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Experimental investigations on performance of concrete incorporating Precious Slag Balls (PS Balls) as fine aggregates

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Abstract. Substitution of natural fine aggregates with industrial by-products like precious slag balls (PS Balls) offers various advantages like technical, economic and environmental which are very important in the present era of sustainability in construction industry. PS balls are manufactured by subjecting steel slag to slag atomizing Technology (SAT) which imparts them the desirable characteristics of fine aggregates. The main objective of this research paper is to assess the feasibility of producing good quality concrete by using PS balls, to identify the potential benefits by their incorporation and to provide solution for increasing their utilization in concrete applications. The study investigates the effect of PS balls as partial replacement of fine aggregates in various percentages (20%, 40%, 60%, 80% and 100%) on mechanical properties of concrete such as compressive strength, splitting tensile strength, and flexural strength. The optimum mix was found to be at 40% replacement of PS balls with maximum strength of 62.89 MPa at 28 days curing. Permeability of concrete was performed and it resulted in a more durable concrete with replacement of PS balls at 40% and 100% as fine aggregates. These two specific values were considered as optimum replacement is 40% and also the maximum possible replacement is 100%. Scanning electron microscope (SEM) analysis was done and it was found that the PS balls in concrete were unaffected and with optimum percentage of PS balls as fine aggregates in concrete resulted in good strength and less cracks. Hence, it is possible to produce good workable concrete with low water to cement ratio and higher strength concrete by incorporating PS balls.

Keywords: precious slag balls; concrete; sustainability; fine aggregates; durability

1. Introduction

In the era of incessant infrastructure development, the availability of virgin aggregates has been a big concern due to depleting resources. Moreover, environmental impact of extracting virgin aggregates has been significant, which has paved way to look for several suitable alternatives across the world. Concrete being one of the largely used construction materials is actively promoting the objectives of sustainable construction and encouraging many research activities such as alternatives for virgin coarse and fine aggregates, green building concepts, and light weight concrete. The concrete industry is improving its performance, particularly in terms of cleaner production with improved concrete specifications. By considering the entire life cycle of concrete i.e., extraction, processing, construction, operation, demolition and recycling - concrete could significantly contribute to adverse environmental impacts. Therefore, emphasis is placed on investigating the feasibility of using industrial by-products, that would end up in landfills and pollute the environment, to be used in concrete (Havanagi *et al*. 2012).

These can be used in the cement kiln or can be added to concrete mixes to provide desirable characteristics. Based on the physical and chemical properties of industrial waste, it could be used as substitution as a construction material (Chandler *et al*. 1997). Over the past decade, researchers are working on utilization of various waste materials such as mining wastes, ceramic waste, glass and slag produced in various industries as substitute for fine aggregates. The use of these industrial by-products in concrete can pave way for safe disposal of waste, leading to recycling of materials, conserve the natural resources, and reducing adverse impacts on environment along with reducing the stress on new mining activities.

The essential construction resources (such as sand) are becoming scarce and expensive due to excessive cost of extraction and transportation. On the other hand, depletion of river sand also creating serious environmental problems. Sand mining from the river bed is banned in some of the states in India, some other states restricted sand mining by making various stringent policies like collection & selling points, managed directly by the Government (Gayana and Chandar 2018). Such acts impose concrete industry to look for alternative materials for river sand. Therefore, research is required to find the use of cheaper, easily available, and sustainable alternative materials to replace natural river sand partially or completely without compromising the characteristics of concrete (Bederina *et al*. 2013).

One such industry is mining industry i.e., overburden mine waste and tailings. The waste produced is generally

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dumped outside the mine in the form of overburden dumps. These dumps occupy a large amount of land, which loses its original fertility characteristics and generally become degraded. Maintaining stability of the dump is also a major issue for the mining industry (Sastry and Chandar 2013). Chandar *et al.* (2016a, 2016b) partially replaced sand with laterite and sandstone respectively, and found that though there is not much improvement on strength properties of concrete, yet these materials can be used as a replacement for sand. A review on sustainable use of iron ore waste rock and tailings with admixtures for concrete pavements was carried out by Gayana and Chandar (2018). The strength aspects of Self Compacting Concrete (SCC) prepared by partial replacement of cementitious materials by Red Mud (RM) at 1%, 2%, 3% and 4% and in the same mix by partially replacing sand by Iron Ore Tailings (IOT) at 10%, 20%, 30% and 40%, resulted a compressive strength and flexural strength more than the conventional mix at 2% RM and 30% IOT (Shetty *et al.* 2014).

Utilization of granulated blast furnace slag (GBFS) and LD slag produced in steel industries were used as a substitute for fine aggregates and experimental studies resulted that steel slag aggregate concrete achieved higher values of compressive, tensile, flexural strength and modulus of elasticity compared to natural aggregate concrete (Alizadeh *et al.* 1996). The properties of mechanical strength, stiffness and wear resistance of slag afford optimistic view with the possibility of using slag as aggregates (Geiseler 1996). The free Calcium Oxide (CaO) content present in these slags generates the problems of volume expansion (Tang 1973). The use of GBFS in Self Consolidating Concrete (SCC) improved the drying shrinkage, chloride ion penetration, water absorption, sulfate attack resistance and corrosion resistance of SCC (Deepankar *et al.* 2016, Yahiaoui *et al.* 2017). Gaurav *et al.* (2015) conducted experiments on concrete by replacing fine aggregates with GBFS. Maximum compressive strength was obtained for 50% replacement of sand by GBFS and the mixes containing GBFS showed higher compressive strength than the reference mix. Also while using GBFS as fine aggregate, the 90 day strength was higher than 28 day strength, with the increase in strength attributed to pozzolanic property of GBFS. Another cost effective and environmental-friendly method to produce SCC might be the use of Recycled Concrete Aggregate (RCA) for SCC production. Omar *et al.* (2018) investigated the enhancement of workability of SCC mixes with recycled aggregates. With 25 to 50% replacement of virgin aggregates by RCA and cement replacement of 15% by GBFS resulted in optimum proportion to produce satisfactory SCC without any bleeding or segregation. Hence, the addition of slag to recycled concrete aggregates of SCC mixes reduces strength losses at the long term (i.e., 56 and 90 days). The effect of heat curing on electric arc furnace oxidizing slag (EOS) concrete was investigated and the results showed that to limit the rate of expansion, EOS should be in the range of 20% to 30% (Shu *et al.* 2016). Walid (2017) investigated the effects of use of GBFS as replacement for cement (15% and 25%) in fresh and hardened concrete. The durability of SCC concrete improved with GBFS with 25% cement replacement in long term.

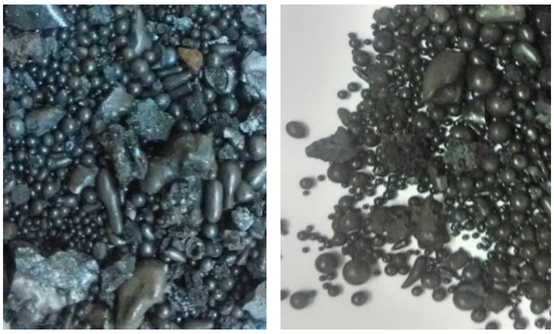

Fig. 1 PS Balls

Yi *et al.* (2018) reviewed the utilization of steel slag characteristics in cement and concrete and concluded that, adequate aging/weathering and treatments can enhance the hydrolyses of free-CaO and -MgO to mitigate the instability. Considering the environmental and economic aspects, steel slags are also considered to have a potential use as the raw meal in cement clinker production.

The difficulty associated with the usage of slag is volume instability (changes in volume when exposed to moisture) and reactivity, forming secondary compounds under certain conditions initiating the need for research to produce inert and stable material. PS Balls and steel grit were proposed as such materials based on research.

A sustainable material considered in the present study is PS balls (Fig. 1). It has a stable molecular structure produced from molten slag generated from steel making process at steel melting plant. PS balls are of solid spherical balls obtained by slag atomizing technology involving super-cooling of molten slag and at the same time transforming it to induce a stable spinel structure.

PS balls are produced using SAT to attain a spinel structure with general chemical formula AB2O4 which is octahedron in shape. This spinel structure imparts solidity, lustre like that of glass and high index of reflection to PS balls. The surface of PS balls formed by oxide compound does not allow easy movement of ion or electron. Due to this, the ion or electron movement from the PS balls required for chemical reaction to take place becomes difficult and therefore PS balls can be considered as stable material which offers very strong resistance to chemical and physical weathering. Hence, the PS balls produced using slag atomizing technology being very stable, they do not break and do not casue any pollution problems.

2. Experimental study

Laboratory experiments were conducted using the different concrete samples prepared with different combinations of cement, fly ash, natural coarse aggregates, fine aggregates, and PS balls. The following sections give the details of characteristics of the materials used, details of sample preparation, and the tests conducted.

2.1 Characterization of materials

2.1.1 Cement

Table 1 Physical properties of cement

Properties	Values	Remarks
Specific Gravity	3.15	The cement satisfies the requirement for 53 grade OPC stipulated by IS 12269:2013. Tests are conducted as per guidelines of IS 4031.
Standard Consistency	29%	
Fineness	300 m^2/kg	
Initial Setting Time	60 minutes	
Final Setting Time	450 minutes	
Soundness (By Le Chatelier Mould)	2 mm	

Table 2 Properties of aggregates and PS balls

Aggregate type	Specific gravity	Bulk density (kg/m^3)		Voids (%)	Water absorption (%)	Fineness modulus	Grading zone as per IS 383
		Loose	Dense				
Natural coarse aggregates	2.8	1370	1670	40	0.5	6.76	-
Natural fine aggregates	2.7	1440	1700	38	1	2.51	Zone II
PS balls-fine aggregates	3.58	2300	2550	28.8	0.2	3.14	Zone I

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 (BIS, 2013) was used. Specific gravity of the cement obtained was 3.15, and the fineness obtained using Blaine's air permeability apparatus was 300 m^2/kg. The physical properties of the cement used are shown in Table 1.

2.1.2 Fly ash

Class 'F' Fly Ash conforming to BIS 3812 Part 1 (BIS, 2013) was used for the experiments. The specific gravity of Fly Ash was 2.2 and the amount of Fly Ash retained on 45µm sieve was measured equal to 30%, which is within the prescribed limit. Fly Ash was utilized for the experiments in order make the mix cohesive and to improve workability.

2.1.3 Coarse aggregates

Locally available coarse aggregate of size 20mm down with fineness modulus 6.76 and specific gravity 2.8 was used for this study. The specific gravity, density, and water absorption are shown in Table 2.

2.1.4 Fine aggregates

River sand and PS balls are used as fine aggregates for this study.

River sand: River sand used as fine aggregate conforming to grading zone II of BIS 383: 1970 (BIS, 1970) with fineness modulus - 2.51 and specific gravity - 2.70. The physical properties of sand are show in in Table 2.

PS Balls: PS balls were procured from a steel plant in South India. Sampling was done according to IS 2430: 1986 (BIS, 1986). The tests conducted on PS Balls showed that they had a specific gravity of 3.58 and conform to grading zone I of IS 383:1970 (BIS, 2009) with fineness modulus of 3.14. The results are shown in Tables 2. The particle size distribution based on the sieve analysis is shown in Fig 3. Table 3 provides the details of chemical composition of PS balls.

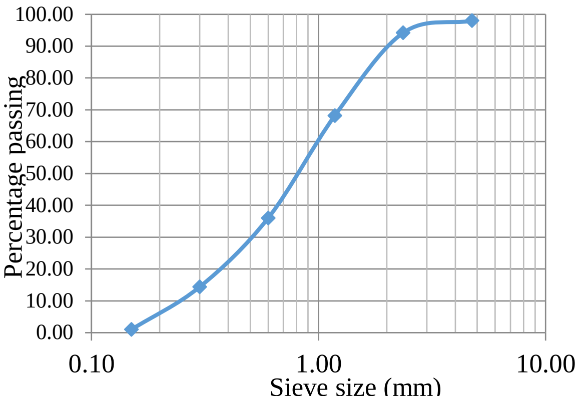

Fig. 3 Particle size distribution of PS balls

Table 3 Chemical composition of PS balls

Component	Percentage (%)
SiO_2	15.50 to 21.30
Al_2O_3	7.98 to 8.27
CaO	22.60 to 27.60
MgO	6.02 to 6.56
Fe_2O_3	21.40 to 29.20
Others	13.70 to 19.87

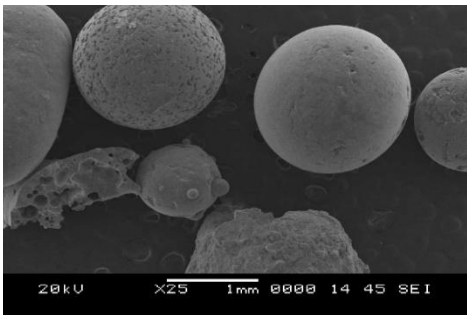

Fig. 4 SEM images of PS balls (25X)

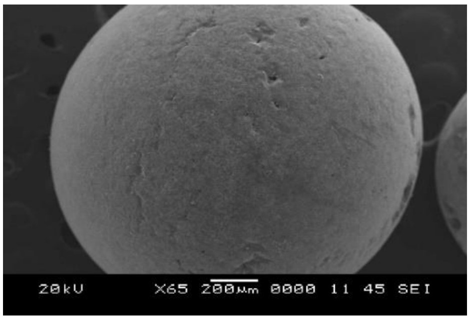

Fig. 5 SEM images of PS balls (65X)

Further, SEM (Scanning Electron Microscope) analysis was done on PS balls to know the surface morphology of the samples as shown in in Figs. 4-7.

2.1.5 Water

Water used was conforming to the requirements of water for concreting and curing.

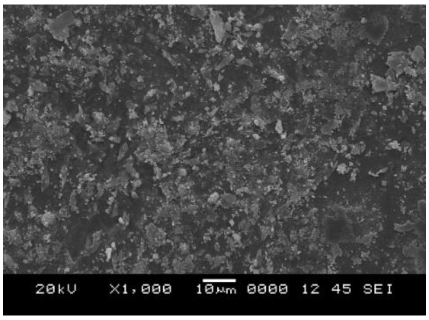

Fig. 6 SEM images of PS balls (1000X)

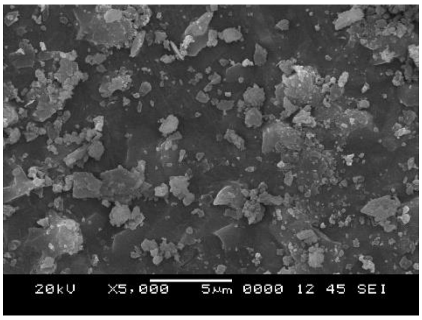

Fig. 7 SEM images of PS balls (5000X)

2.1.6 Super plasticizer

Sulphonated naphthalene polymer based Conplast SP430 superplasticizer conforming to IS 9103 was used.

2.2 Concrete mix proportion

Concrete mix of M40 grade was designed following the BIS 10262: 2009 (BIS 2009). Since PS Balls have a very high specific gravity compared to other materials used in the mix, PS balls were found settling at the bottom in the compacted moulds. To address this, fly ash was used to make the mix cohesive, to reduce settling of PS balls and care was taken to ensure sufficient vibration to compact concrete without segregation. Sulphonated naphthalene polymer based Conplast SP430 superplasticizer was used to improve the workability of concrete.

The cement content of 326 kg/m^3 with 0.4 water-cement ratio was kept constant for all the concrete mixes. Concrete mixer of 160 l capacity was used and all the concrete mixes were blended for 5 minutes before addition of water for better mix. Mixes contained sand and PS balls with 100% replacement of PS balls with 20% intervals. Fly ash content was kept constant for all mixes at 20% of cement content. Superplasticizer content was kept constant at 1% of cement content for all mixes. Table 5 shows the quantities of concrete ingredients per m^3 of concrete for the different mixes.

Table 5 Mix proportion

Mix	Water (liter)	Cement (kg)	Fly ash (kg)	Fine Aggregate (kg)	PS balls (kg)	Coarse Aggregate (kg)
SP 0	163	326	81	815	0	1145
SP 20	163	326	81	652	212	1145
SP 40	163	326	81	489	424	1145
SP 60	163	326	81	326	636	1145
SP 80	163	326	81	163	848	1145
SP 100	163	326	81	0	1060	1145

2.3 Mixing, casting and curing of specimens

For each concrete mix, 6 cubes (150 mm×150 mm×150 mm), 6 cylinders (150 mm×300 mm) and 6 beams (100 mm×100 mm×500 mm) were casted to study hardened concrete properties (compressive strength, tensile strength, and flexural strength, respectively). Concrete was mixed in drum mixer, by adding coarse aggregate, fine aggregate, PS balls, cement and fly ash and dry mixed till uniform mix was observed and then by adding 60% of water and mixed again and then the superplasticizer was mixed with remaining 40% water adding to the concrete during mixing. Once the uniform mix was obtained, fresh concrete properties were studied i.e., slump of concrete was measured and observed to check if there was any segregation or bleeding. Concrete was loaded into moulds and sufficient compaction was done using table concrete vibrator as per Indian standard BIS: 516-1959 (BIS 1959). Specimens were demoulded after 24 hours and immersed in water for curing until the test date. For hardened concrete, compressive strength was measured at 7, 28 and 90 days of curing age and splitting tensile strength and flexural strength were measured at 28 days of curing age.

2.4 Test procedures

2.4.1 Workability

Workability of concrete was measured using the compaction factor test as per BIS 1199 (1999) (BIS 1999). Workability of concrete gives an idea about the mixing ability, transportability, molding ability and compacting ability of concrete. Slump cone test was used to measure the workability of concrete and this fresh concrete mix was checked for signs of segregation and bleeding. Necessary corrections were made to the mix proportioning based on the observations on trial mixes.

2.4.2 Compressive strength

The compressive strength of concrete specimens was determined as per BIS: 516-59 at various curing days i.e., 7 days, 28 days and 90 days. The compression testing machine of capacity 2000 kN was used to test the concrete samples.

2.4.3 Splitting tensile strength

Splitting tensile strength of concrete specimens was determined as per BIS: 516-59 (BIS 1999) at 28 days curing age. Compression testing machine of 2000 kN capacity was used.

2.4.4 Flexural strength

Flexural strength of concrete specimens was determined at 28 days as per BIS: 516-59 (BIS 1979).

2.4.5 Permit-ion permeability test

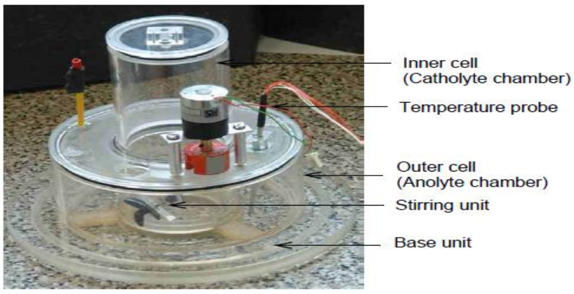

Fig. 8 (a) Permit ion permeability test apparatus

Fig. 8 (b) Permit ion permeability test on PS ball concrete sample

The coefficient of ionic transport is determined using this instrument. A steady state ionic flow is established, from which the ionic transport coefficient (i.e., the coefficient of diffusion/migration) is calculated. The apparatus and the testing of the sample is as show in in Fig. 8(a) and 8(b).

3. Results and discussions

3.1 Workability

It can be observed that, with the increase in PS balls aggregates, workability increased compared to the control concrete as shown in Fig. 9. When the natural aggregates were completely replaced by PS balls aggregates, an increase of 40% in compaction factor was observed. This fact is attributed to low water absorption and it possess round shape which helps in increasing the workability of concrete with increasing content of PS Ball as fine aggregates.

3.2 Density

Increased PS balls increased the density of hardened concrete due to higher specific gravity of PS Balls compared to natural river sand. The density of different mix is shown in Fig. 10.

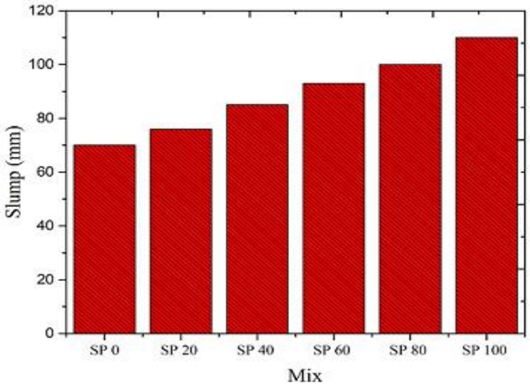

Fig. 9 Workability of concrete containing PS balls

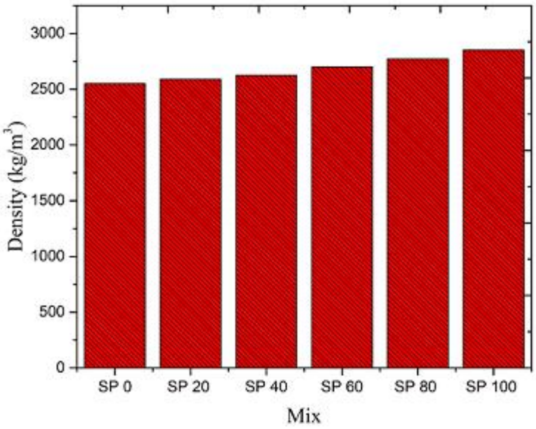

Fig. 10 Density of concrete with PS balls

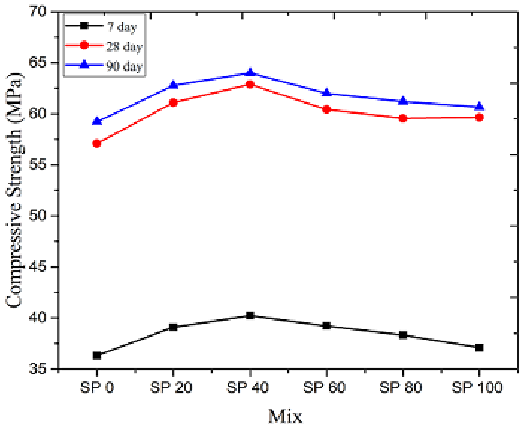

Fig. 11 Variation in compressive strength of concrete

3.3 Compressive strength

Compressive strength for concrete specimens with various curing days of 7, 28 and 90 days are shown in Fig. 11. It was observed that, the concrete mix in which 40% of sand was replaced with PS balls showed the highest increase in compressive strength. With reference to the control mix the percentage increase in 7 days compressive strength of the mix SP 20, SP 40, SP 60, SP 80 and SP 100 were 7.6%, 10.7%, 7.9%, 5.5% and 2.1% respectively and percentage increase in 28 day compressive strength of the mix SP 20, SP 40, SP 60, SP 80 and SP 100 with respect to reference mix were 7.0%, 10.1%, 5.8%, 4.3% and 4.4% respectively. With PS balls content more than 40% of fine aggregates, even though the density of the concrete increased with increase in substitution for sand with PS balls, the compressive strength decreased. This decrease in strength may be attributed to the smooth surface of the PS

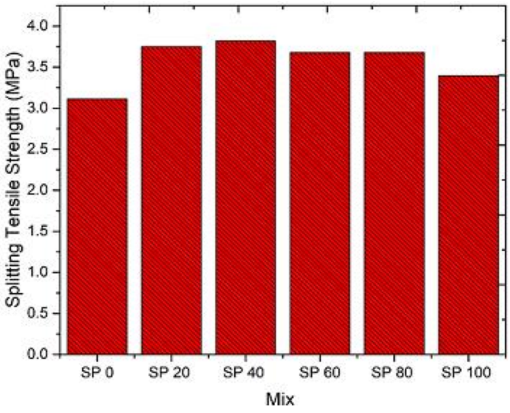

Fig. 12 Variation in splitting tensile strength for 28 days curing

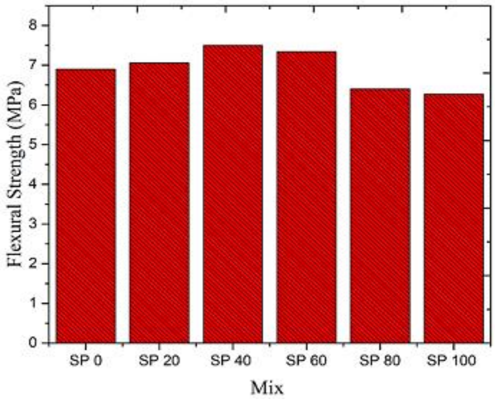

Fig. 13 Variation in flexural strength for 28 days curing

balls. No significant difference in the results of 28 and 90days curing, but 7 days curing results are comparatively very lower than the other two curing durations..

3.4 Splitting tensile strength

The concrete mixes with PS balls had higher splitting tensile strength compared to the control mixes. The concrete specimens containing PS balls exhibited brittle failure similar to that of the reference concrete. The percentage variation of split tensile strength of SP 20, SP 40, SP 60, SP 80 and SP 100 with respect to control mix was 20%, 22.8%, 18%, 18% and 9%, respectively. The tensile strength improved 1.18 to 1.20 times when replacement ratio ranged from 20% to 80%. Fig. 12 shows the variation in splitting tensile strength for different percentage of replacement of sand by PS balls.

3.5 Flexural strength

Both splitting tensile strength and flexural strength showed similar behavior to that of compressive strength with increasing trend till 40% replacement of sand by PS balls and decreasing trend afterwards. The decrease in strength may be attributed to smooth surface of PS balls.

The concrete mixes containing 80% and 100% fine aggregate as PS balls had lesser flexural strength than that of control mix. The percentage change of flexural strength

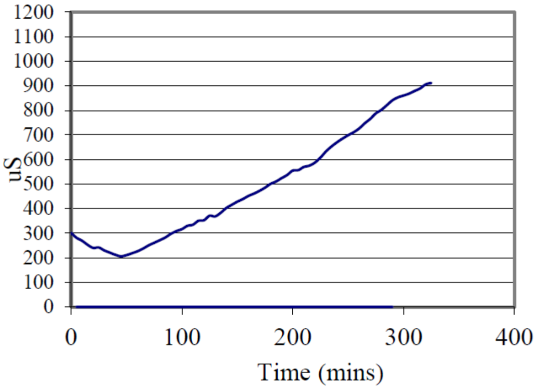

Fig. 14 (a) Conductivity time plot for SP 40 mix for 28 days curing

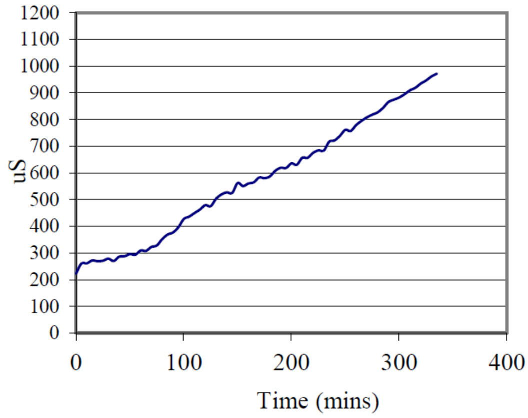

Fig. 14 (b) Conductivity time plot for SP 100 mix for 28 days curing

of SP 20, SP 40, SP 60, SP 80 and SP 100 with respect to control mix was 2.2%, 8.7%, 6.2%, -7.2% and -9.2% respectively. The variation in flexural strength for different percentage of replacement of sand by PS balls is shown in Fig. 13.

3.6 Permit-ion permeability test

The rate of conductivity at steady state was calculated for reference concrete, concrete with PS balls replaced as 40% of fine aggregates, and concrete with PS balls replaced as 100% of fine aggregates at the age of 28 days. The rate of conductivity of reference concrete with water cement ratio 0.4 is 3.33 micro Siemens per minute (mS/min), and for 40% and 100% replacement with PS balls is 3.06 and 2.47 mS/min, respectively. Lower the rate of conductivity, permeability of concrete will be lower, resulting in denser concrete with less voids and better durability. It is evident that the rate of conductivity decreases with the addition of PS balls as fine aggregates in concrete as shown in Fig. 14(a) and (b).

3.7 Microstructural analysis

SEM analysis was carried out on tested specimens of SP 100 mix, and the SEM images showed that the PS balls remained unaffected. Most of the PS balls did not break.

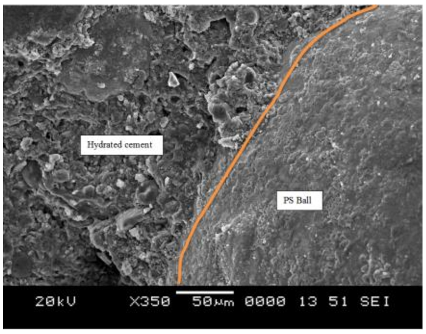

Fig. 15 (a) Interfacial zone

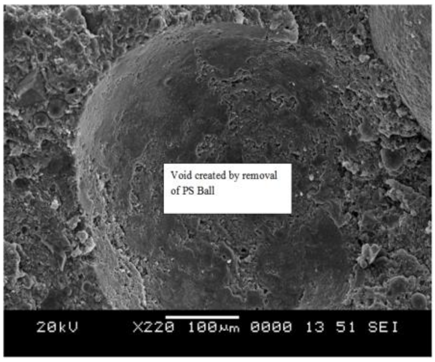

Fig. 15 (b) Void created by removal of PS balls

They were found either fixed to concrete or unattached from concrete as a whole. The surface after failure was found to be similar to the surface of PS balls before being added to concrete. Fig. 15(a) shows that there were no major cracks at the interface of PS balls and hydrated cement. Fig. 15(b) shows the image of void created by the removal of PS balls in concrete. It can be seen that the zone of contact between the PS balls and the hydrated cement paste is smooth. This may be a reason for lesser strength of concrete as PS ball content increases in concrete. When the load is applied, the concrete gives up near the surface of PS balls. Cracks will be formed and these cracks propagate. With higher PS ball content, more cracks will be formed at lower loads, leading to lower strength of concrete.

3.8 Correlation analysis

Pearson's correlation coefficient is a statistical measure of the strength of a linear relationship between paired data. In this study, curing days and compressive strength are the paired data sets. Correlation is an effect size which can describe the strength of the correlation and suggests for the absolute value of *r*. The compressive strength increased along with the increase in curing period for 7 days, 28 days and 90 days. The Pearson correlation coefficient values range from 0.722 to 0.753. Hence the results are shown in Table 6 with strong positive correlation between the two variables.

Table 6 Pearson correlation of curing days and compressive strength with respect to various % replacement levels of PS balls in concrete

Control Mix	
Pearson correlation	0.753
P-Value	0.457
20% replacement by PS balls	
Pearson correlation	0.74
P-Value	0.47
40% replacement by PS balls	
Pearson correlation	0.725
P-Value	0.484
60% replacement by PS balls	
Pearson correlation	0.738
P-Value	0.471
80% replacement by PS balls	
Pearson correlation	0.741
P-Value	0.469
100% replacement by PS balls	
Pearson correlation	0.722
P-Value	0.486

5. Conclusions

The following are the main conclusions drawn based on the test results obtained in this research study:

- It is possible to use PS balls as a fine aggregate in concrete in the condition as it is produced in the industry without any modification.
- The slump values increased with increase in PS balls content and this shows that PS balls can be used to produce better workable concrete at lower water content. With lower water content, higher strength can be obtained at an earlier age.
- In concrete incorporating PS Balls as fine aggregate, the quantity of superplasticizer to be used for obtaining a specific range of slump can be reduced, when compared to concrete with only sand as fine aggregate.
- PS Balls, due to their higher specific gravity, can be used to obtain high density concrete. High density concrete is useful in applications such as earthworks, breakwater blocks, foundations, road construction (Surface layer, sub base layer), radiation insulators, and other cases as applicable.
- The experimental study showed that, incorporating PS balls in concrete withstood higher compressive loads than conventional concrete, which is a useful property in various applications.
- The higher flexural strength of concrete containing PS balls is a very important parameter making it suitable to be used as pavement material. Higher flexural strength and higher density concrete is favourable for concrete pavements.
- With the addition of PS balls, the rate of conductivity decreases resulting in decrease in permeability of concrete leading to a more durable concrete.
- In general it was found that 40% of replcement with PS balls gives optimum results.

Overall, the possibility of substituting natural fine aggregate with PS balls, produced using slag, which is a waste produced in steel industries, offers environmental advantages.

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