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AN INVESTIGATION OF THE MECHANICAL PROPERTIES OF SINTERED FLY ASH LIGHTWEIGHT AGGREGATE CONCRETE (SFLWAC) WITH STEEL FIBERS

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Abstract: this study investigates the fresh and mechanical performance of concrete incorporating sintered fly ash lightweight aggregates (SFLWA) both with and without steel fibers. Comparative assessments of natural aggregates with sintered fly ash aggregates were evaluated. Mix design was obtained by the IS method for M30 grade concrete, and within the natural aggregates were replaced with 20%, 40%, and 60% amounts of SFLWA. The addition of SFLWA shows an increase in the workability of the concrete. Replacement with SFLWA increases with an increase in slump value, and decreases in strength parameters. Compressive strength of 42.6 MPa was achieved with a 40% replacement of SFLWA with steel fibers. The mechanical properties such as compressive strength, split tensile strength, flexural strength, elastic modulus, and structural efficiency of SFLWAC were examined, both with and without fibers. The incorporation of fibers drastically improved the mechanical properties of the mix.

Keywords: Sintered fly ash aggregates, slump, compressive strength, split tensile strength, flexural strength, elastic modulus, structural efficiency

1. INTRODUCTION

India delivers around 120 million tons of fly ash yearly. The absence of reasonable innovation and nonattendance of the market have deterred Indian business visionaries from delivering sintered fly ash aggregates. Fly ash-based artificial lightweight aggregates offer potential for wide range use in

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the construction industry. Apart from utilizing it in solid industry as a cement replacement, fly ash uses in other related enterprises have been, for example, exploited in cell concrete, pre-assembled products, and road development. However, around 75% of fly ash remains unutilized. Concrete compounded with lightweight aggregates (LWAs) has been used successfully for structural purposes since the second half of the twentieth century, and has become a very satisfactory alternative, when compared with conventional concrete. Expanded clay and sintered fly ash, which are commercially light weight aggregates, are acquired through heat treatment in temperatures of 1000 to 1200°C [1]. Sintering is a technique for making aggregates from powder by heating the material in a sintering furnace below its liquefying point (solid state sintering) until its particles adhere to each other. Sintering is customarily utilized for producing earthenware protests, and has likewise discovered uses in such fields as powder metallurgy. Sintering is compelling when the process decreases the porosity and improves properties, for example, quality, translucency, and thermal conductivity; yet, in different cases, it might be helpful to build its quality, yet keep its gas permeability consistent. During the firing process and as it continues; grain size becomes smaller and more spherical because the particle's surface tends to flow into the pores within based on the difference between vapor-pressure and the cross-sectional area of the pore's neck [2]. LWC can be made with compressive strength ranging from 30 to 80 MPa and can without much effort be made while by utilizing such aggregates, while LWC with compressive strength ranging from 20 to 50 MPa might be basically produced [3,4]. The expanding uses of LWC have brought about a requirement for artificial lightweight aggregate generation which could be accomplished by the sintering process. Also, utilizing fly ash in the generation of lightweight aggregates diminishes the natural harm. Mix design methodology for conventional aggregate concrete has a deterministic technique to acquire a required strength and workability. Lightweight concrete mix design is represented by a careful mix design technique, as the aggregates are naturally permeable with requires an underlying immersion, and further increment the water demand for acquire the desirable workability [5, 6]. Compressive properties of concrete were influenced with increments of aggregates, and, in addition, sort of aggregates were utilized as a part of the concrete mix. Sintered fly ash aggregates show higher compressive strength compared to cold bonded fly ash aggregates [7]. The expansion of the fibers into concrete is another strategy helping to improve building properties of concrete. The most helpful upgrade is directed to the flexural capacity, toughness, post-failure ductility, and crack control [8]. The fibers can be made from either natural materials (asbestos, sisal, and cellulose) or a manufactured product (glass, steel, carbon, and polymers). Steel is the most commonly used type among the various fibers for most structural and non-structural purposes [9]. A systematic study was undertaken on natural aggregates with sintered fly ash aggregate as: (i) Crushing Strength and Impact Test (ii) Replacement of SFLWA of 20%, 40%, and 60%, for Compressive strength, Split Tensile strength, Flexural strength, and stress-strain behaviour of SFLWAC with and without steel fibers.

2. Materials used

In this experimental program, ordinary grade 53 Portland cement [10] was used as a binding material in the concrete with a specific gravity of 3.15 and fineness [11] of 4%. This cement was obtained from Coimbatore, a local supplier. The 7 and 28 day compressive strength of the cement was 34.45 MPa and 51.41 MPa, respectively. Locally available river sand was used as a fine aggregate in the concrete mix with a specific gravity of 2.65 and a fineness of modulus of 2.54. The maximum nominal grain size of this fine aggregate was 4.75 mm. Two types of coarse aggregates were used in the concrete mix; one is a natural aggregate and the other is sintered fly ash aggregate (Fig.1). The natural aggregates were procured from local suppliers in Coimbatore and the sintered fly ash aggregates were supplied by GBC India private limited, Gujarat. The sintered aggregate is a fly ash-based aggregate and it is manufactured by the sintering process. The sieve analysis of the natural and sintered fly ash aggregates is shown in Table 1. Mechanical properties of natural aggregates and SFLWA were obtained from the crushing strength and impact test. A sample consisting of particle sizes passing through a 12.5 mm sieve and retained on a 10 mm sieve size was taken. These tests were conducted as per standard procedure, given in IS code [12]. The surface of the aggregates is levelled in a 150 mm diameter open-ended steel cylinder, the plunger is inserted, and then placed in the compression testing machine loaded at a uniform rate, so as to achieve a 40 ton load in 10 minutes. Afterwards, the load is released. The crushing strength was determined from the weight fraction of a sample passing through a 2.36 mm sieve to the total weight of aggregate sample used. Similarly, the impact testing machine was placed on a levelled surface with a rigid base, and the test consisted of releasing the hammer suddenly from a height of 380 mm, with a total number of 15 blows given. The impact test was determined from the weight fraction of a sample passing through a 2.36 mm sieve to the total weight of aggregate sample used. The mechanical properties of both the natural and sintered fly ash aggregates are given in Table 2. Loose hook-ended and low carbon steel fibers with an aspect ratio of 55, a length of 30 mm, and diameter of 0.55 mm . The tensile strength of these loose hook-ended fibers was 1450 MPa. Conplast SP430, a sulphonated naphthalene polymer-based super Plasticizer was used to produce the SFLWAC mixtures. Potable water collected from the laboratory water supply system has been used for all the mixes.

Fig.1. Sintered fly ash aggregate

Table 1. Sieve analysis results of the natural and sintered fly ash aggregates

Aggregate Type	Sieve Size (mm)	Cumulative Percentage Weight retained (%)	Percentage Passing (%)
Natural Aggregate	20mm	0	100
	16mm	2.5	98
	12.5mm	28.1	72
	10mm	71.8	28
	4.75mm	99.9	0
	PAN	100	0
Sintered Fly Ash Aggregate	20mm	0	100
	16mm	4.7	95
	12.5mm	24.9	75
	10mm	62.7	37
	4.75mm	98.9	1
	PAN	100	0

Table 2. Physical and mechanical properties of natural and sintered fly ash aggregates

Physical and mechanical properties	Natural aggregate	Sintered fly ash aggregate
Specific gravity (saturated surface dry)	2.65	1.395
Water absorption for 24 h (%)	0.9	16.8
Loose bulk density (kg/m^3)	1490	830
Rodded bulk density (kg/m^3)	1626	895
Fineness modulus	2.02	1.91
Aggregate impact value (%)	19.42	27.78
Aggregate crushing strength (%)	12.77	15.63

3. Mix proportions

In this study, concrete mixtures were designed for a target strength of M30 grade with a high workability [13]. The water-cement ratio has been kept as 0.35. About 2% of the super plasticizer was used in the mixes to attain workability. The proportioning and descriptions of the concrete mixtures are summarized in Table 3.

Table 3. Mix proportions

MIX ID	Cement Content (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Sintered fly ash aggregate (kg/m^3)	Water content (kg/m^3)	w/c ratio	SP (%)	V_f (%)
CC	435	891.5	969	0	152.4	0.35	2.0	0
SFLWAC1	435	891.5	776	194	152.4	0.35	2.0	0
SFLWAC2	435	891.5	582	388	152.4	0.35	2.0	0
SFLWAC3	435	891.5	435	535	152.4	0.35	2.0	0
SFLWAC4	435	891.5	969	0	152.4	0.35	2.0	0.5
SFLWAC5	435	891.5	776	194	152.4	0.35	2.0	0.5
SFLWAC6	435	891.5	582	388	152.4	0.35	2.0	0.5
SFLWAC7	435	891.5	435	535	152.4	0.35	2.0	0.5
Notes: w/c ratio – water to cement ratio; SP-Super Plasticizer; V_f – Volume of Steel fibers; CC- Control Concrete; SFLWCA1- Sintered fly ash lightweight aggregate concrete mixture 1								

4. Casting and curing of concrete specimens

Concrete production using sintered fly ash lightweight aggregates requires careful estimates of the water content. Therefore additional water was required to achieve the desired workability level due to the consumption of water for the saturation of pores in the aggregates. This initial wetting of the sintered fly ash aggregates in water, which were later air dried for 30 min, ensures an initially saturated surface's dry conditions. Concrete mix was prepared in a laboratory drum mixer with dry ingredients like cement, fine aggregate, and pre-soaked sintered fly ash. After homogenizing the aggregates and the binder (after 30 seconds of mixing) about a third of the mixing water was added slowly into the mixer and mixing continued for an additional minute. Finally, the superplasticizer (along with the remaining water) was introduced, and the concrete was mixed for 3 minutes and then left to sit for an additional 2 minutes. Afterwards, all the materials were mixed again for 2 more minutes to complete the mixing sequence. In addition, to improve the bond strength of the sintered fly ash aggregates, steel fibers were added during casting. The fresh concrete was then cast into 100 mm sized cubes and 100 mm x 200mm cylindrical specimens for an estimate of their mechanical strength properties after 28 days of normal water curing. Flexural strength tests were also performed on 100 x100 x 500 mm prismatic specimens according to the standard testing method [14]. In total, 24 concrete cube specimens, 40 cylindrical specimens, and 24 prismatic specimens were cast and tested across 8 different concrete mixtures.

5. RESULTS AND DISCUSSION

5.1 SLUMP AND UNIT WEIGHT OF CONCRETE

Slump [15] and unit weight test results of 8 different concrete mixes are shown in Table 4. As shown in this table, the slump values of the concretes vary between 76 mm and 205 mm. The mixtures containing without steel fibers show that the slump value is increasing as the SFLWA content increases. The addition of steel fibers decreases the slump and increases the unit weight of the concrete mixtures.

Table 4. Slump values and unit weights of concrete mixtures

MIX ID	Slump Value[a] (mm)	Unit weight[b] (kg/m^3)
CC	100	2422
SFLWAC1	140	2297
SFLWAC2	175	2110
SFLWAC3	205	2093
SFLWAC4	76	2434
SFLWAC5	82	2356
SFLWAC6	87	2267
SFLWAC7	94	2198

CC- Control Concrete; SFLWCA1- Sintered Fly ash lightweight aggregate concrete mixture1; [a]Tested Values by using slump cone; [b] Tested Values by using Density Buket.

5.2 COMPRESSIVE STRENGTH

The 28-day compressive strength values of the SFLWACs are given in Table 5. Compressive strength of the control concrete was 32.1 MPa [13]. Mixtures SFLWAC1, SFLWAC2, and SFLWAC3 indicate the compressive strength results without the addition of steel fibers. Among these, SFLWAC2 shows better results. This indicates the optimum percentage of sintered fly ash aggregate for the concrete mix. Mixtures SFLWAC5, SFLWAC6, and SFLWAC7 indicate the compressive strength results of SFLWAC with steel fibers. SFLWAC6 shows a higher compressive strength (42.6 MPa) than all the mixtures. The relative compressive strength values of SFLWACs are also given in Table 5. It can be seen from the results that compressive strengths of SFLWACs are higher by about 4–32 % than the control mixture. From the observed results for compressive strength on the cubes, the highest strength was achieved by SFLWAC6 manufactured with 40 % of sintered fly ash aggregates with steel fibers. While the control concrete exhibits the lowest compressive strength, 32.1 MPa, the average compressive strength of SFLWAC6 32 % increased.

5.3 Split tensile strength

The 28-day split tensile strength values of SFLWACs are given in Table 5. The split tensile strength of the control concrete was 2.69 MPa [13]. Mixtures SFLWAC1, SFLWAC2, and SFLWAC3 indicate the split tensile strength results without the addition of steel fibers. Among these, SFLWAC2 shows better results. This indicates the optimum percentage of sintered fly ash aggregates for concrete. Mixtures SFLWAC5, SFLWAC6, and SFLWAC7 indicate the split tensile strength results of SFLWAC with steel fibers. SFLWAC5 shows a higher split tensile strength (5.124 MPa) than all the mixtures. The relative split tensile strength values of SFLWACs are also given in Table 5. It can be seen from the results that the split tensile strengths of SFLWACs are higher by about 4–90 % than the control mixture. From the observed results for split tensile strength on the cylinders, the highest strength was achieved by SFLWAC5 manufactured with 20 % of sintered fly ash aggregates with steel fibers. While the control concrete exhibits the lowest compressive strength, 2.69 MPa, the average split tensile strength of SFLWAC5 90 % increased.

5.4 Flexural strength

The 28-day flexural strength values of SFLWACs are given in Table 5. The flexural strength of the control concrete was 7.68 MPa [13]. Mixtures SFLWAC1, SFLWAC2, and SFLWAC3 indicate the flexural strength results without the addition of steel fibers. Among these, SFLWAC2 shows better results. This indicates the optimum percentage of sintered fly ash aggregates for concrete. Mixtures SFLWAC5, SFLWAC6, and SFLWAC7 indicate the flexural strength results of SFLWAC with steel fibers. SFLWAC5 shows a higher flexural strength (8.23 MPa) than all the mixtures. The relative flexural strength values of SFLWACs are also given in Table 5. It can be seen from the results that flexural strengths of SFLWACs decrease about 6-17 % comparing to the control mixture. From the observed results for flexural strength of the beams, the highest strength was achieved by SFLWAC5 manufactured with 20 % sintered fly ash aggregates with steel fibers. While the control concrete exhibits the lowest flexural strength, 7.68 MPa, the average flexural strength of SFLWAC5 7 % increased.

Table5. Mechanical properties of SFLWAC mixtures

MIX ID	Compressive strength [a] (MPa)	Relative Compressive strength (%)	Split Tensile strength [a] (MPa)	Relative Split Tensile strength (%)	Flexural strength [a] (MPa)	Relative Flexural strength (%)
CC	32.1	100	2.69	100	7.68	100
SFLWAC1	34.40	107	2.80	104	6.25	81
SFLWAC2	40.93	127	3.92	145	7.25	94
SFLWAC3	35.73	111	3.09	114	6.40	83
SFLWAC4	33.5	104	3.91	145	7.85	102
SFLWAC5	35.3	110	5.12	190	8.23	107
SFLWAC6	42.6	132	4.61	171	7.31	95
SFLWAC7	39.2	122	4.04	150	7.26	94
[a]Tested values are average of 3 specimens						

5.5 Elastic modulus of SFLWAC mixtures

The 28-day elastic modulus of the control concrete was 20.18 GPa[14]. Mixtures SFLWAC1, SFLWAC2, and SFLWAC3 indicate the elastic modulus results without the addition of steel fibers. Among these, SFLWAC3 shows better results. This indicates the optimum percentage of sintered fly ash aggregates for concrete. Mixtures SFLWAC5, SFLWAC6, and SFLWAC7 indicate the elastic modulus results of sintered fly ash lightweight aggregate concrete (SFLWAC) with steel fibers. Mixture SFLWAC7's elastic modulus was 45.74 GPa, which is less than that of SFLWAC3. The elastic modulus values of the SFLWACs mixtures are given in Table 6. It can be seen from the results that the elastic modulus of the SFLWACs increases about 63-228% over the control mixture. The SFLWAC mixtures with the addition of 0.5% steel fibers improved compressive stress-strain behaviour when compared to those without the addition of steel fibers. This shows that addition of steel fibers to concrete mixtures will improve the stress-strain behaviour considerably. From the observed results for young's modulus on the cylinders, the highest young's modulus value was achieved for SFLWAC3 manufactured with 60 % sintered fly ash aggregates without steel fibers. While the control concrete exhibits the lowest young's modulus value of 20.18 GPa, the average young's modulus value of SFLWAC3 28% increased.

Table 6. Elastic modulus of SFLWAC mixtures

Mix ID	Young's modulus [a] (GPa)	Relative Young's modulus (%)
CC	20.18	100
SFLWAC1	32.89	163
SFLWAC2	41.21	204
SFLWAC3	46.06	228
SFLWAC4	41.55	205
SFLWAC5	33.23	164
SFLWAC6	32.25	159
SFLWAC7	45.74	226
[a]Tested values are average of 2 specimens		

5.6 Structural Efficiency

In lightweight concrete or mortars, the compressive strength is firmly connected with their density; compressive strength diminishes with a reduction in density. Particularly when connected in long-span or tall structures, the density and strength of lightweight concrete is pivotal to achieve a high strength while holding low density. This connection is normally researched utilizing the alleged structural efficiency, which is calculated from the proportion of compressive strength at 28 days to density, as

$$st_{\eta}=\frac{f_{ck}}{\rho} \qquad (1)$$

Where, $st_{\eta}$is the structural efficiency (Nm/kg), $f_{ck}$is the compressive strength at 28 days (MPa), and ρ is the actual density of the sample (kg/m^3).

Table7. Compressive strength, density, and calculated structural efficiency of the SFLWACs

Mix ID	Compressive strength at 28 days (MPa)	Dry Density at 28 days (kg/m^3)	Structural efficiency (Nm/kg)
CC	32.1	2487	12,907
SFLWAC1	34.40	2420	14,215
SFLWAC2	40.93	2300	17,796
SFLWAC3	35.73	2213	16,146
SFLWAC4	33.5	2571	13,030
SFLWAC5	35.3	2420	14,587
SFLWAC6	42.6	2303	18,498
SFLWAC7	39.2	2253	17,399

The structural efficiencies as well as the densities of these mixes and their appropriate compressive strengths at 28 days are listed in Table 6. The structural efficiency of the control mixture was 12,907 Nm/kg. Mixtures SFLWAC1, SFLWAC2, and SFLWAC3 indicate the structural efficiency results of without the addition of steel fibers. Among these, SFLWAC2 shows the best results. This indicates the optimum percentage of sintered fly ash aggregate for concrete. Mixtures SFLWAC5, SFLWAC6, and SFLWAC7 indicate the structural efficiency results of SFLWAC with steel fibers. SFLWAC6 shows the highest structural efficiency among all the mixtures. This indicates that the structural efficiency is in indirect proportion to the density. Mixture SFLWAC6 shows better structural efficiency due to a reduction in the permeability of concrete and the addition of steel fibers.

6. CONCLUSIONS

Based on the present experimental work conducted on sintered fly ash aggregates, the following conclusions are drawn:

1. Crushing and impact strength of sintered fly ash aggregates were found to be satisfactory as required for use for lightweight structural applications.
2. The slump of the mixtures increased when the proportion of SFLWA content increased.
3. The unit weight of the concrete mixtures increased in the concrete containing steel fibers.
4. Reduction in mechanical properties was reported for the higher substitution of sintered fly ash aggregate.
5. Usage of steel fibers increases the compressive strength of SFLWAC mixtures about 4 - 32%.
6. The split tensile and flexural strength of SFLWAC mixtures decreased when the sintered fly ash aggregate content increased beyond 20%. This decrease in strength can be overcome by usage of a higher aspect ratio in the fibers in concrete.
7. The addition of SFLWA into concrete mixtures increases the elastic modulus; this may be due to the reduction in the permeability of the concrete matrix. The addition of steel fibers increase the elastic modulus of the SFLWACs mixtures.
8. Comparing to SFLWAC3, SFLWAC7 shows a decreased elastic modulus. This is caused by the concrete matrix having a higher amount of SFLWA and no adverse effects on the steel fibers.
9. The structural efficiency shows that sintered fly ash aggregates containing concrete mixtures are suitable for high-rise constructions.

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BADANIE WŁAŚCIWOŚCI MECHANICZNYCH BETONU LEKKIEGO KRUSZYWOWEGO ZE SPIEKANEGO POPIOŁU LOTNEGO (SFLWAC) Z WŁÓKNEM STALOWYM

Słowa kluczowe: Kruszywa ze spiekanego popiołu lotnego, spadek, wytrzymałość na ściskanie, wytrzymałość na rozciąganie, wytrzymałość na zginanie, moduł sprężystości i efektywność konstrukcyjna.

PODSUMOWANIE:

Kruszywa z popiołu lotnego mogą być wytwarzane zarówno z kruszyw wiążących na zimno jak i z kruszyw spiekanych. Naukowcy koncentrują się wyłącznie na wytwarzaniu kruszyw i bezpośrednim wykorzystaniu gruboziarnistych kruszyw w betonie. Kruszywa spiekane wykazują się lepszą wydajnością w porównaniu do kruszyw wiążących na zimno. Kilku naukowców przeprowadziło badanie poświęcone naturalnym kruszywom oraz spiekanym kruszywom. W niniejszym badaniu, kruszywa ze spiekanego popiołu lotnego zostały częściowo zastąpione naturalnymi kruszywami w gatunku betonu M30, w celu zbadania właściwości mechanicznych i sprężystych. To pokazuje, że kruszywo może być wykorzystywane do zastosowań konstrukcyjnych. Włączenie włókien stalowych do tej betonowej matrycy miało na celu porównanie zachowania na świeżym i utwardzonym podłożu. W pracy skupiono się na przydatności kruszyw ze spiekanego popiołu lotnego w betonie. Początkowo kruszywa ze spiekanego popiołu lotnego zostały poddane badaniu pod kątem właściwości fizycznych, takich jak gęstość w stanie suchym, ciężar właściwy, wchłanianie wody, udatność i wytrzymałość na zgniatanie dla przydatności kruszywa do mieszania z betonem. Miało to również na celu sprawdzenie wytrzymałości kruszyw ze spiekanego popiołu lotnego w betonie. Opracowano docelową wytrzymałość na ściskanie na poziomie 30 N/mm2 i otrzymano próbne mieszaniny w oparciu o IS 10262: 2009. Te próbne mieszaniny zostały następnie poddane badaniu pod kątem 20%, 40% i 60% częściowej wymiany na naturalne gruboziarniste kruszywo, a następnie wybrano najlepszą mieszaninę na podstawie wytrzymałości na ściskanie próbek betonu. Wyniki pokazują, że 40% wymiana kruszyw ze spiekanego popiołu lotnego okazała się lepszym rozwiązaniem w porównaniu do innych mieszanin. Mieszaniny te zostały następnie dokładniej zbadane w odniesieniu do różnych proporcji włókien stalowych w mieszaninach betonowych, dla współczynnika kształtu wynoszącego 55 i objętości wynoszącej 0,5% w mieszaninach betonowych. Następnie do mieszanin dodano włókna szklane, co powoduje zwiększenie ich wytrzymałości i właściwości wiążących w mieszaninach betonowych.