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Use of Steel Slag in Concrete as Fine Aggregate

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Abstract*— Industrial waste slag is one of the burning issues concerning the environmentalists today. Steel slag is obtained as an industrial byproduct from the steel manufacturing industry. It is produced in large quantities during the steel-making operations which utilize Electric Arc Furnaces (EAF) and by smelting iron ore in the Basic Oxygen Furnace (BOF).Steel slag finds umpteen uses in the construction industry like in the hot mixture asphalt surface applications, in Stone Matrix Asphalt (SMA), in construction of berms and embankments, for manufacture of Portland cement, as fine and coarse aggregates, to name a few. But steel slag has a negative impact on the environment when disposed. In that case wide variety of use of steel slag becomes relevant. Along with the diversified uses, steel slag efficiently replaces natural aggregates both coarse and fine, in a conventional concrete mixture. Most of the volume of concrete is aggregates. Replacing all or some portion of natural aggregates with steel slag would lead to considerable environmental benefits. This report showcases important studies conducted on use of steel slag as fine aggregate and its effect on the strength, durability, fresh density, workability etc of the resulting mix. A brief discussion on the properties and present uses of steel slag has been incorporated.

Index Words –**Aggregate, Concrete, Fine aggregate, Steel slag.**

I. INTRODUCTION

Concrete is one among the widely used materials after water, certainly not exaggerating. It plays an important role in nation building as it directly affects the infrastructure and also the economy. Concrete is a composite material which is composed of coarse granular materials called aggregates or filler embedded together in the form of a matrix with the help of the cement or binding material that fills the space between the aggregates particles and glues them together. Aggregates are usually obtained from natural rocks, either crushed stones or natural gravels.

According to some estimates after the year 2010, the global concrete industry will require annually 8 to 12 billions metric tons of natural aggregates (U.S.G.S and nationalatlas.gov, accessed Nov 2008). .During the past 25 years, the production of crushed stone has increased at an average annual rate of about 3.3 percent. Production of sand and gravel has increased at an annual rate of less than 1 percent. Based on these numbers, by 2020 U.S. production of crushed stone, which is expected to increase by more than 20 percent, will be about 1.6 billion metric tons, while production of sand and gravel will be just under 1.1 billion metric tons, an increase of 14 percent. In essence the amount of crushed stone to be produced in the next 20 years will equal the quantity of all stone produced during the previous century i.e. about 36.5 billion metric tons.. (U.S. Geological survey).Also there are problems related to durability characteristics of natural aggregates in addition to their availability. About three quarters of the volume of concrete is composed of aggregate. So the important properties of concrete like strength, durability and serviceability etc. depend largely upon the property and quality of aggregates used. Thus introducing suitable alternatives to natural aggregates has always been challenging. Utilizing steel slag in concrete mixes has proved to be useful in solving some of the problems encountered in the concrete industry. Steel slag was used in conventional concrete to improve its mechanical, physical, and chemical properties. Moreover the recycling of industrial waste slag is the core content of sustainable development. The only potential problem with steel slag aggregate is its expansive characteristics and undesirable reactions between slag and components of concrete.

II. PAST RESEARCHES ON STEEL SLAG

Some of the important researches in this field are:

1. Electric arc furnace slag (EAFS) that contains low percentage of amorphous silica and high content of ferric oxides and consequently has low, or no, pozzolanic activities in comparison with blast furnace slag (BFS), is not appropriate to be used in blended cement production. Although many studies have been conducted on the evaluation of steel slag usage in road construction and use of blast furnace slag in concrete mixes, few researches have been performed regarding the utilization of steel slag in concrete.[1]
2. Alizadeh et al. carried out a research to evaluate the effect of using electric arc furnace steel slag on hardened concrete. Experimental results indicated that such steel slag aggregate concrete achieved higher values of compressive, tensile and flexural strength and modulus of elasticity, compared to natural aggregate concrete.[1]
3. Shekarchi et al. conducted comprehensive researches on the utilization of steel slag as aggregate in concrete. They concluded that the use of air-cooled steel slag with low amorphous silica content and high amount of ferric oxides is unsuitable to be used in blended cement. On the other hand, Utilization of steel slag as aggregate is advantages when compared with normal aggregate mixes. [1]

III. WHAT IS STEEL SLAG

The solid material which is generated by the interaction of impurities and flux during the making and refining of steels is called steel slag. It is obtained in following ways:

1. From conversion of iron to steel in a Basic Oxygen Furnace (BOF)

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2. By the melting of scrap to make steel in the Electric Arc Furnace (EAF).
3. Ladle slag generated during refining process.

Plate 1: Steel slag used as fine aggregate [5]

IV. CHEMICAL COMPOSITION

Both BOF and EAF slags are formed during basic steelmaking operations.. Ladle slag is generated during the steel refining processes in which several alloys are added to the ladle furnace to produce different grades of steel.. The predominant compounds in steel slag are dicalcium silicate, tricalcium silicate, dicalcium ferrite, merwinite, calcium aluminate, calcium-magnesium iron oxides, some free lime and magnesia. Steel slag is mildly alkaline, with a solution pH generally in range of 8 to 10.

PHYSICAL PROPERTIES

Steel slag aggregates are fairly angular, roughly cubical pieces having flat or elongated shapes. Some of the positives of steel slag are.

Table 1.Physical properties of steel slag (TFHRC accessed 2008) [2]

Property	Value
Specific Gravity	3.2-3.6
Approximate Dry rodded Unit Weight, kg/m^3 (lb/ft^3)	1600-1920 (100 -120)
Water Absorption	Up to 3%

MECHANICAL PROPERTIES

Table 2: Typical mechanical properties of steel slag (TFHRC accesed 2008)

Property	Value
Los Angeles Abrasion(ASTM C131)%	20-25
Sodium Sulfate Soundness Loss(ASTM C88)%	<12
Angle of internal friction	40^0-50^0
Hardness(measured by Mohr's scale)	6-7
California Bearing Ratio	Upto 300

V. PRODUCTION OF STEEL SLAG

A. BASIC OXYGEN PROCESS

In the Basic Oxygen Furnace (BOF), the hot liquid metal from the blast furnace, scrap and fluxes, which contain lime (CaO) and dolomitic lime, are charged to a furnace. A lance is lowered into the converter and then oxygen in injected with high pressure. The oxygen then combines with and removes the impurities as shown in Fig. 1(a).

B. ELECTRIC ARC FURNACE PROCESS

The Electric Arc Furnace (EAF) does not use hot metal, but uses cold steel scraps. Charged material is heated to a liquid state by means of an electric current (high-power electric arcs, instead of gaseous fuels, are used to produce the heat necessary to melt recycled steel scrap and to convert it into high quality steel) . Meanwhile oxygen is blown into the EAF to purify the steel. This slag which floats on the surface of molten steel is then poured off.

C. LADLE FURNACE REFINING AND SLAG GENERATION

Steel produced from primary steel making operations, the BOF and EAF processes, can be further refined to produce high quality steel. The most important functions of secondary refining processes are final desulfurization, degassing of oxygen, nitrogen, and hydrogen, removal of impurities, and final decarburization (done for ultralow carbon steels).

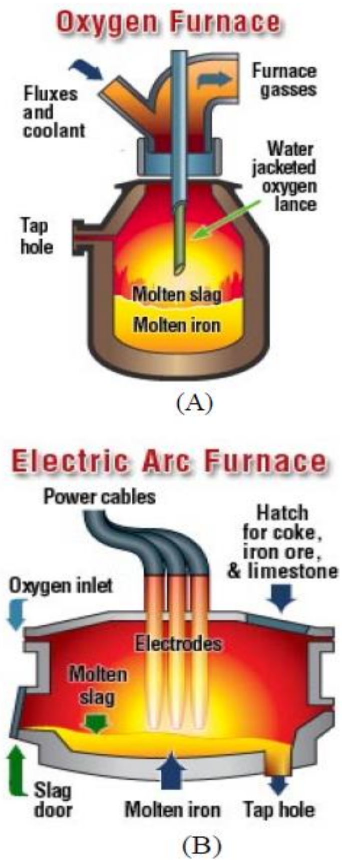

Fig 1. Process of manufacture of steel slag by BOF process (A) and EAF process (B)[2]

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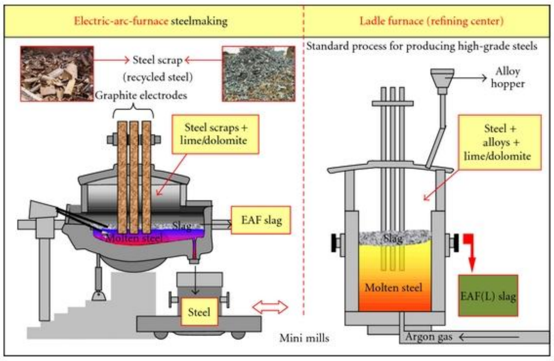

Fig 2: Schematic representation of the electric arc-furnace steelmaking and ladle refining process [3]

VI.USE OF STEEL SLAG AS FINE AGGREGATE-EXPERIMENTAL PROGRAM 1

1) This section deals with the experiments conducted by H. Qasrawi et al.[1] using low CaO unprocessed steel slag as fine aggregate in concrete mixes.

A. *Materials*

1. Coarse aggregate

Limestone normal aggregate of local sources was used in the preparation of all mixes. Gradation of this was obtained following the ASTMC136 standard procedure. It was found to be well graded and within ASTMC33 grading requirements for coarse aggregates of nominal maximum size 25 – 4.75 mm.

2. Fine aggregate

Two types of fine aggregates are used

a) Steel slag as received from the factory without any screening
b) Silica sand of natural resources known locally as desert sand.

Sieve analysis was carried out on both the natural sand and the fine slag according to ASTM C33.Specific gravity and absorption of the aggregates were measured using ASTM C127 and ASTM C128. In each case, three representative samples were taken and tested according to the corresponding ASTM standard. The average of the three obtained values was calculated and presented in Table 4.

Table 3: Sieve analysis of fine aggregates.

Sieve Size-mm	ASTM Designation	Sand % passing	Slag % passing	ASTM limits	BS Grading requirements BS-C	BS-M	BS-F
10	3/8”	100	100	100	100	100	100
5	#4	99.9	99	100	89-100	89-100	89-100
2.40	#8	99.6	95.6	95-100	60-100	65-100	80-100
1.20	#16	98.9	85.4	80-100	30-90	45-100	70-100
.600	#30	91.3	72.1	50-85	15-54	25-80	55-100
.300	#50	45.1	56.2	25-60	5-40	5-48	5-70
.150	#100	8.6	40	10-30	0-15* 0-20a	0-15* 0-20a	0-15* 0-20a
.075	#200	1	20.5	NA	NA	NA	NA

Table 4: Results of Specific gravity and Absorption

Material	Specific Gravity Apparent	Bulk (SSD)*	Bulk (Dry)	Absorption (%)
Sand	2.598	2.55	2.561	0.4
Coarse aggregate	2.69	2.57	2.62	1.65
Fine steel slag	3.25	3.17	3.19	0.8

Table 5: Chemical analysis of the slag used in the study

Oxides	Percentage
Fe_2O_3	97.05
MnO	1.07
TiO_2	0.01
SiO_2	0.8
MgO	0.4
CaO	0.4
C	0.23
S	0.21
Water Solubility	0.009

B. *Experimental procedure*

The following were the main aspects of the research:
a) Conventional concrete mixes of 25, 35 and 45 MPa cube strength were used. All mixes were prepared and adjusted to obtain concrete of medium workability (slump 8–12 cm) .
b) Mixes were tested for workability according to ASTM C143.

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c) Fresh density of mixes were measured according to ASTM C138.Cubes of 100 mm side were prepared , cured and tested at the ages of 3, 7, 28, 90 and 180 days for compressive strength. At each age, a minimum of three cubes were randomly chosen and tested in saturated surface dry condition.

d) 100 x 100 x 500 mm prisms were used for testing flexural strength and were tested at the ages of 7, 28 and 90 days.at each age three prisms were tested using three point loading method described in ASTM C78.

e) Steel slag mixes were prepared replacing sand by 15%, 30%, 50%, and 100% by weight of sand.

F) Steel slag concrete cubes and prisms were prepared. Also pozzolanic activity was checked using ASTM C 618.

C. Results

1. Workability

It was found that use of slag reduced the workability of the mix. Replacing sand by upto 50% slag still gave concrete of medium workability. The mixes with 100% slag were sticky rather than dry. The reduction in workability were due to the following reasons.

1. Lack of mobility in the mix due to increased amount of fines
2. The finer slag is a more absorbing material.
3. More the percentage of fines less is the workability.
4. Slag particles have more angular shapes compared to the normal sand particles.

Plate 2: Slump test being conducted on the concrete sample with 100% steel slag [4]

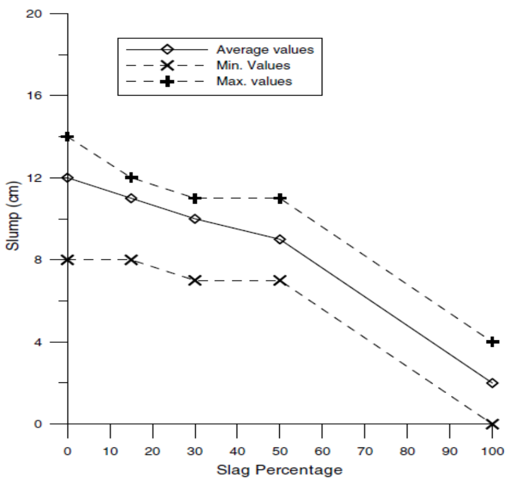

Fig 3: Relationship between the slag percent and the slump of concrete [1]

2. Fresh density

Replacement of sand with steel slag which has a higher specific gravity increases the density of concrete. But the increase in density is small (less than 5%).

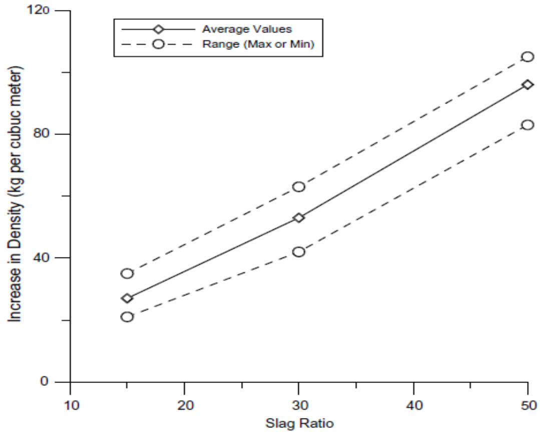

Fig 4 : Relationship between the increase in the density of fresh concrete and the sand-slag replacement ratio.[1]

3. Compressive strength

The variation of compressive strength for all mixes were plotted and figures 5, 6 and 7 show these. The following were the conclusions on variation in compressive strength made from 25 and 35 MPa mixes. (Figures 5 and 6)

1. The strength of concrete increases with age for all mixes.

2. Mixes containing slag showed higher compressive strength in the early ages (the first seven days).

3. The mix containing 100% slag produced compressive strengths less than the normal concrete mix at the ages of 28, 90 and 180 days.

4. The lower the slag ratio, the higher the compressive strength of concrete at the 28, 90 and 180 days.

The first three observations are relevant for 45 MPa mix also. the mixes containing 50% slag produced lower strength than the control mix. Also, both mixes containing 15% and 30% slag produced strength values at later ages higher than the control mix. If slag ratio is plotted against the strength of concrete for all ages, 7 to 180 days, and all the grades, a peak can be observed for the range between 15% and 30% slag replacement ratios. (Figure 8)

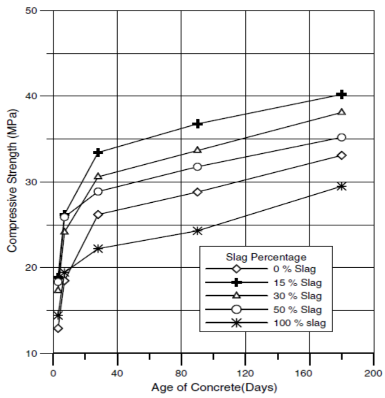

Fig 5: Relationship between age of concrete and its compressive strength for various slag replacements (25 MPa concrete). [1]

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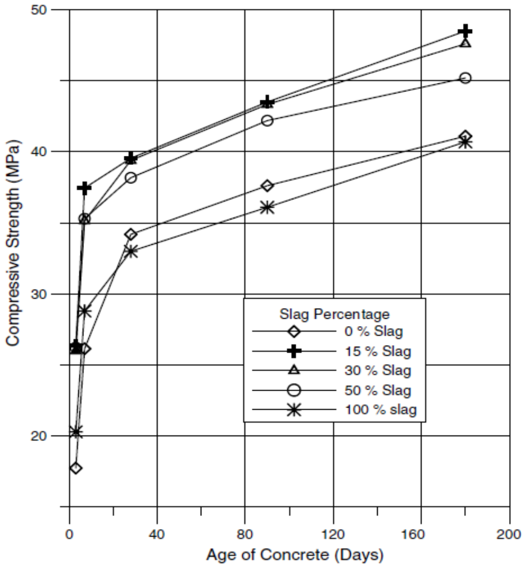

Fig 6: Relationship between age of concrete and its compressive strength for various slag replacements (35 MPa concrete).[1]

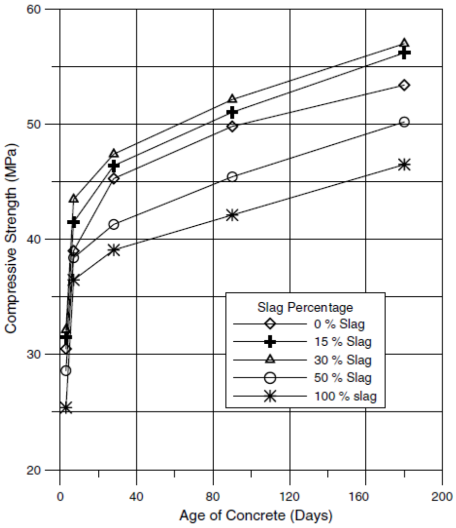

Fig 7: Relationship between age of concrete and its compressive strength for various slag replacements (45 MPa concrete).[1]

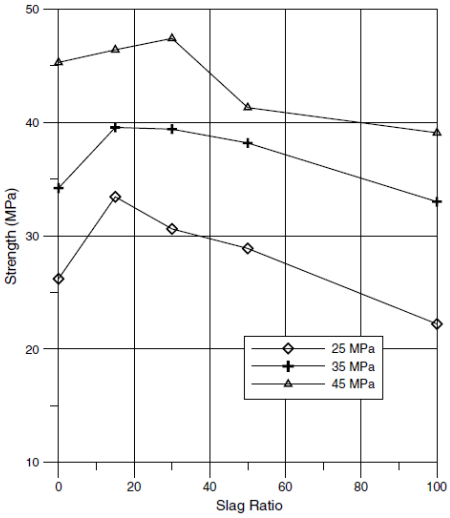

Fig 8 : Relationship between the slag ratio and the compressive strength of concrete at the age of 28 days.[1]

4. Tensile Strength

The flexural tensile strength of concrete increases by the increase in slag ratio up to 50% steel slag, The use of 100% slag replacement was not found to be beneficial when compared to other replacements at ages of 28 and 90 days..The figures 9, 10 and 11 show these experimental results.

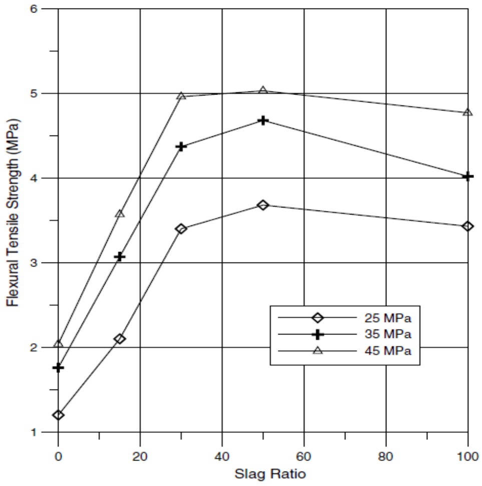

Fig 9 : Relationship between the slag ratio and the tensile strength of concrete at the age of 7 days.[1]

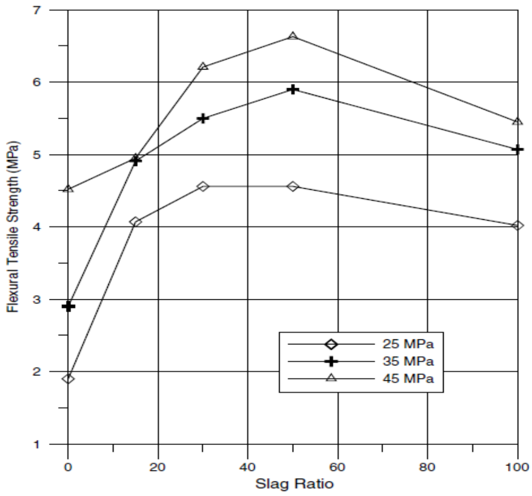

Fig 10: Relationship between the slag ratio and the tensile strength of concrete at the age of 28 days.[1]

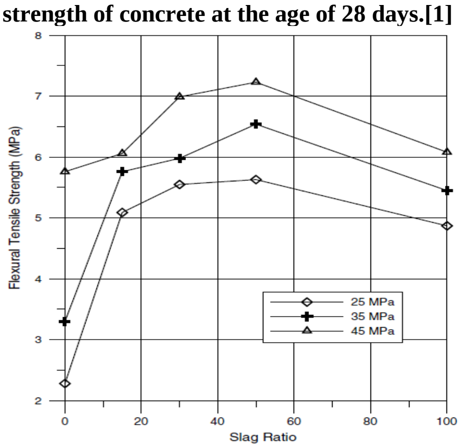

Fig 11: Relationship between the slag ratio and the tensile strength of concrete at the age of 90 days

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5 General Observations

- From tensile strength plots in figure 14 following conclusions were derived:

1. The use of steel slag increases the tensile strength of concrete by 1.4 to 2.4 times the strength of normal concrete, depending on the used ratio.
2. The optimum tensile strength value occurs when the sand is replaced by 30–50% slag, while this value is 15–30% for compressive strength.
3. The lower the grade of concrete, the higher the effectiveness of slag on strength improvement.
4. All tensile strength values, including those with 100% sand replacement, are always higher than concrete containing no slag.

Plate 3: Shows the Compression test conducted on a concrete specimen with steel slag aggregates [2]

- The conclusions reached from compressive strength plots in figure 14 are:

1. The use of steel slag increases the compressive strength of concrete by a maximum of 1.3 times the strength of normal concrete, depending on the ratio used. However, reduction in strength can occur beyond the 50% replacement ratio.
2. The optimum value occurs when the sand is replaced by 15 to 30% slag.
3. The lower the grade of concrete, the higher the effectiveness of slag on strength improvement.
4. The compressive strength in all mixes containing 100% sand slag replacement is always lower than those mixes with no slag.

Plate 4: Splitting tensile Test conducted on concrete specimen [2]

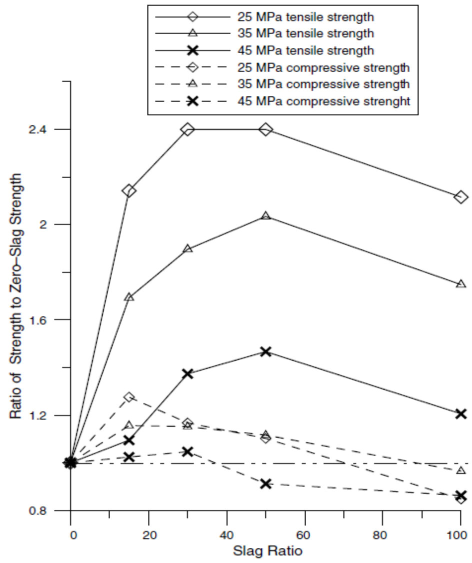

Fig 12: Relationship between slag ratio and the ratio of strength to zero-slag strength for the three grades of concrete. [1]

VII. EXPERIMENTAL PROGRAM 2

The main objective of this research was to utilize the steel slag aggregate in the concrete mixture and identify the properties of the mixture, its durability, expansion and also its fresh and hardened concrete properties.

A. MATERIALS

The materials used are:

1. The cement used in this project was supplied by St. Mary.s Cement Group. This is Type **I** Portland cement as classified by ASTM C150.
2. The steel slag used in this research was provided by Stein Inc. and originated from Mittal Steel USA located in Cleveland, Ohio, which is involved in the manufacture of many types of steel.
3. The fine aggregate used for the research was Shalersville natural sand from b Lafarge Corporation supplied by Cuyahoga Concrete and Stone. This Aggregate has absorption of 1.18%. The Bulk Specific Gravity of the fine aggregate was 2.60 while its SSD Specific Gravity was 2.63.
4. Two types of coarse aggregates were used in this research.
5. Two chemical admixtures were used in this research: high range water reducer and air entrainment admixture.

B. FRESH CONCRETE PROPERTIES

1. Unit weight test

The unit weight of the mixture was tested according to ASTM C138: Density (unit weight), Yield, and Air Content (Gravimetric) of concrete.

2. Air content test

The air content test is the most important test for determining the durability of concrete in the freeze thaw conditions. The air content of the fresh concrete was performed following ASTM C231: Air Content of Freshly Mixed Concrete by the Pressure Method. ODOT specifies an air content of 6 ± 2% for Class C Option 1 mixture.

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C. HARDENED CONCRETE PROPERTIES

This section discusses only the split tensile strength test and freeze thaw durability test as the results of compression and tensile strength test were discussed with respect to the research paper 1.

1. Splitting tensile strength

The splitting tensile strength of the concrete specimens was tested at 7 and 28 days. The four inch (102 mm) and eight inch (203 mm) cylindrical specimens were molded at the same time as the compressive strength specimens. The specimens were tested on a hydraulic loading machine following ASTM C 496. The splitting tensile strength can be obtained from the following equations:

$$T = \frac{2P}{\Pi LD} \qquad (1)$$

T = splitting tensile strength (psi) (MPa)

P = maximum applied load (lbf) (N)

l = length (in) (mm)

d = diameter (in) (mm)

2. Resistance to freezing and thawing

The resistance of the concrete due to rapid freezing and thawing cycles was tested according to ASTM C 666. The concrete prisms were placed into a Logan Freeze Thaw machine after curing for 14 days. At intervals of approximately 25 cycles the specimens were removed from the machine and their dimensions and weight were determined. The transverse frequency was then recorded utilizing an Olson Engineering Model RT-1Resonance Tester according to ASTM C 215. From this frequency measurement the relative Modulus of Elasticity was calculated by using the following equation;
Relative Dynamic Modulus of Elasticity (ASTM C 666)

$$Pc = \frac{N1^2}{N^2} \times 100 \qquad (2)$$

Pc = Relative dynamic modulus of elasticity after *c* cycles of freezing and thawing (%).
N = The Fundamental transverse frequency at 0 cycles of freezing and thawing.
N1 = The Fundamental transverse frequency after *c* cycles of freezing and thawing.

ASTM C 666 specifies that the test ends after 300 cycles, or when the relative dynamic modulus of elasticity falls below 60%. The durability factor was then calculated using the equation; Durability Factor (ASTM C 666)

$$DF = \frac{PN}{M} \qquad (3)$$

DF = The Durability factor of the test specimen.

P = The relative dynamic modulus of elasticity at *N* cycles (%).

N = The Number of cycles at which *P* reaches the specific minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less, *M* is the specified number of cycles at which the exposure is to be determined (usually300).

D. Brief analysis of results

1. Splitting tensile strength - The splitting tensile strength of the concrete specimens was determined at 7 and 28 days following ASTM C 496. The splitting tensile test is an indirect way of estimating the tensile strength of cylindrical concrete specimens. Since the concrete is much weaker in tension than in compression, the failure would be at a much lower load than in compression. The cylinders were tested according to ASTM C 496.. The control mixture showed splitting tensile strength after 28 days around 600 psi while all other specimens had around 500 psi (3.5 MPa).For ordinary structural concrete splitting tensile strength is about 3 MPa
2. Freeze thaw durability - According to ASTM C 666, the freeze-thaw resistance test is considered complete when either the specimen is subjected to 300 freeze-thaw cycles or when the dynamic modulus of elasticity drops below 60 %. The results showed that the control mixtures did not undergo any change in the durability factor and the relative dynamic modulus for the control mixture was 100 percent throughout 300 cycles.

Plate 5: 100% A steel slag specimen with no air entraining admixtures under the freeze-thaw machine

VIII. ENVIRONMENTAL CONCERN

There can be scepticm on the use of steel slag in construction as it is an industrial waste product Various studies have been conducted on this aspect and it is proved that steel slag has no threats to human health or the environment when used in residential, agricultural, industrial and construction applications. Slag has also been effectively used to treat acid mine drainage discharge and is also useful in the removal of excess phosphorous from waste water discharges, thus rendering the waste water more ecologically beneficial. So replacing the natural aggregates in concrete applications with steel slag would lead to considerable environmental benefits and would be economical.

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IX. PROBLEMS ASSOCIATED WITH STEEL SLAG AGGREGATES

Volume expansion and high particle density are the major problems with steel slag aggregates. During the making of steel there is a small percentage of calcium and magnesium oxides which is left undissolved in the slag. These non hydrated calcium and magnesium oxides then later come in contact with moisture which leads to hydration process. The volume expansion is primarily caused by the reaction between the free lime in slag and water during the hydration process to produce calcium hydroxide. As a result there is a great increase in volume due to the difference of specific density of the hydration product. Density of steel slag is also an important issue to be considered. Steel slag is a heavier material than natural rock types such as basalt, granite, or limestone. Thus, any given volume would require about 15 to 25% greater tonnage of steel slag than traditional natural aggregates which may create an economic disadvantage for steel slag in some applications where transportation costs are significant.

X.CONCLUSION

The demand for aggregates especially fine aggregates is increasing rapidly and so as the demand of concrete. Thus, it is becoming more important to find suitable alternatives for aggregates in the future. The results showed that it has properties similar to natural aggregates and it would not cause any harm if incorporated into concrete. From the research studies discussed the important conclusions on using steel slag as fine aggregate are as following. The use of steel slag affects workability adversely but it improves the tensile strength and compressive strength to a considerable extent. The negative effect on workability can be compensated for by using appropriate admixtures. When replacement percentages are between 15 and 30% , best results are obtained for compressive strength. The tensile strength increases by 1.1-1.3 times. The use of steel slag improves tensile strength of mixes with all replacement ratios. It has also better durability and freeze thaw properties. Up to 50 to 75 % of steel slag aggregates when incorporated in the traditional concrete, there would not be much change in the durability of concrete. A much more extensive field study on a concrete structure made with steel slag aggregates used in the mixture should be conducted and changes in durability and mechanical properties should be investigated and correlated to laboratory results.

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