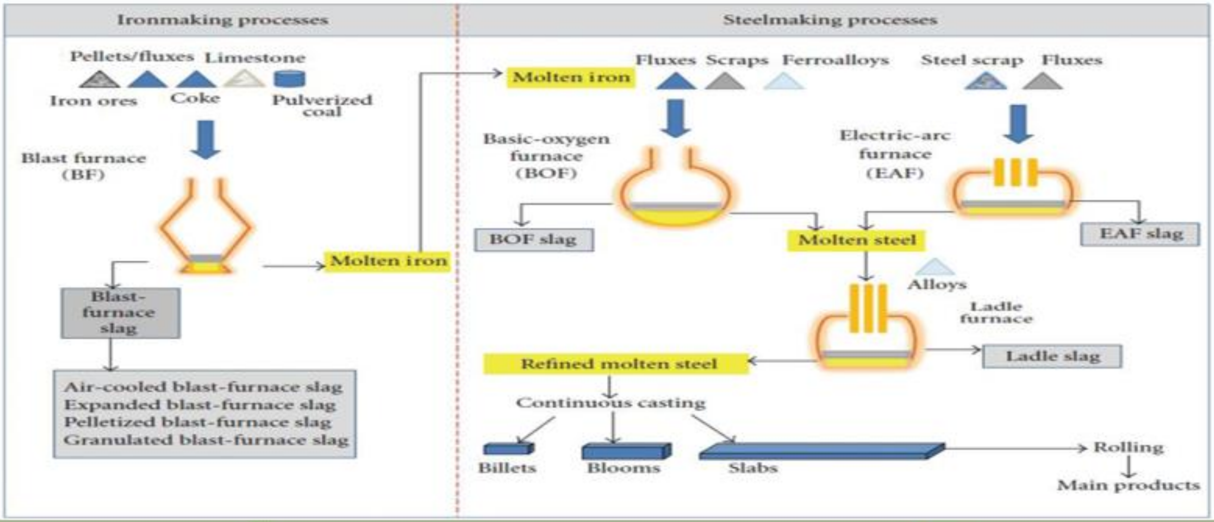
- Slag is the main by-product generate during iron and steel production.
- **P**roduced during the separation of the molten steel from **impurities** in steel-making furnaces.
- The slag occurs as a molten liquid melt and is a complex solution of silicates and oxides that solidifies upon cooling.

Various oxides, those of iron, silicon and manganese are formed... react with each other to form SLAG.



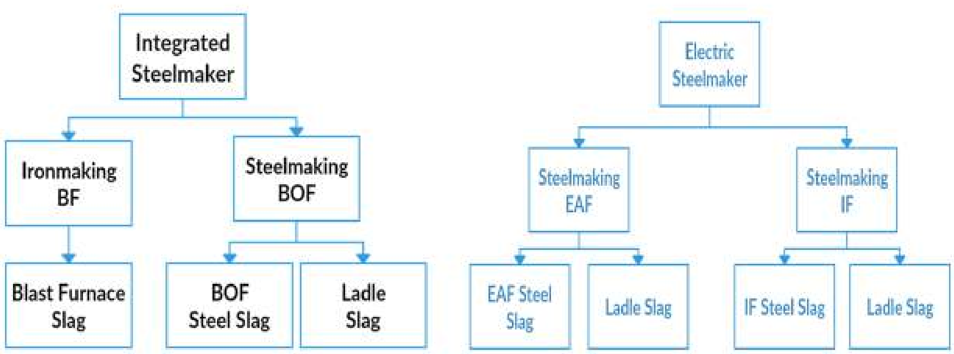
[C]+[O]= {CO}
[Si]+2[O]= (SiO2)
[Mn]+[O]= (MnO)
2[P]+5[O]= (P2O5)
[C]+(FeO)= {CO}+[Fe]
[Fe]+[O]= (FeO)

Background: Slag Formation



Background: Types of Slag

- The nature and composition of slag depends on the type of steel made and also the raw materials used for steel making.



Background: Slag Formation during and Steelmaking

- Slag from blast furnaces may be estimated to be **25% to 30% of crude (pig) iron** production and steel furnace slag may be estimated to be **10% to 15% of raw steel production** (1).
- On average the production of one tonne of steel results in **200 kg (EAF)** to **400 kg (BF/BOF)** of co-products. These include slag, dust and other materials (2).
- In 2021, world iron slag production was estimated to be between **340 million and 410 million tons**, and steel slag production was estimated to be between **190 million and 280 million tons**(1)

1. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-iron-steel-slag.pdf
2. https://worldsteel.org/wp-content/uploads/Fact-sheet-Steel-industry-co-products.pdf

Background: Chemical Compositions of Slag

Typical Compositions of Slag (Wt %)

Constituents	EAF[1]	LRF[2]	IF[3]	BOF[4]	BF[5]
CaO	22-60	40-65	2-4	30-55	34-43
SiO_2	6-34	10-40	35-45	8-20	27-38
Fe_2O_3	10-40	0.2-5	20-40	10-30	0.2-1.6
MgO	3-13	5-20	0.5-2.6	5-15	0.15-0.76
Al_2O_3	3-14	2-15	4-12	1-6	7-15

1. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8003827/#:~:text=EAF%20slag%20has%20a%20chemical,MgO%20(3%E2%80%9313%25).
2. https://www.researchgate.net/figure/Chemical-composition-of-LF-slag_tbl1_233555012
3. https://link.springer.com/article/10.1007/s42452-021-04299-9#:~:text=The%20major%20metal%20oxides%20present,metalloid%20SiO2%20(66.42).
4. Liang, Y., Li, W., & Wang, X. (2013). Influence of water content on mechanical properties of improved clayey soil using steel slag. Geotechnical and Geological Engineering, 31, 83-91.
5. https://www.researchgate.net/figure/Chemical-composition-of-granulated-blast-furnace-slag_tbl1_311387351

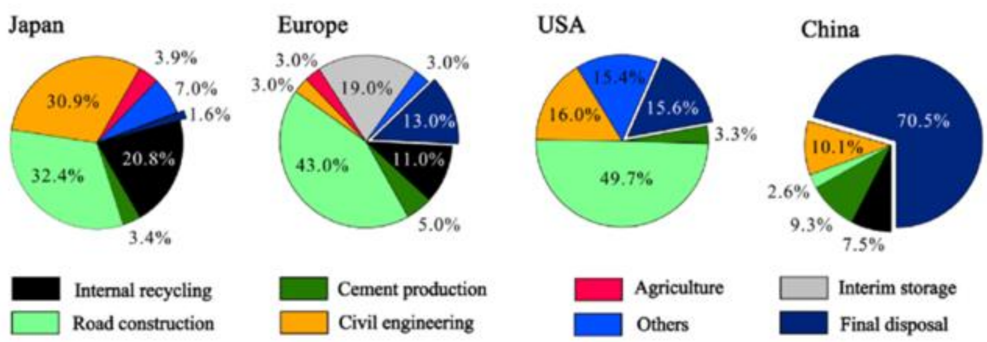
Background: Phases of Steel Slag

Phases	wt.%
Tricalcium silicate (C_3S), Ca_3SiO_5	0–20
Dicalcium silicate (C_2S), Ca_2SiO_4	30–60
Magnesiocalciowustite	15–30
Dicalcium aluminoferrite ($Ca_2(Fe, Al, Ti)_2O_5$	10–25
(Fe, Mn, Mg, Ca)O	0–5
Lime phase (Ca, Fe)O	0–15
Periclase (Mg, Fe)O	0–5
Fluorite CaF_2	0–1

Background: Slag management

- In Bangladesh most of the steel making plants dump these solid wastes only for landfill purpose.
- The current utilization rate of steel slag in Bangladesh is far behind the developed countries like USA, Japan, Germany, France, of which the rates have been close to 100%.
- In these developed countries, 50% of slag has been used for the road project directly.

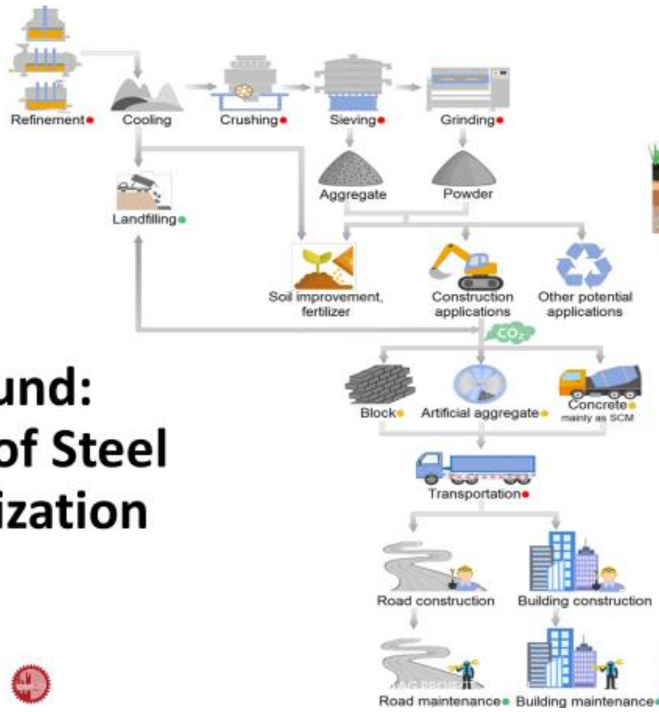
Background: Slag management



Background: Why Utilize Slag?

- When processed and marketed correctly, slag is not a waste, it is a **resource**.
- **Landfill** becoming scarce or more expensive or both.
- **Natural aggregate** resources are becoming more difficult to develop
- Why remove aggregate from the ground when slag can be used as a substitute (reduce waste – conserve resources).
- The world is becoming more **environmentally aware** – Protect and preserve our environment.

Background: Process of Steel Slag Utilization



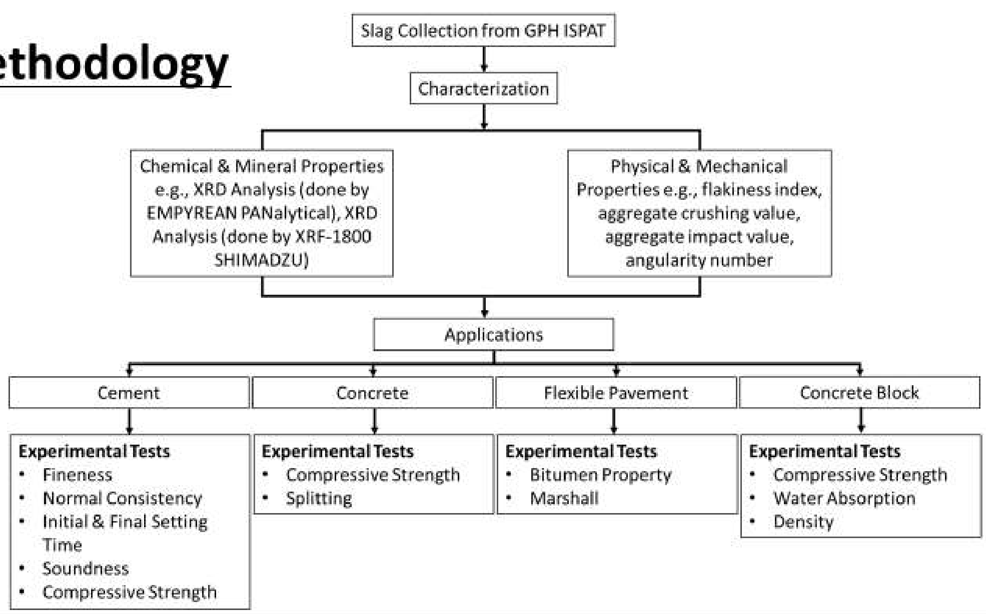
Objective of The Present Study

- Study the physical, chemical and mechanical properties of QEAF and LRF slags produced in GPH Ispat.
- Investigate possible utilization of QEAF and LRF slags in the production of Cement
- Determine optimum percentages of replacement by volume of coarse and fine aggregate in concrete by QEAF and LRF slag.
- Observe the performance of QEAF slag in partial replacement of coarse aggregate in Flexible Pavement
- Investigate possible utilization of QEAF and LRF slag in the production of Concrete Block

Work Schedule

Methodology	Timeline (in month)						
	1-2	3-4	5-6	7-8	8-9	9-10	11-12
[1] Collection of QEAF and LRF slag							
[2] Determination of initial parameters for making block , aggregate in concrete , cement production, flexible pavement							
[3] Making blocks and concrete samples on trial basis							
[4] Characterization of the products							
[5] Structural tests							
[6] Suitability to be used in cement production							
[7] Optimization of parameters on continuous trial and assessment basis to obtain desired results							
[8] Final report preparation and submission							

Methodology



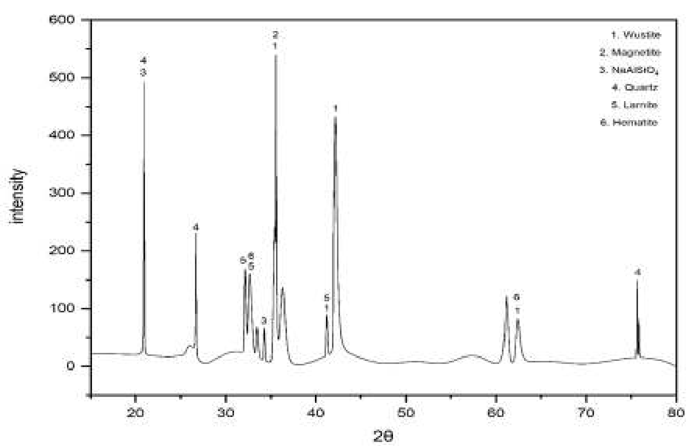
Methodology: Sample Collection

QEAF Slag

LRF Slag

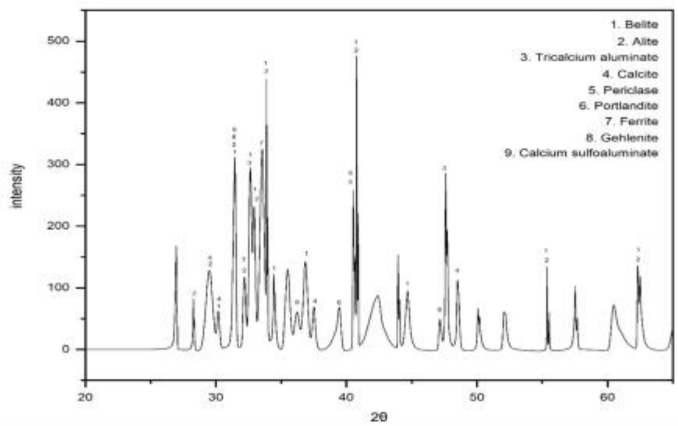
As-received Slag Sample from GPH ISPAT

Methodology:
Characterization: XRD Analysis (QEAF Slag)



- ✓ Wustite (FeO)
- ✓ Magnettite (Fe_3O_4)
- ✓ Sodium aluminosilicate ($NaAlSiO_4$)
- ✓ Quartz (SiO_2)
- ✓ Larnite (Ca_2SiO_4)
- ✓ Hematite (Fe_2O_3)

Methodology:
Characterization: XRD Analysis (LRF Slag)



- ✓ Belite (C_2S)
- ✓ Alite (C_3S)
- ✓ Tricalcium aluminate (C_3A)
- ✓ Calcite ($CaCO_3$),
- ✓ Periclase (MgO)
- ✓ Portlandite ($Ca(OH)_2$)
- ✓ Ferrite
- ✓ Gehlenite (C_2AS)
- ✓ Calcium sulfoaluminate (CSA)

Methodology:
Characterization: XRF Analysis

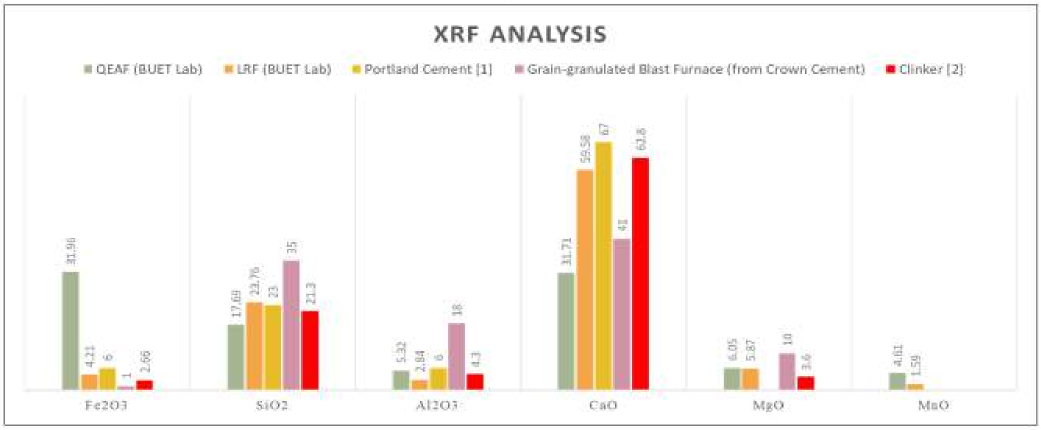
Composition	QEAF Slag		LRF Slag	
	Reported by GPH (2022)	XRF (BUET)	Reported by GPH (2022)	XRF (BUET)
Fe_2O_3%	11-36	31	0-4	4
SiO_2%	8-17	17	14-36	23
Al_2O_3%	5-11	5	3-13	2
CaO%	18-33	31	40-64	59
MgO%	7-20	6	3-20	5
MnO%	4-9	4	0-2	1
SO_3%	<1	<1	0-2	1
Cr_2O_3%	1-4	2	<1	<1
P_2O_5%	<1	<1	<1	<1

Methodology:
Characterization: Metallic Iron & Free Lime Tests

- %Metallic Iron (Fe) in Slag was calculated by Wet Analysis Method -
  - ✓ Metallic Iron in QEAF slag = 2.23%
  - ✓ Metallic Iron in LRF slag = 1.12%
- Free lime test was conducted to determine the quantity of unreacted calcium oxide (CaO) in the samples.
  - ✓ Free lime in QEAF slag= 0.168%
  - ✓ Free lime in LRF slag= 1.204 %

Application in Cement Production

Comparison of Chemical Composition



Application in Cement Production

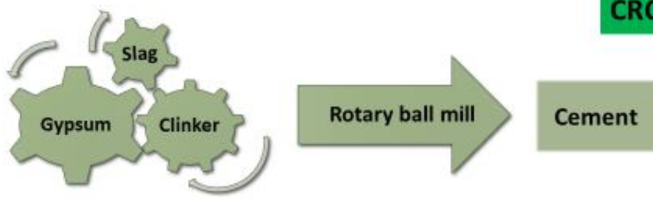
Mix Design

	Serial No.	Clinker wt%	Gypsum wt%	LRF Slag wt%	QEAF Slag wt%	Total wt%
No addition of slag	S-1	97	3	-	-	100
Addition of LRF slag	S-2	92	3	5	-	100
	S-3	87		10		
	S-4	82		15		
	S-5	77		20		
	S-6	72		25		
	S-7	67		30		
Addition of QEAF slag	S-8	92	3	-	5	100
	S-9	87			10	
	S-10	82			15	
	S-11	77			20	
	S-12	72			25	

Application in Cement Production

Experimental Procedure

Performed at CROWN CEMENT



Gypsum

Clinker

Adding slag

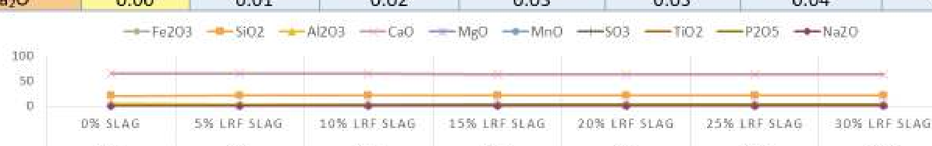
Weighing

Rotary ball mill

Application in Cement Production

Chemical Composition (Final Samples)

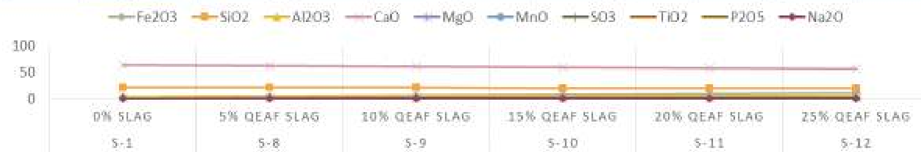
Element	S-1	S-2	S-3	S-4	S-5	S-6	S-7
	0% slag	5% LRF slag	10% LRF slag	15% LRF slag	20% LRF slag	25% LRF slag	30% LRF slag
Fe_2O_3	3.54	3.57	3.60	3.62	3.65	3.68	3.71
SiO_2	21.08	21.18	21.28	21.38	21.48	21.59	21.69
Al_2O_3	4.89	4.78	4.67	4.56	4.45	4.34	4.23
CaO	64.73	64.43	64.12	63.81	63.51	63.20	62.90
MgO	1.45	1.67	1.89	2.11	2.33	2.55	2.77
MnO	0.00	0.08	0.16	0.24	0.32	0.40	0.48
SO_3	1.60	1.64	1.68	1.72	1.76	1.80	1.84
TiO_2	0.00	0.03	0.07	0.10	0.13	0.16	0.20
P_2O_5	0.00	0.00	0.00	0.01	0.01	0.01	0.01
Na_2O	0.00	0.01	0.02	0.03	0.03	0.04	0.05



Application in Cement Production

Chemical Composition (Final Samples)

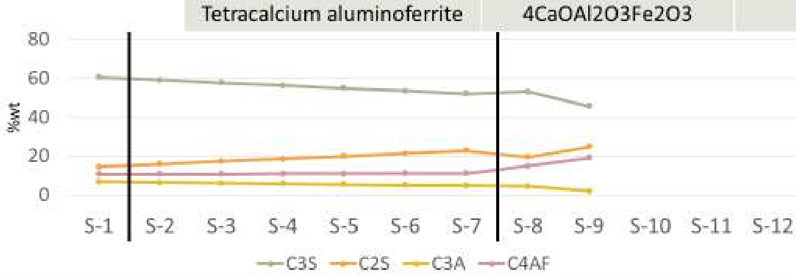
Element	S-1	S-8	S-9	S-10	S-11	S-12
	0% slag	5% QEAF slag	10% QEAF slag	15% QEAF slag	20% QEAF slag	25% QEAF slag
Fe_2O_3	3.54	4.96	6.37	7.79	9.20	10.62
SiO_2	21.08	20.88	20.67	20.47	20.27	20.07
Al_2O_3	4.89	4.90	4.92	4.93	4.94	4.96
CaO	64.73	63.03	61.33	59.63	57.94	56.24
MgO	1.45	1.67	1.90	2.13	2.36	2.59
MnO	0.00	0.23	0.46	0.69	0.92	1.15
SO_3	1.60	1.60	1.61	1.61	1.62	1.63
TiO_2	0.00	0.04	0.08	0.12	0.16	0.21
P_2O_5	0.00	0.02	0.05	0.07	0.09	0.12
Na_2O	0.00	0.02	0.03	0.05	0.06	0.08



Application in Cement Production

Bogue's Compound Composition (Final Samples)

Major compounds of Portland cement (Bogue's compound composition)		
Compound	**Chemical formula**	**Abbreviation**
Tricalcium silicate	3CaOSiO2	C3S (Alite)
Dicalcium silicate	2CaOSiO2	C2S (Belite)
Tricalcium aluminate	3CaOAl2O3	C3A (Aluminate)
Tetracalcium aluminoferrite	4CaOAl2O3Fe2O3	C4AF (Ferrite)



Standard	
Al2O3/Fe2O3	>0.64
C3S	40 to 80
C2S	0 to 30
C3A	7 to 15
C4AF	4 to 15

Application in Cement Production

Experimental: Tests Performed

Tests Performed	Standard
Fineness test	ASTM C204-11
Normal Consistency test	ASTM C187-11
Initial and final setting time of cement	ASTM C191-08
Soundness test: Expansion of Cement Mortar Bars	ASTM C1038-18
Soundness test: Le-Chatelier accelerated test	BS 4550: Part 3
Compressive Strength test	ASTM C150-18
Loss On Ignition	EN 197-1
Free Lime Test	ASTM C150

Application in Cement Production

Results: Fineness Test

- ASTM specification C204-11
- Minimum fineness required is 300 m^2/kg

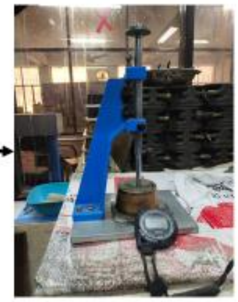
Serial No.	Clinker	Gypsum	LRF Slag	QEAF Slag	Blaine Test
	wt%	wt%	wt%	wt%	m^2/kg
S-1	97	3	-	-	307
S-2	92	3	5	-	403
S-3	87		10		411
S-4	82		15		400
S-5	77		20		407
S-6	72		25		422
S-7	67		30		417
S-8	92	3	-	5	411
S-9	87			10	422
S-10	82			15	426
S-11	77			20	433
S-12	72			25	407

Application in Cement Production
Experimental: Normal Consistency Test

❖ ASTM standard specification C187-11

Morter mixing machine

Ring containing cement paste



Normal consistency test using Vicat's apparatus

Application in Cement Production
Results: Normal Consistency Test

❖ ASTM standard specification C187-11
- OPC – Type I varies from 21-30%

Serial No.	Clinker wt%	Gypsum wt%	LRF Slag wt%	QEAF Slag wt%	Normal Consistency
S-1	97	3	-	-	23.5%
S-2	92		5		24.5%
S-3	87		10		21.0%
S-4	82		15		21.0%
S-5	77	3	20	-	21.5%
S-6	72		25		22.0%
S-7	67		30		22.5%
S-8	92			5	24.0%
S-9	87			10	23.0%
S-10	82	3	-	15	22.5%
S-11	77			20	22.5%
S-12	72			25	22.5%

Application in Cement Production
Experimental: Initial and final Setting Time of Cement

- ASTM standard specification C191-08

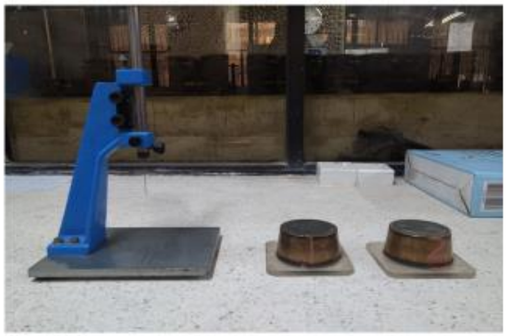



Figure: Determination of initial setting time and final setting time of sample using Vicat's apparatus

Application in Cement Production
Results: Initial and final Setting Time of Cement

Type of cement	Initial setting time	Final setting time
OPC (ASTM C191-08)	Not less than 45 mins	Not more than 375 mins

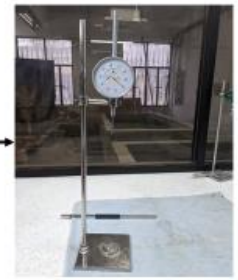
Application in Cement Production
Experimental: Soundness Test by Expansion of Cement Mortar Bars

❑ **ASTM standard specification C1038-18**

Cement + Ottowa sand + water

Cement mortar expansion bar mold containing cement

Place in water for 30 minutes the specimen before initial measurement



Length comparator

Application in Cement Production
Results: Soundness Test by Expansion of Cement Mortar Bars

❖ **ASTM standard specification C1038-18**

Serial No.	Clinker wt%	Gypsum wt%	LRF Slag wt%	QEAF Slag wt%	Average Mortar bar expansion, %
S-1	97	3	-	-	-0.014
S-2	92	3	5	-	-0.012
S-3	87		10		-0.006
S-4	82		15		-0.008
S-5	77		20		-0.012
S-6	72		25		-0.012
S-7	67		30		-0.008
S-8	92	3	-	5	0.02
S-9	87			10	0.03
S-10	82			15	0
S-11	77			20	-0.01
S-12	72			25	-0.004

Type of Cement	Range
All types of OPC	Maximum 0.02 percent expansion

Application in Cement Production

Experimental: Soundness test by Le-Chatelier Accelerated Test

❖ StandardBS 4550: Part 3

Submerge the whole assembly in water bath maintained at a temperature of27 ± 2^{0}C and keep there for 24 hours.

Bring to the water to boiling in 27 ± 3 minutes

Measure the distance between the indicator points

Application in Cement Production

Results: Soundness Test by Le-Chatelier accelerated Test

Serial No.	Clinker wt%	Gypsum wt%	LRF Slag wt%	QEAF Slag wt%	Average Mortar bar expansion,%
S-1	97	3	-	-	1.00
S-2	92	3	5	-	0.50
S-3	87		10		0.50
S-4	82		15		0.83
S-5	77		20		0.50
S-6	72		25		1.17
S-7	67		30		1.00
S-8	92	3	-	5	1.00
S-9	87			10	0.50
S-10	82			15	0.50
S-11	77			20	0.83
S-12	72			25	0.67

Type of Cement	Standard BS 4550: Part 3
	Range
All types of OPC	Maximum 10 mm expansion

Application in Cement Production
Experimental: Compressive Strength Test of Hydraulic Cement Mortars

- ASTM standard specification C150-18

Cement + Ottowa sand + water

→

Cement mortar cube mold

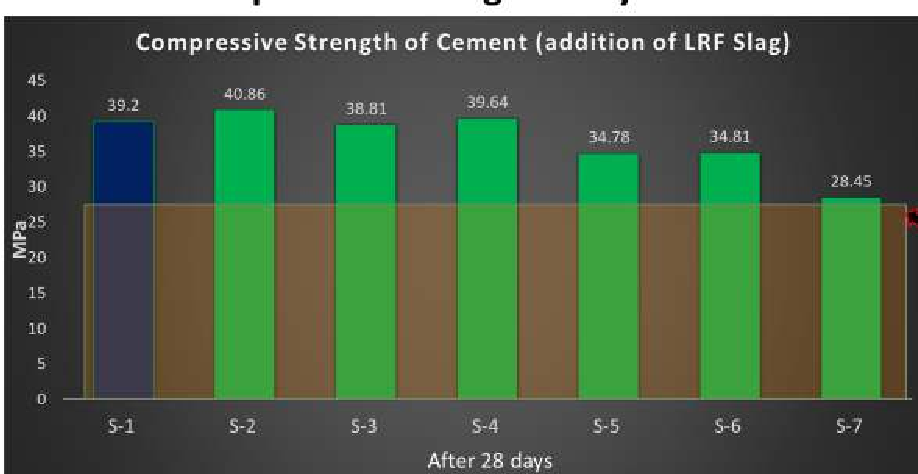
→

Tamping the mold

→

Leveling the mortar

Application in Cement Production
Results: Compressive Strength of Hydraulic Cement Mortars



Minimum compressive strength of OPC = 28MPa [according to ASTM C150-18]

Application in Cement Production

Results: Compressive Strength of Hydraulic Cement Mortars

Minimum compressive strength of OPC = 28MPa [according to ASTM C150-18]

Application in Cement Production

Results: Loss On Ignition Test & Free Lime Test

S-4 (15% LRF Slag)

- Loss on ignition (L.O.I) = 3.47%
- Percentage of Free lime = 1.93%

Loss On Ignition		
Standard	**Type**	**Range**
European Standard EN 197-1	**Portland cement (CEM I)**	**should not exceed 5%**

S-9 (10% QEAF Slag)

- Loss on ignition (L.O.I) = 2.85%
- Percentage of Free lime = 1.12%

Free Lime Test		
Standard	**Type**	**Range**
ASTM C150	**Portland cement (OPC type 1,2,3)**	**should not exceed 4%**

Utilization of Quantum Electric Arc Furnace (QEAF) and Ladle Refining Furnace (LRF) Slag Generated in GPH Ispat as Fine Aggregate and Coarse Aggregate Replacement in CONCRETE

Application as Aggregate Replacement in CONCRETE

Aggregates for Construction Industry

Many breakthroughs have been made in the research of slag waste utilization into aggregates for the construction industries.

The ingredients of slag are similar to those of natural aggregates.

Research has found that normal concrete failure is mainly a result of failure of the bonding between aggregate and cement paste.

Concrete using steel slag aggregate presents a different situation.

The shape and surface texture features of aggregate have significant influence on the bonding and, therefore, the compressive and tensile strength of the concrete.

In most cases the mechanical bond is improved by an aggregate with a rough surface texture, and chemical bond also is improved as the slag aggregate has certain chemical activity with cement.

Application as Aggregate Replacement in CONCRETE

Tests Performed

SI NO.	Performed Test	Standard	Sample Description
Aggregate Mechanical Property Test			
1	Angularity Number Test	BS 812	Coarse Slag of ¾" downgrade size
2	LA Abrasion Test	ASTM C131-89	
3	Unit Weight	ASTM C29	
4	AIV	BS 812	
5	ACV	BS 812	
6	TFV	BS 812	
7	Flakiness Index	BS 812	
8	Elongation Index	BS 812	
9	Absorption Capacity	ASTM C127	
10	Bulk Specific Gravity	ASTM C127	
Fresh Concrete			
11	Slump Value Test	ASTM C143	Fresh Concrete
Hardened Concrete			
12	Compressive Strength	ASTM C39/C39M-21	4"x8" Cylinder
13	Splitting Strength	ASTM C496	4"x8" Cylinder

Application as Aggregate Replacement in CONCRETE

Mix Design

All concrete mixing was performed in the concrete research laboratory of BUET.

Cement: Sand: Aggregate = 1:1.5:3

Concrete specimens were cured under water and tested at **7,14 and 28** days

Mix No.	Slag Type	Stone Chips (% vol^{m})	Sand (% vol^{m})	Slag (Coarse) (% vol^{m})	Slag (Fine) (% vol^{m})	W/C ratio
Mix with no slag						
1	-	100	100	0	0	0.45
First Step Experiment						
2	QEAF slag (Coarse)	40	100	60	0	0.45
3		20	100	80	0	
4		0	100	100	0	
5	QEAF slag (Fine)	100	90	0	10	
6		100	80	0	20	
7		100	70	0	30	
8		100	60	0	40	
9		100	50	0	50	
10	LRF slag	100	90	0	10	0.45
11		100	80	0	20	
12		100	70	0	30	
13		100	60	0	40	
14		100	50	0	50	

Application as Aggregate Replacement in CONCRETE

Mix Design

Mix No.	Slag Type	Stone Chips (% vol^{m})	Sand (% vol^{m})	Slag (Coarse) (% vol^{m})	Slag (Fine) (% vol^{m})	W/C ratio
Second Step Experiment						
15	QEAF slag (Coarse and Fine)	20	95	80	5	0.45
16		20	90	80	10	
17		20	85	80	15	
18		0	95	100	5	
19		0	90	100	10	
20		0	85	100	15	

Application as Aggregate Replacement in CONCRETE

Concrete Making Process

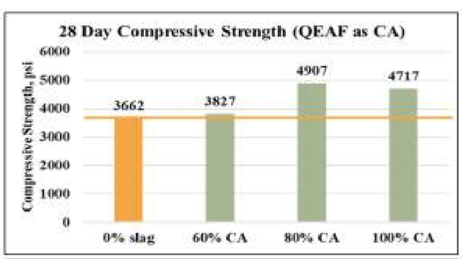
Application as Aggregate Replacement in CONCRETE

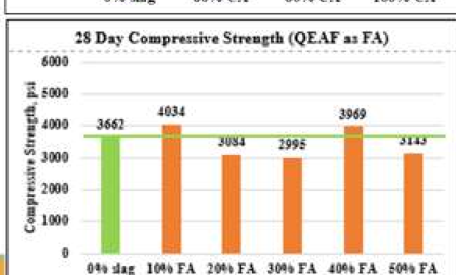
Results: Properties of QEAF Slag (size ¾" downgrade)

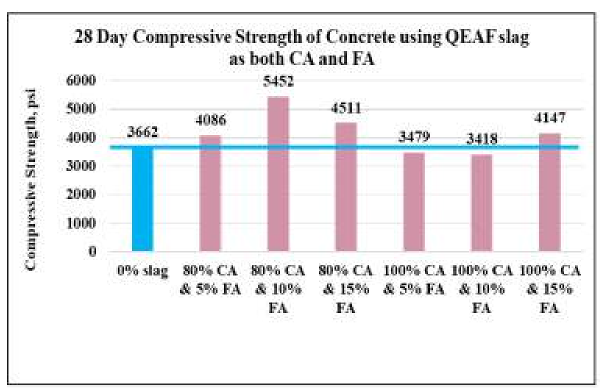
	QEAF Slag	Standard	Recommended
Angularity Number Test	11	BS 812	0-12
Los Angeles Abrasion Test	24	ASTM C131-89	< 30
Unit Weight	12718 kg/m^3	ASTM C29	
AIV	28	BS 812	< 30
ACV	25	BS 812	< 30
TFV	130	BS 812	
Flakiness Index	6	BS 812	
Elongation Index	20	BS 812	
Absorption Capacity	1.8	ASTM C127	
Bulk Specific Gravity	3.68	ASTM C127	

Application as Aggregate Replacement in CONCRETE

Results: Compressive Strength [QEAF Slag as Coarse and Fine Aggregate]

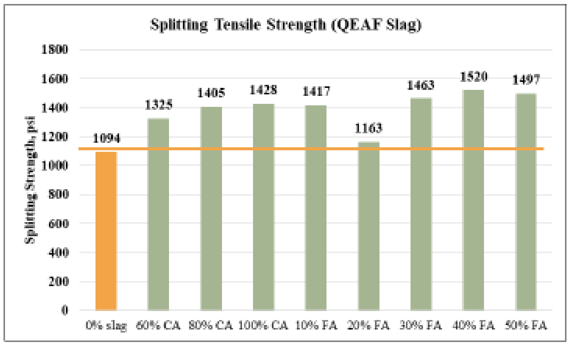


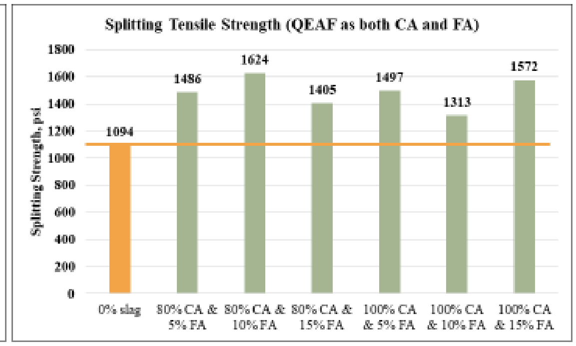




Application as Aggregate Replacement in CONCRETE

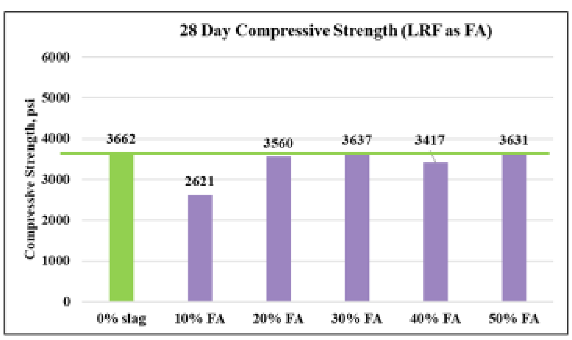
Results: Splitting Tensile Strength [QEAF Slag]

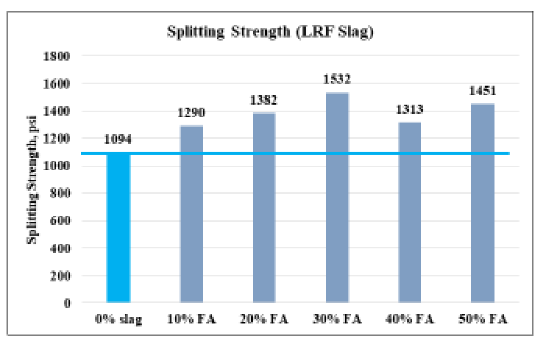




Application as Aggregate Replacement in CONCRETE

Results: Compressive and Splitting Strength [LRF Slag]





Application as Aggregate Replacement in CONCRETE

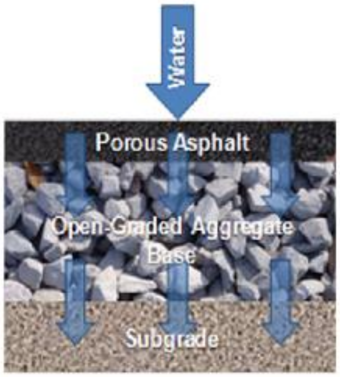
Results Summary

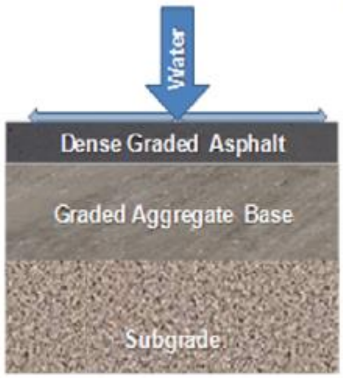
Reference → Normal Concrete

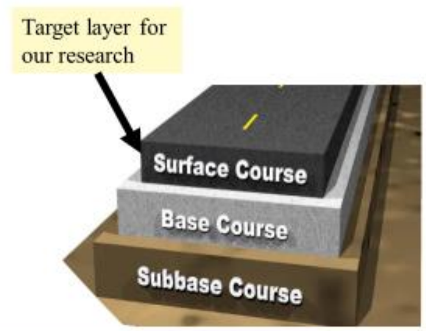
Findings from present study → QEAF coarse aggregate, QEAF fine aggregate, QEAF coarse and fine aggregate, LRF fine aggregate

Sample ID	Compressive Strength (psi)
Normal Concrete	2900 - 5800
QEAF coarse aggregate	3827 - 4717
QEAF fine aggregate	3143 – 4034
QEAF coarse and fine aggregate	3418 - 5452
LRF fine aggregate	2621 - 3637

Application as Aggregate Replacement in FLEXIBLE PAVEMENT







Application as Aggregate Replacement in FLEXIBLE PAVEMENT

Test Performed

Sl NO.	Performed Test	Standard	Sample Description
Bitumen Property Test			
1	Specific Gravity	AASHTO T43	Bitumen
2	Loss on Heating	AASHTO T47	
3	Penetration Test	AASHTO T49	
4	Softening Point Test	AASHTO T53	
5	Ductility	AASHTO T51	
6	Flash and Fire Point	AASHTO T48	
Aggregate Mechanical Property Test			
1	Angularity Number Test	BS 812	Coarse Slag of 1" downgrade size
2	LA Abrasion Test	ASTM C131-89	
3	Unit Weight	ASTM C29	
4	AIV, ACV, TFV	BS 812	
7	Flakiness & Elongation Index	BS 812	
9	Absorption Capacity and Bulk Specific Gravity	ASTM C127	
Hot Mix Asphalt (HMA) Pavement			
11	Marshall Test	ASTM D6927	4"x2.5" Cylinder

Application as Aggregate Replacement in FLEXIBLE PAVEMENT

Mix Design

- A total of six mix design was chosen for this research where replacement the coarse aggregate by QEAF slag varied from 20% to 60% by weight.
- Bitumen was varied from 4 to 6% by weight.

Sample ID	Stone Chips (kg)	QEAF Slag	Bitumen
Standard	1155	0	4%, 4.5%, 5%, 5.5%, 6%
20% Replacement	925	231	
30% Replacement	809	346	
40% Replacement	693	462	
50% Replacement	578	578	
60% Replacement	462	693	

Application as Aggregate Replacement in FLEXIBLE PAVEMENT

Results: Bitumen Properties

	Bitumen	Standard	Recommended
Specific Gravity	1.015, 25 ºC/25 ºC	AASHTO T43	-
Loss on Heating	0.004%	AASHTO T47	-
Penetration Test	65	AASHTO T49	<350
Softening Point Test	49 ºC	AASHTO T53	-
Ductility Test	100+	AASHTO T51	100+
Flash Point	310 ºC	AASHTO T48	-
Fire Point	360 ºC	AASHTO T48	-

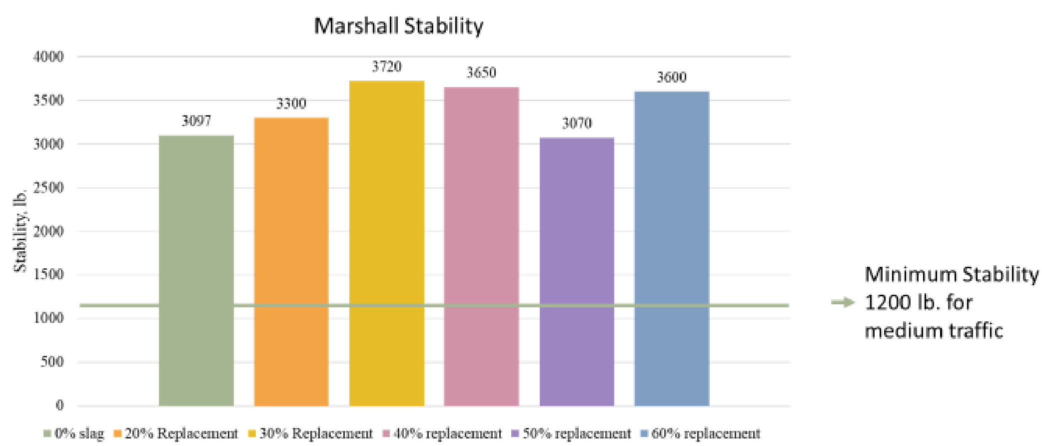
Application as Aggregate Replacement in FLEXIBLE PAVEMENT

Results: Properties of QEAF Slag (1” downgrade)

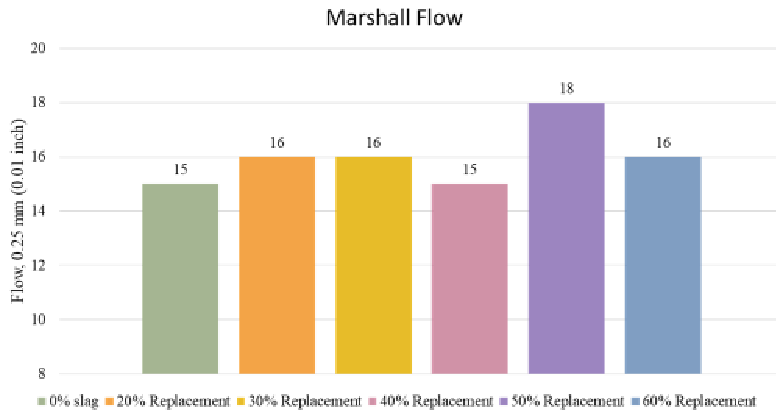
	QEAF Slag	Standard	Recommended
Angularity Number Test	6	BS 812	0-12
Los Angeles Abrasion Test	23	ASTM C131-89	< 30
Unit Weight	13072 kg/m^3	ASTM C29	
AIV	22	BS 812	< 30
ACV	30	BS 812	< 30
TFV	110	BS 812	
Flakiness Index	17	BS 812	The lower the better
Elongation Index	7	BS 812	The lower the better
Absorption Capacity	2.1	ASTM C127	
Bulk Specific Gravity	3.28	ASTM C127	

Application as Aggregate Replacement in FLEXIBLE PAVEMENT

Results for Marshall Stability

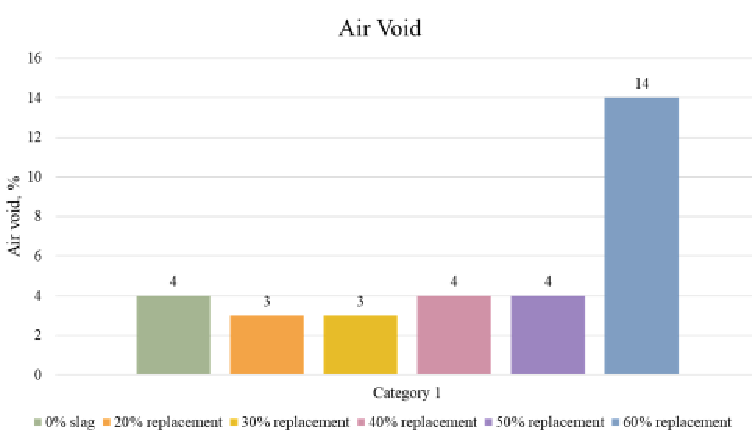


Application as Aggregate Replacement in FLEXIBLE PAVEMENT
Results for Marshall Flow



Flow criteria for medium traffic is 8-16.

Application as Aggregate Replacement in FLEXIBLE PAVEMENT
Results for Marshall Air Void



Air void criteria 3-5% for medium traffic

Making Concrete Blocks Using EAF and LRF Steel Slag

Application: Concrete Block Making

- **Why the Non-fired Method?**

Energy concern

Environment friendly

Mechanical **properties**

Green building practices gaining momentum

EAM Asaduzzaman
Thu Aug 11, 2022 09:30 AM Last update on: Thu Aug 11, 2022 10:36 AM

Application: Concrete Block Making

Experimental

Raw materials

- ✓ Steel slag
- ✓ Cement
- ✓ Sand
- ✓ Admixture

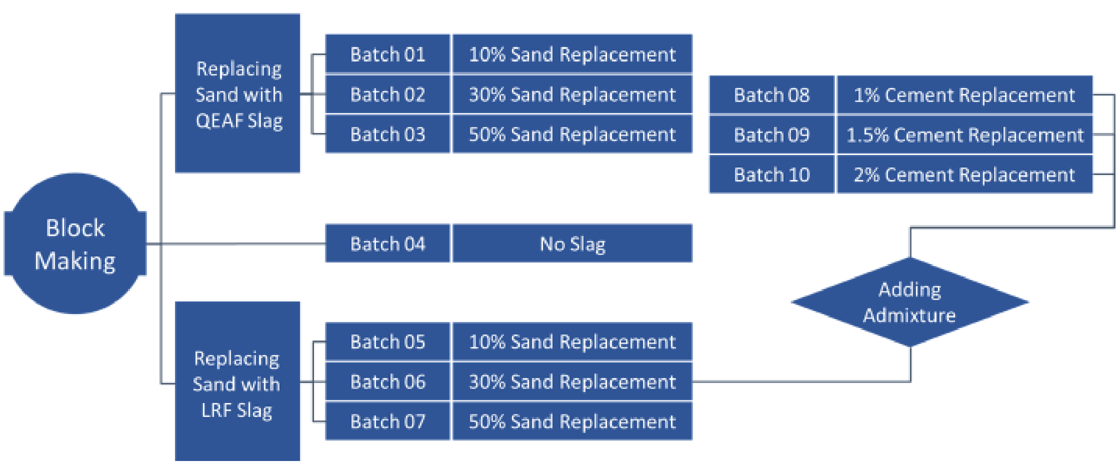
Tests

- ✓ Compressive strength
- ✓ Water absorption
- ✓ Density
- ✓ Porosity

} According to IS 2185 (Part 1)

Application: Concrete Block Making

Mix Design



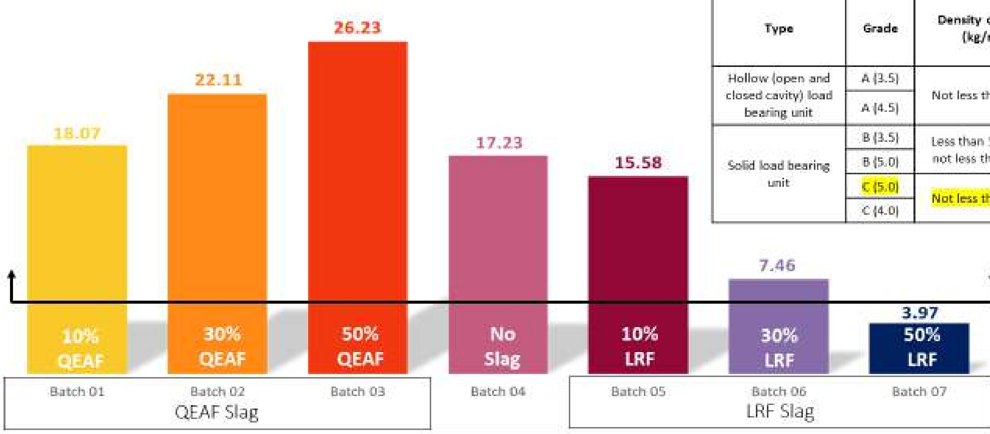
Application: Concrete Block Making

Block Manufacturing Process

Application: Concrete Block Making

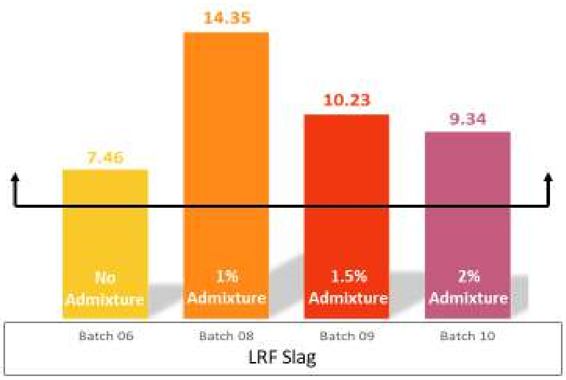
Results: Compressive Strength Tests after 28 Days (MPa)

Physical Requirements of Concrete Blocks (IS 2185)			
Type	Grade	Density of Block (kg/m^3)	Minimum average Compressive Strengths of Units (MPa)
Hollow (open and closed cavity) load bearing unit	A (3.5)	Not less than 1500	3.4
	A (4.5)		4.5
Solid load bearing unit	B (3.5)	Less than 1500 but not less than 1100	3.5
	B (5.0)		5.0
	C (5.0)	Not less than 1800	5.0
	C (4.0)		4.0



Application: Concrete Block Making

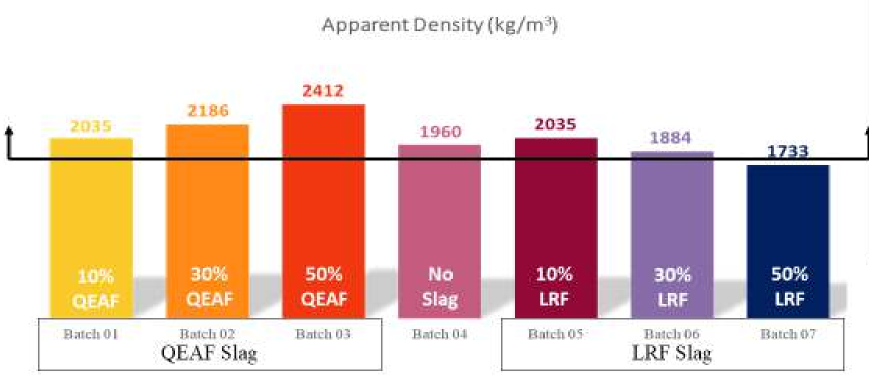
Results: Compressive Strength Tests (Adding Admixture) after 28 Days



Physical Requirements of Concrete Blocks (IS 2185)			
Type	Grade	Density of Block (kg/m³)	Minimum Compressive Strengths (MPa)
Hollow (open and closed cavity) load bearing unit	A (3.5)	Not less than 1500	3.4
	A (4.5)		4.5
Solid load bearing unit	B (3.5)	Less than 1500 but not less than 1100	3.5
	B (5.0)		5.0
	C (5.0)	Not less than 1800	5.0
	C (4.0)		4.0

Application: Concrete Block Making

- Results: Apparent Density (kg/m³)

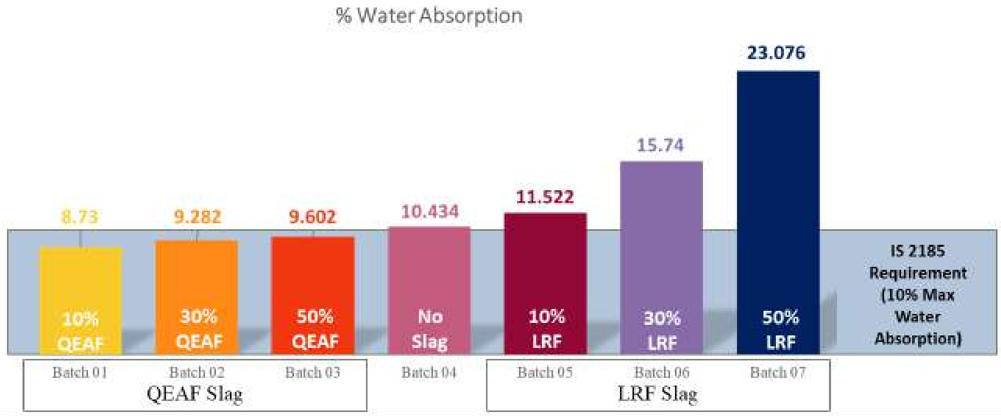


Physical Requirements of Concrete Blocks (IS 2185)			
Type	Grade	Density of Block (kg/m³)	Min Compressive Strengths (MPa)
Solid load bearing unit	B (3.5)	Less than 1500 but not less than 1100	3.5
	B (5.0)		5.0
	C (5.0)	Not less than 1800	5.0
	C (4.0)		4.0

Application: Concrete Block Making

- **Results: Water Absorption**

As per IS 2815, the maximum allowable water absorption of concrete blocks is 10% by mass.



Application: Concrete Block Making

Results: Summary

Type	Batch	Grade Categorization according to the IS 2185 Standard
With QEAF Slag	Batch 01	C
	Batch 02	C
	Batch 03	C
No Slag	Batch 04	C
With LRF Slag	Batch 05	C
	Batch 06	C
	Batch 07	B
With Admixture	Batch 08	C
	Batch 09	C
	Batch 10	C

Summary:

- The chemical composition of both QEAF and LRF slags are very similar to the chemical compositions of clinker used in cement production; except that QEAF has higher percentages of Iron (Fe) oxide than the clinker and the LRF slag.
- For **LRF slag up to 15% of the clinker** can be replaced without hampering the traditional cement clinker performances. On the other hand, **10% of the clinker can be replaced by QEAF slag** without hampering the traditional cement clinker performances.
- All the combinations considered in production of cement in this research met the minimum required compressive strength of mortar for OPC cement according to ASTM C150-18

Summary:

- The concrete produced by replacing coarse aggregate and fine aggregate by QEAF slag **met the minimum required compressive strength at 28 days according to ASTM C39. About 80% to 100% of coarse aggregate** in concrete can be replaced by QEAF slag and 10% of fine aggregate in concrete can be replaced by QEAF slag.
- From the Marshall testing on sample for flexible pavement, it was found that **20 to 40% of the stone chips** of wearing courses can be replaced by the QEAF slag, as they met all the criteria for medium traffic according to ASTM D6927.
- The concrete blocks produced with QEAF slag met the required standards outlined in IS 2185:1 for block densities, compressive strength values, and water absorption. The use of **QEAF slag as a substitute for sand up to 30% in the production of concrete blocks resulted in higher compressive strength values**, whereas LRF slag yielded unsatisfactory outcomes. However, the properties of blocks made with LRF slag can be improved by adding a small amount of admixture (1% of cement amount).

Summary:

Cost savings per Cubic Feet of Construction by Using Slag

- When slag is employed as a partial substitute for clinker in cement production, savings of approximately 60 to 75 takas per cubic feet can be realized, owing to the replacement of 10% to 15% clinker with slag.
- Current price of one cubic feet concrete is 300 to 350 takas. When slag is used as partial replacement of coarse aggregates in concrete, according to current price of stones, 210 to 250 takas can be saved in per cubic feet concrete, as 80% to 100% coarse aggregates can be replaced by QEAF slag.
- 40% of the stones can be replaced by QEAF slag in flexible pavement. This means a saving of 100 takas can be expected from one cubic feet of flexible pavement.

Summary: Application Priority

1. QEAF slag can be a possible replacement for **coarse and fine aggregate replacement in concrete**. The size requirement is 3/4 inch downgrade for coarse aggregate replacement and 1/5-inch downgrade for fine aggregate replacement.
2. QEAF slag can be used as **partial replacement of coarse aggregate in wearing course in flexible pavement**. For application in roads, slag particle size should be 1.5-inch downgrade.
3. Both QEAF and LRF slag can be used **in concrete block production**; slag particle size should be 1/5-inch downgrade.
4. Slag performance as **partial replacement of clinker in cement** is recommended according to the findings of this research, fineness should be achieved more than 400 m2/kg.

Financial Benefit of GPH ISPAT

Considering 8.4 lakh tons of steel production/year in GPH ISPAT: 84000-126000 tons of slag/year is generated

Considering slag as a replacement of stone chips.

Lead to a financial benefit of **34-50 crore BDT** each year *

(*At present market sale value of stone chips is 4000 BDT/per ton*)

* Slag processing cost is not included in this calculation.

Environmental Aspects of Utilization of Slag

- The cement industry contributes approx 5% of global man-made CO_2 emissions.
- Brick kilns release over 1,072 million tonnes of carbon dioxide emissions into the atmosphere every year which is 2.7% of total emissions.

Major contributors to climate change ,damage air quality and human health, impact agricultural progress by damaging soil, crop production and food security.

- Natural resources like stones, gravels are becoming scarce in nature due to rapid urbanization and high demand of stones globally.



THE TIMES OF INDIA, AHMEDABAD
TUESDAY, MARCH 15, 2022

Country's first 'steel slag road' laid in Surat

Dipak.Dash@timesgroup.com

New Delhi: The country's first 'steel slag road' has come up in Surat, promising a huge potential to reduce the demand for aggregates in road construction. The successful implementation of the 1.2km six-lane connectivity stretch of the Hazira Port will also pave the way for utilisation of huge mounds of steel slag lying as waste across the country. Aggregates are inert granular materials such as sand, gravel and crushed stone used in road construction.

This research project under the steel ministry was sponsored by ArcelorMittal Nippon Steel under the technical guidance of the Central Road Research Institute (CSIR-CRRI). This stretch has been built by substituting natural aggregates with 100% processed steel slag aggregates in all layers of bituminous pavement. Considering its higher strength, the thickness of the road has also been reduced by 30%.

Three other major steel majors — Tata Steel, JSW Steel and Rashtriya Ispat — are participating as industrial partners to accomplish the steel slag utilisation in road construction.

"Around 1,000-1,200 heavy commercial vehicles are using the road per day for the last one year and still it is performing well on different serviceability parameters. Around one lakh tonnes of processed steel slag aggregates have been utilised in this project. We will soon come up with guidelines for usage of processed steel slag in road and highway construction," said Satish Pandey, principal scientist at CSIR-CRRI.

PILOT PROJECT

Annually, nearly 18.5 million tonnes (MTs) of steel slag is generated from various integrated steel plants. Only in Vizag, around 60MT of steel slag is lying unused.

Utilisation of steel slag aggregates as a substitute of natural aggregate in road construction will reduce the unsustainable quarrying and mining of natural aggregates.

Highways projects in several states are now getting delayed due to shortage of aggregates and other raw materials.

Slag Utilization: Road construction

Sabekun Nahar Sony Hall Entrance Road, BUET

Project Team

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Co-Principal Investigator I

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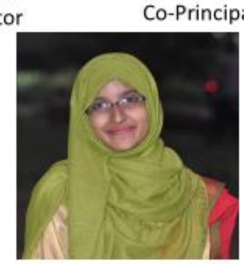

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