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Rheological and Strength Behavior of Binary Blended SCC Replacing Partial Fine Aggregate with Plastic E-Waste as High Impact Polystyrene

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Abstract: Disposing electronic plastic waste into construction materials is an eco-friendly and energy efficient solution to protect the environment. This work is aimed at enhancing the strength of self-compacting concrete (SCC) replacing sand with electronic waste, namely, High Impact polystyrene (HIPS) plastic granules and cementitious material with fly ash. SCC is designed with the optimized binder content of 497 kg/m^3 using Fly Ash (30% by weight of cement) and 0.36 as water-to-binder ratio for all the mixtures. High Impact Polystyrene granules are replaced with sand up to 40% (by volume) at a regular interval of 10%. Rheological behavior is observed with the slump flow test for slump diameter, V-funnel test for flow time, and the L-box test for heights ratio, respectively. Strength behavior is studied by performing split tensile strength, and compressive strength tests after a period of 7, 28, and 90 days, respectively. Both fly ash and HIPS aggregate in addition to SCC up to 30% exhibits a minimal strength reduction with a promising performance in workability. Hence incorporation of both fly ash and HIPS granules up to 30% in SCC is a viable eco-friendly technique, with the beneficial economic impact on the construction industry.

Keywords: high impact polystyrene; fly ash; self-compacting concrete; strength; workability

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1. Introduction

Self-compacting concrete (SCC) is a widely spread feasible technique mainly characterized by its high fluidity to long distances and compacting on self-weight without any vibration. It is accepted across the world due to the excellent deformability and durability [1,2]. Aggregates in SCC do not segregate due to the achievement of moderate viscosity and a low yield stress in optimization of workability [3,4]. SCC can consume huge amounts of supplementary cementitious materials for replacing mainly cement to reduce the ill-effects of cement like thermal effects, drying shrinkage, porosity created by the leaching of calcium hydroxide etc., [5–9]. The strength of SCC is controlled by the composition of the cementitious material and water–cementitious ratio [10,11]. Water-cementitious content affects the strength than the total paste volume in SCC [12]. Mineral additive fly ash enhances SCC properties at low water to binder ratio mitigating the heat of hydration due to the high cement paste content [8,13]. Fly ash mineral composition is identical to cement and its pozzolanic reaction eliminates the growth of calcium hydroxide and transforms the calcium hydroxide into Calcium-Silicate-Hydrate (C-S-H) gel [14,15]. The higher the porosity, the more it is diminished by the migration of ions during hydration and the bond between paste and aggregate of the (ITZ) interfacial transition zone is improved. This pozzolanic action changes the hydration products in longer periods of curing [16]. Compressive strength of SCC containing Class F fly ash continued to increase with time [17].

Large amount of fly ash in SCC favors limited amount of micro cracking in ITZ and improves tensile strength of concrete with good bonding between paste and aggregate [18]. However, the thickness of the interface also depends on the aggregate's size and quantity [19]. Generally, SCC possesses high deformability with higher paste volumes, lower size, and moderate amount of coarse aggregate [9]. Since aggregate shortage problems exist around the world, enormous research is being carried out to identify the suitable substitute for aggregate in concrete with both environmental and ecological benefits. As part of this investigation, the possibilities of considering plastic waste as an aggregate were studied. Few researchers initiated their investigations by shredding available plastic content [20–25]. Interestingly, plastic waste proved its efficiency in enhancing fresh properties and strength retention of concrete at low level replacement with aggregates [20,26]. It is reported that the size and shape of the processed plastic particles influenced the properties of self-compacting concrete [24,25]. Polystyrene aggregate is termed as Building System Technology (BST) in Australia since it improves properties of concrete and generally applied as cement filler in the lightweight concrete. Performance of all fresh property tests in SCC tend to decline with the increase of polystyrene percentage. Densities of SCC represented moderate weights [27]. The huge difference in the densities between light weight aggregates and binders increases the segregation [28–30]. Sufficient viscosity-modifying admixtures (VMAs), low levels of SP, and the more binder content in SCC ensure the good flow-ability to suspend aggregates without segregation [3,27]. Fine particles in admixtures of SCC prevent aggregates from floating or sinking [4,20,27–30]. Increase in V-funnel flow times is observed due to incremental replacement of Light Weight Aggregate (LWA) [25,31]. Slump value is reduced with the replacement of sharp-edged plastic aggregates. Spherical shape of aggregates improves flow-ability with less internal friction and blocking of SCC [32]. Internal bleeding water surrounds the plastic particles due to non-absorption nature of plastic. This results in a poor bond between plastic aggregate and cement paste [33,34]. Compressive strength is directly related to the particle shape of light weight aggregate that also affects the bonding between aggregate and cement paste [26,35]. Splitting tension occurs through the weaker strength path of light weight aggregate rather than the cement paste of concrete [32]. The structural efficacy of SCC with waste plastic was lower than ordinary SCC due to the poor bonding between the cement paste content and plastic aggregates. Replacement of sand with polyethylene terephthalate plastic particles reduced the rheological, mechanical, and durability properties of SCC. Plastic particles decreased the compressive and flexural strengths of SCC mixtures [20]. It is also known that exposure of concrete to fire (or) elevated temperature has severe effects on the properties [36]. Few studies examined the lightweight SCC properties exposing to the prolonged high temperatures in comparison with the normal SCC [27,37]. Polystyrene aggregates exhibited less percentage of mass loss and the average mass loss at 100 °C, 300 °C, 600 °C, and 900 °C, respectively. It is observed that SCC performed better up to 30% BST replacement at elevated temperatures in the tests of modulus of elasticity, compression and tension. Peak strains were less in compressive stress-strain curves. Spalling observed was also minor at 900 °C. The concrete composite with expanded polystyrene granules showed good insulating properties but lowered compressive strength than the ordinary concrete [27]. Hence, concrete with plastic aggregates can be easily applicable in low strength bearing elements such as backfilling trenches, pavements, concrete bricks, and nonstructural elements like gutter, manhole, manhole cover, pipes of low-pressure flow etc. According to the Environmental Protection Agency 2015, recycling 3 million tons of plastic waste reduces 3.8 million tons of carbon dioxide emissions [38]. Plastic particle as an aggregate for light weight concrete production is an economical way of recycling waste in concrete technology [20]. The cost-effective analysis need not be considered for the fact that plastic aggregates in the matrix possess unique properties related with high ductility [39]. It is studied that the global consumption of construction aggregates is advanced to 51.7 billion metric tons in 2019 with an annual growth rate of 5.2 percent [40]. Therefore, it is essential to substitute aggregate with the suitable material to build sustainable constructions. SCC produced with the plastic waste can attain strength more than 35 MPa easily, though the compressive strength decreases systematically [25]. Self-compacting lightweight concrete is generally applied in large-span bridge structures in practical engineering due to some advantages identified such as ease of construction, light weight, lower noise level, less prone to fire and thermal attacks, and less consumption of man power etc., [24]. Hence in this work, it is investigated to identify the maximum extent of HIPS replacement for sand in SCC without affecting rheological and strength properties. M_{30} grade SCC behavior is studied by replacing cement with fly ash (30% by weight) and fine aggregate with varying percentages of electronic plastic waste (0–40% by volume).

2. Experimental Program

2.1. Materials

Cement: Ordinary 53 Grade Portland cement maintaining the BIS 12269-1987 standards and with the specific gravity of 3.15 was used in concrete.

Coarse aggregate: Coarse aggregates having the specific gravity of 2.7 and passing from 10mm and 12 mm sieves were used in the ratio of 60:40. Dry rodded unit weight of coarse aggregate used was 1656 kg/cum. Fineness modulus of coarse aggregate 20 mm and 10 mm are 6.98 and 5.86, respectively. Water absorption of coarse aggregate was 0.3%

Fine aggregate: River sand with the particle maximum size of 4.75 mm was used. The bulk specific gravity in oven dry conditions (OD) and water absorption of the sand as per IS 2386 are 2.60 and 1%, respectively. Fineness modulus of sand is 2.26. The bulk density of fine aggregate is 1609 kg/cum.

Plastic: High impact polystyrene (HIPS) granules of size ranging from 1.18–3 mm were used to replace fine aggregate partially. The specific gravity of sand was 1.04 and the surface of HIPS aggregate was smooth in surface texture and round in shape.

Fly ash: Class F Fly ash obtained from Narla Tata Rao Thermal Power Plant (Vijayawada Thermal Power Plant, Vijayawada, India), a specific gravity of 2.2 was used.

Water: Potable water according to IS 456:2000 was used.

Super plasticizer: Fosroc Conplast Super plasticizer 430 with a specific gravity of 1.22 was used. 0.9% of weight by cementitious material was used and the % of dry material in Super plasticizer was 40.

Viscosity Modifying Agent: Fosroc Viscosity Modifying Agent was used and the % of dry material in SP was 40.

2.2. Methodology

The methodology followed for optimization of materials in SCC is summarized as shown in Figure 1. SCC design criteria should satisfy the standards of European Federation of National Associations Representing for Concrete 2005 (EFNARC).

The following steps are considered during design of SCC:

1. Air content was assumed as 2% of the concrete volume.
2. The dry-rodded unit weight (DRUW) of coarse aggregate for a blend of 12.5 mm and 10 mm particles in 60:40 proportions was determined. The coarse aggregate content was calculated using DRUW.
3. Minimum coarse aggregate content of 28% was maintained by the percentage weight of total aggregate. Coarse aggregate can range from 28–34% for SCC mix.
4. Fine aggregate volume around 50% of the mortar volume was adopted. Mortar volume ranges from 66–72%.
5. The required paste volume in the range of 36–40% can be adopted in the concrete volume. 38% was used in the SCC mix.
6. Water/binder (w/b) ratios were finalized by performing rheological tests. The optimized binder (cementitious material) content was calculated replacing cement with fly ash by weight.

7. The dosages of super plasticizer (SP) and viscosity modifying agent were optimized for the obtained w/b ratio for reference mix using Rheological tests.
8. Sand is replaced with plastic waste HIPS ranging from 10–40% by volume and SP and VMA were finalized for better flow-ability.
9. Finally tests on the hardened properties were performed.

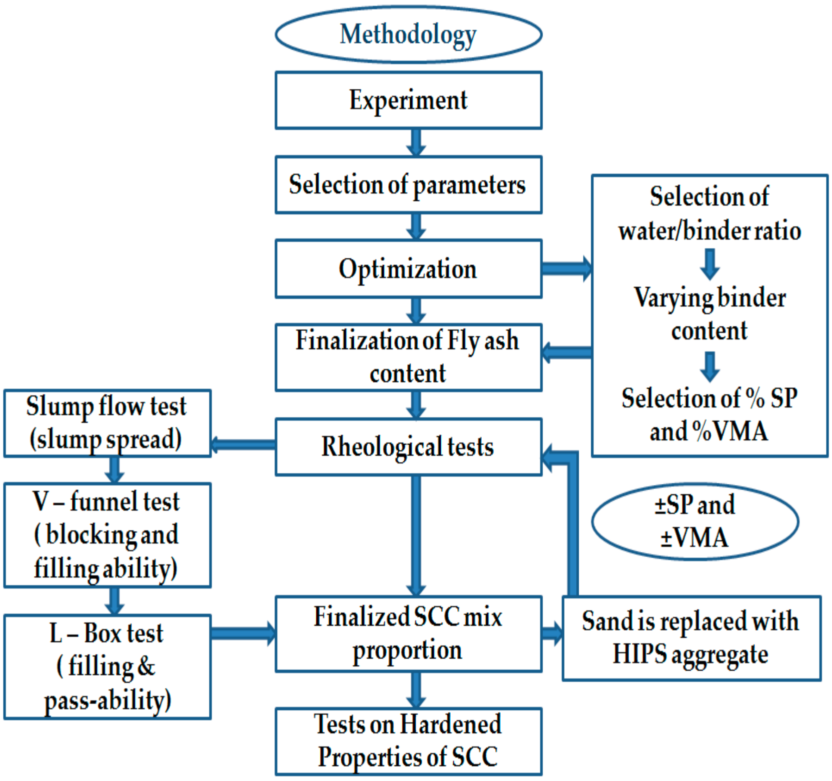

Figure 1. Methodology of self-compacting concrete (SCC) mix design.

2.3. Mix Proportions

Self-compacting concrete was designed as shown in Table 1 with the cementitious (binder) content of 497 kg/m^3 and the water to binder (i.e., cement + fly ash) ratio was 0.36 for all SCC mixtures. Coarse aggregates collected were 28.08% (by weight) passing from 12 mm and 18.72% (by weight) passing from 10 mm. Fine aggregate content used was 54.13% by volume. The concrete replaced cement with 30% fly ash was considered as the reference SCC. Fine aggregate was replaced with HIPS aggregates from 10% to 40% at a regular interval of 10%. SCC mix with both HIPS and fly ash showed the improvement in workability compared to the reference mix. The final mix proportions used in SCC mixtures were shown in Table 2.

2.4. Test Procedures

To study the rheological behavior of SCC, filling and passing abilities were tested by performing Slump flow, V-funnel, and L-box tests. Concrete was placed without any vibration into the molds of cubic (150 × 150 × 150 mm) and cylindrical (height = 300 mm, diameter = 150 mm) shapes. All the specimens were placed for curing in a water tank at 22 ± 2 °C until testing. Compressive and split tensile strength tests were performed after a period of 7, 28, and 90 days according to IS 516:2004 and IS 5816:1999, respectively.

Table 1. Design of self-compacting concrete and optimization of constitute materials.

Material Data				**Coarse Aggregate (CA) Optimization**			**Constituent Materials for Concrete**				
Material	**Specific Gravity**	**% Absorption**		**Material**	**% by Weight**		**Material (kg/m^3)**	**Initial**	**Adjusted**	**Per cum 0.0062**	**g/mL**
Cement	3.15	N/A		CA 10 mm	40		Cement	347.90	347.90	2.16	2156.90
				CA 12 mm	60						
Fly Ash	2.20	N/A		CA (kg/cum)	758.44		FA	149.10	149.10	0.92	924.42
CA 12mm	2.70	0.3		% of CA	28.09		Water	178.90	186.50	1.16	1156.50
CA 10mm	2.70	0.3					Sand	861.90	861.90	5.34	5343.80
Sand	2.60	1.0					CA 12 mm	455.00	455.00	2.82	2821.40
Input parameters		Concrete Mix proportions by volume (lit/cum)		Aggregate Proportions			CA 10 mm	303.30	303.30	1.88	1880.90
DRUW (kg/cum)	1656	CA	280.91	Material	% Vol	% Wt	VMA (lit)	0.99	0.99	0.01	6.16
% of CA in DRUW	45.80	Mortar	719.00	CA 12 mm	27.50	28.00	SP (lit)	4.47	4.47	0.03	27.73
% of Sand	46.10	Sand	331.50	CA 10 mm	18.30	18.70	Unit Wt.	2152	Total(kg)	13.39	13393
% of Fly ash	30	Paste	387.50	FA	54.10	53.10	Total quantity for slump test			6.09 Liters	
				Total	100	100					
Wt. Water/Binder	0.36	Total aggregates (kg/cum)		1620.35							
Binder (kg/cum)	497.00	Sand (kg/cum)		861.90							
SP (% wt. of binder)	0.90	Vol. Water/Powder		1.00							
VMA (% wt. of binder)	0.20	Paste composition									
% of Air content	2.00	kg/cum								lit/cum	
% of dry material (SP)	40	Cement		Fly Ash		Water	SP		VMA	Paste	
% of dry material (VMA)	40	347.90		149.10		178.90	4.47		0.99	382.60	

Table 2. Mix proportions with different % of High impact polystyrene (HIPS) aggregates in concrete.

Materials Used (Kg/m^3) for Water/Binder Ratio of 0.36								
HIPS (%)	Cement (Kg/m^3)	Fly Ash (Kg/m^3)	Coarse Aggregate (Kg/m^3)		Sand (Kg/m^3)	HIPS (Kg/m^3)	SP (mL)	VMA (mL)
			12 mm	10 mm				
0%	347.90	149.10	455.07	303.38	861.69	0.00	4.47	0.99
10%	347.90	149.10	455.07	303.38	776.18	34.48	4.65	1.00
20%	347.90	149.10	455.07	303.38	690.13	69.01	4.80	1.10
30%	347.90	149.10	455.07	303.38	603.85	103.51	4.83	1.12
40%	347.90	149.10	455.07	303.38	517.53	138.00	4.90	1.15

3. Results and Discussion

3.1. Properties of Fresh SCC

3.1.1. Slump Test Test

SCC design should fulfill the requirements for workability according to the European Federation of National Associations Representing for Concrete 2005 as mentioned in Table 3.

Table 3. Recommendations of European Federation of National Associations Representing for Concrete.

Slump Flow Classes	Slump Flow Diameter (mm)	Viscosity Classes	V-Funnel Time (sec)
SF1	550–650	VS1/VF1	≤8
SF2	660–750	VS2/VF2	9–25
SF3	760–850		
Passing ability classes			
PA1		≥0.8 with two rebar	
PA2		≥0.8 with three rebar	

3.1.2. Slump Test Test

Slump flow and slump loss in general reduces with the increment of plastic replacement in concrete. The shape of particles affects the workability. Spherical light weight aggregates enhance the flow-ability. High volume plastic replacement reduces the workability of SCC specimens [20]. Here in this study, fly ash proportion is optimized by replacing cement for better flow-ability as shown in Figure 2. In trial mixing, flow-ability without bleeding is observed at 0.36 and thus the w/b ratio is finalized. Slump flow diameter with HIPS aggregate replacement up to 40% in SCC is measured as shown in Figure 3. Both fly ash and HIPS enhances workability and super plasticizer maintains uniformity among the cohesive matrix. Super plasticizer contributes its effort for better fluidity and less slump loss of SCC. However, excessive addition can cause SCC to bleed and segregate. Due to spherical geometry of fly ash and HIPS particles, slump spread and slump retention capacity improved even at high volume replacement. However, the spherical shape and smooth surface of HIPS in high volume replacement make concrete non-cohesive due to less packing density among the matrix and excessive water among matrix bleeds. Since HIPS is hydrophobic, fly ash alone absorbs water in the matrix filling the voids. Slump diameter of SCC without HIPS is less and falls in the SF1 class. The water to binder ratio should be corrected before more sand is replaced. The non-absorptive nature of HIPS increases free water content in SCC and as a result fluidity increases [24]. SCC with HIPS ranging from 10–30% replacement satisfies the SF2 class and further replacement exhibits bleeding classified as the SF1 class. There is almost a maximum difference of 15% slump flow with and without

HIPS aggregate in SCC mixtures. Different plastic waste exhibited different slump flows as shown in Figure 4. Slump flow diameter of SCC satisfies SF2 class suits for the normal structural applications.

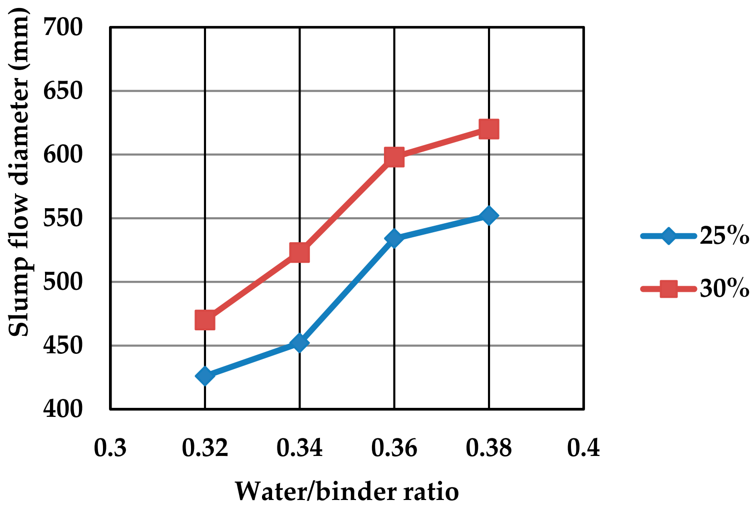

Figure 2. Slump flow variations at different fly ash proportions w.r.t w/b ratios.

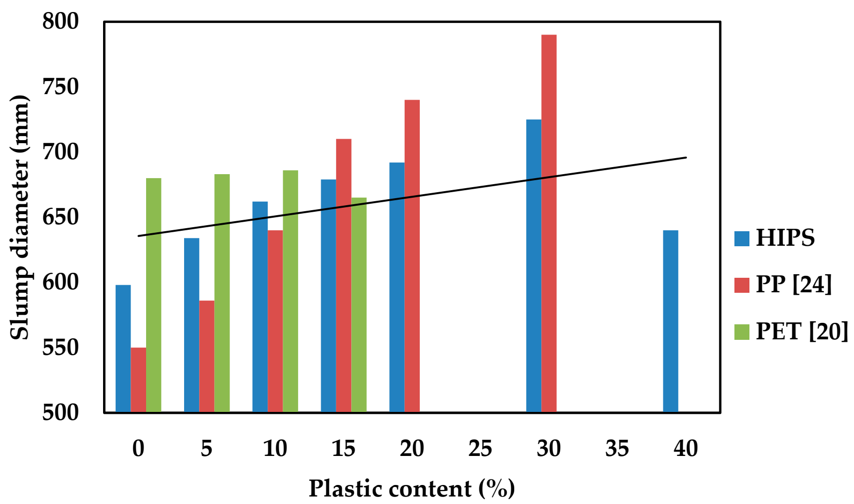

Figure 3. Slump flow variations with different plastic replacements for sand.

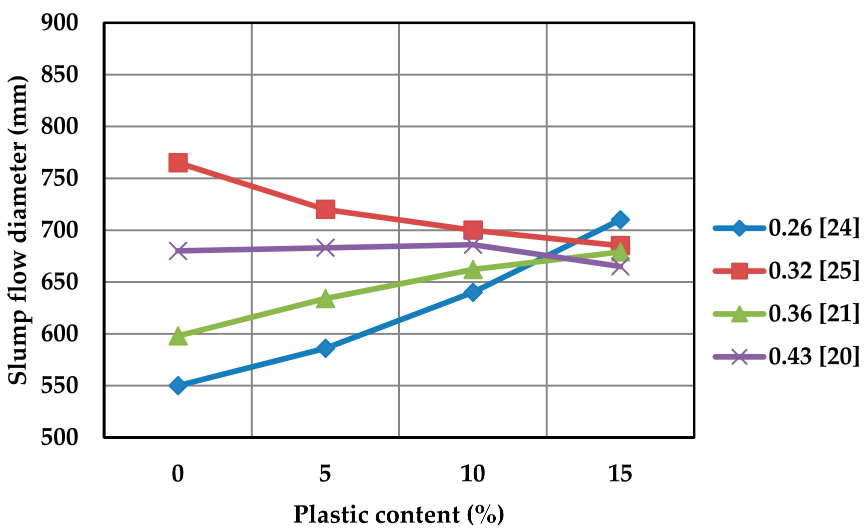

Figure 4. Slump flow variations with different w/c ratios.

3.1.3. V-Funnel Test

As the plastic replacement increases for sand, viscosity is reduced due to the non-absorption nature of the plastic. Irregular shape of aggregates increases the flow times systematically with the increment of plastic [20,24]. High volume replacement increases the flow times due to the shape of the particles but exhibited bleeding of SCC from 30% replacement onwards [24]. Here in this work, V-funnel flow times observed in all SCC mixtures are in the class of VS2/VF2 satisfying the criteria mentioned in EFNARC 2005. All the flow times are above 8seconds of time and exhibited a declined trend in flow time values up to 30% replacement. Spherical shape and smooth surface of HIPS enhanced flow times due to free water available in the matrix. SCC with high volume HIPS replacement showed bleeding and delayed flow time. There is a little separation of HIPS from concrete matrix due to bleeding and concrete has flown irregularly at high volume HIPS replacement from 40%. Flow times varying HIPS replacement in SCC mixtures is measured in V-funnel as shown in Figure 5.

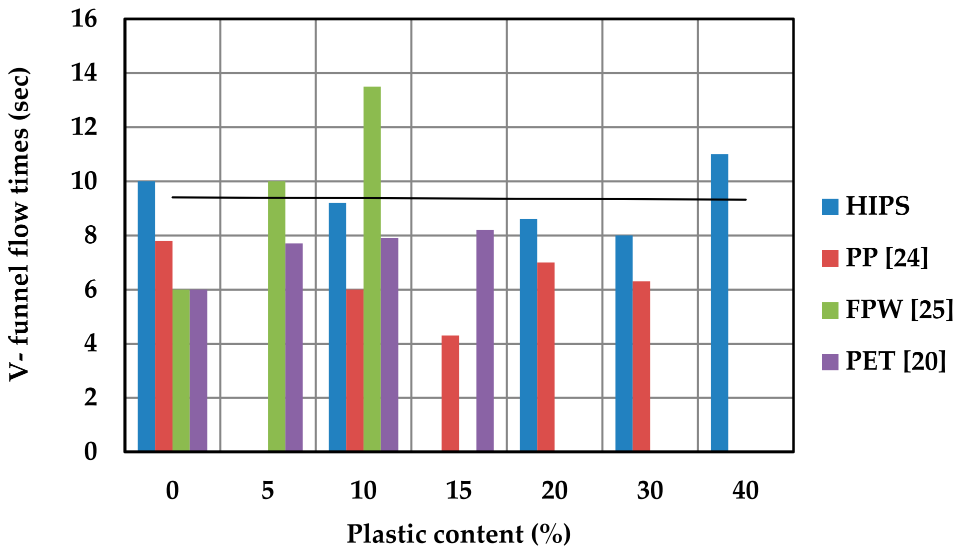

Figure 5. V-funnel flow time variation with different % of plastic content.

3.1.4. L-Box Test

All SCC mixtures with HIPS up to 30% reached the EFNARC standards as shown in Figure 6. Size of HIPS granules does not affect the heights ratio but increasing its content in SCC reduced the height's ratio [25]. SCC with fly ash and plastic waste exhibited decrease in the heights ratio but in the range of 0.8–1.0 [20]. As the replacement volume reaches 30%, gradual decrements in height variations at gates are observed. Incorporation of HIPS helped the free movement of SCC in support with fly ash and reached almost equilibrium level height at 30%. Concrete bleeds due to excess free water available and improper bonding among the matrix with further replacement after 30%. HIPS segregates and floats at the end gate showing drastic variation in heights. And hence, HIPS replacement up to 30% for sand is feasible to obtain better fresh properties.

In comparison to the literature survey, HIPS aggregate performs better than all other investigated plastic aggregates. Different plastics with different shapes and sizes were investigated but not successful in obtaining better rheological properties of SCC. As some researchers [24,25] reported the shape and size affects the rheological properties of SCC, the only reason for the better performance of HIPS in all their tests is due to the spherical shape. In this work, all SCC mixtures showed a good performance satisfying the criteria mentioned as shown in Figure 7a–c.

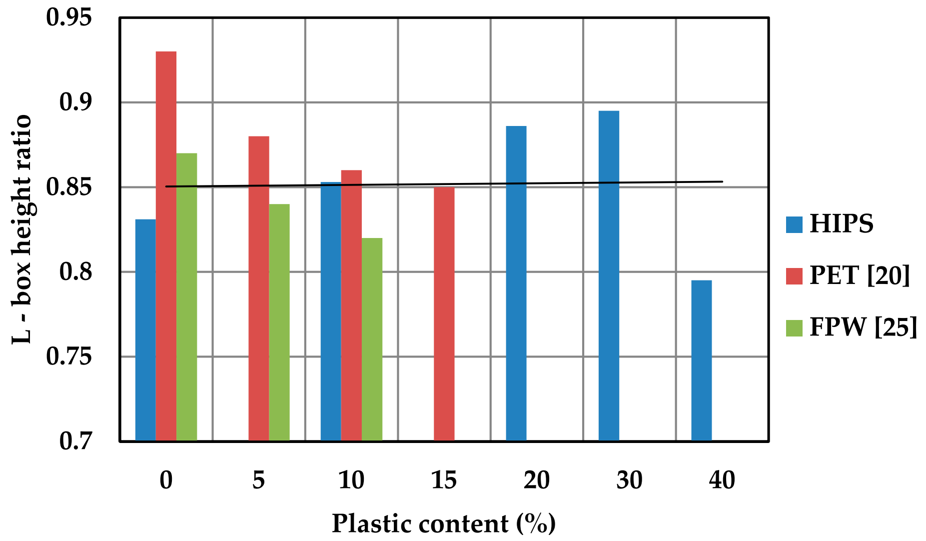

Figure 6. L-box height ratio of SCC at different % of plastic content.

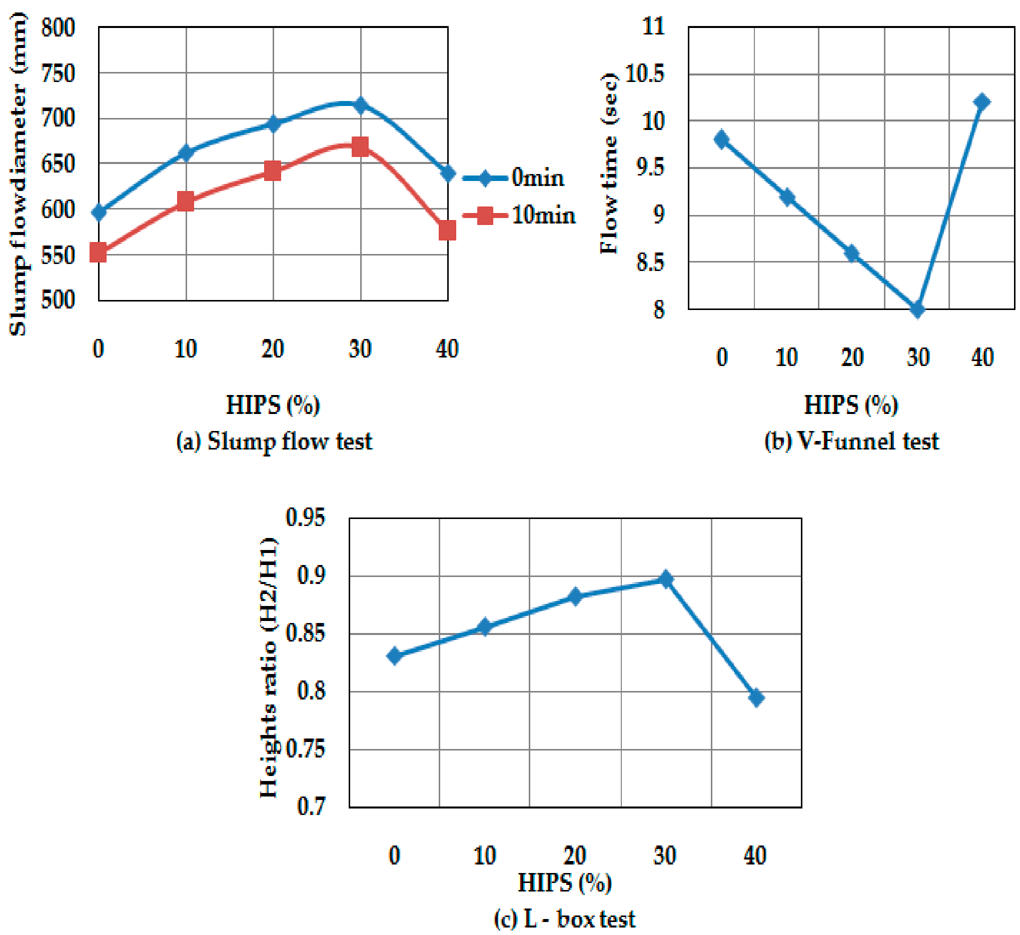

Figure 7. Rheological behavior of SCC with HIPS aggregates.

3.1.5. Density

SCC possesses more cement paste content and attains low density if supplementary cementitious materials are added. In this work, both cement and sand are replaced to reduce density and to enhance workability.

3.1.6. Fresh Density

The fresh density of all SCC concrete mixtures is measured at the time of concrete casting into the molds as given in Figure 8. Both fresh and dry densities were reduced as the plastic content increases in concrete due to the lower specific weight or density of plastic than sand [20,24]. The fresh density of SCC produced with 0.36 w/b ratio reduces with an increase in HIPS aggregates replacement (by volume) for sand. The fresh densities exhibited a linear decreasing trend and were reduced by 4.10%, 8.52%, 10.29%, and 15.08% with the use of HIPS in 10%, 20%, 30%, and 40%, respectively. Reason for density reduction of SCC is due to the density difference found between HIPS and fine aggregate as 60%.

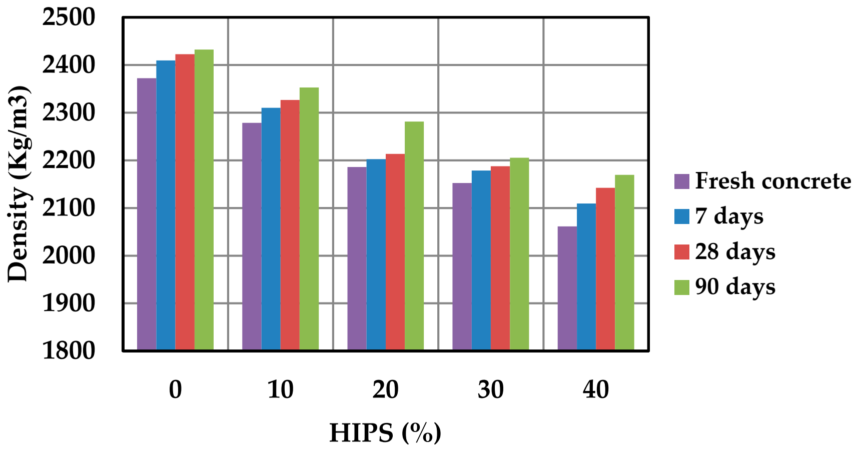

Figure 8. Unit weight variations with respect to HIPS (%) replacement for sand.

3.2. Properties of Hardened SCC

3.2.1. Dry Density

The densities of air-dried specimens were measured at the curing periods of 7, 28, and 90 days as shown in Figure 8. Dry densities were linearly reduced by 4.29%, 9.39%, 10.59%, and 14.22% with the use of HIPS in 10%, 20%, 30%, and 40% respectively at the age of 7days. In addition, they were reduced linearly by 4.12%, 9.45%, 10.73%, and 13.08% with the use of HIPS in 10%, 20%, 30%, and 40%, respectively, at the age of 28days. Similarly, 3.27%, 6.20%, 9.33%, and 10.80% were reduced compared to the reference concrete at the age of 90 days. SCC with HIPS showed a linear reduction in densities from 0–40% replacement of fine aggregate at all ages of curing. Since SCC absorbs water for hydration process and forms a high amount of C-S-H gel from 28 to 90 days, densities increase with the increase in curing periods. In SCC, Cement Paste Content (CPC) is high and so both cement and sand are replaced with a light weight material to reduce the density.

3.2.2. Compressive Strength

Compressive strength values at 7, 28, and 90 curing days are shown in Figure 9. In the current investigation, the compressive strength was linearly reduced with HIPS replacement from 10–40% at all curing periods. Since plastic is a soft material compared to sand, its replacement for sand leads to reduction of strength [25]. Since flow-ability increased up to 30%, the mix was compact and less porous at low percent HIPS replacement. At 40% replacement of HIPS, strength reduction was insignificant due to the less packing density among the matrix. Hence porosity and micro cracks at ITZ increased, even fly ash tried to fill the gap between plastic and matrix at high volume plastic replacement. Due to the reinforcing effect of fly ash in an interfacial transition zone, the addition of HIPS aggregate had a negligible negative effect up to 30% on strength. The pozzolanic reaction of fly ash in ITZ reduced crystals of Calcium Hydroxide and thus the density of transition region was increased by filling empty spaces due to the formation of high density C-S-H gel [24]. However, the smooth surface of HIPS granules in interfacial transition zone attributed to the poor bond strength with the cement matrix due to more plastic is available per volume of concrete [25]. The strengths decreased because of poor interfacial bonding between the plastic and matrix. The compressive strengths of SCC with HIPS were compared with reference SCC mix. They were reduced about 11.53%, 16.96%, 18.70%, and 39.23%, respectively, at the age of 7 days ranging from 10–40%. In addition, they were reduced about 2.64%, 4.80%, 6.73%, and 21.17% at the age of 28 days, respectively. Similarly at the age of 90 days, compressive strengths were reduced by 2.90%, 7.21%, 20.36%, and 32.71% with an increment in HIPS from 0–40% as shown in Figure 10.

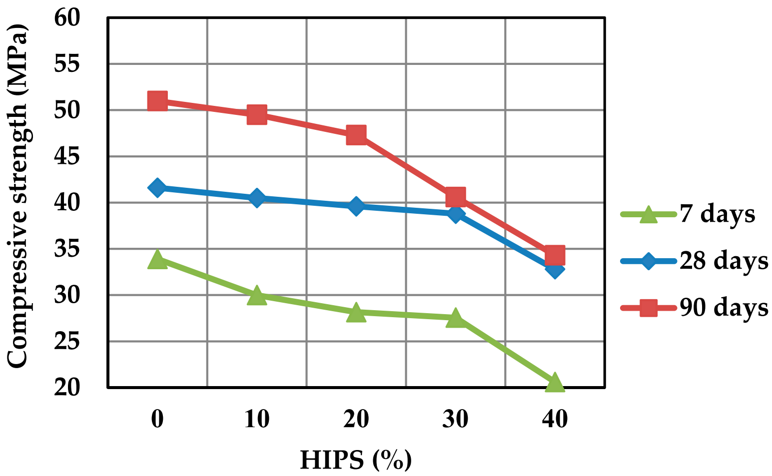

Figure 9. Compressive strength variation with % of HIPS aggregate.

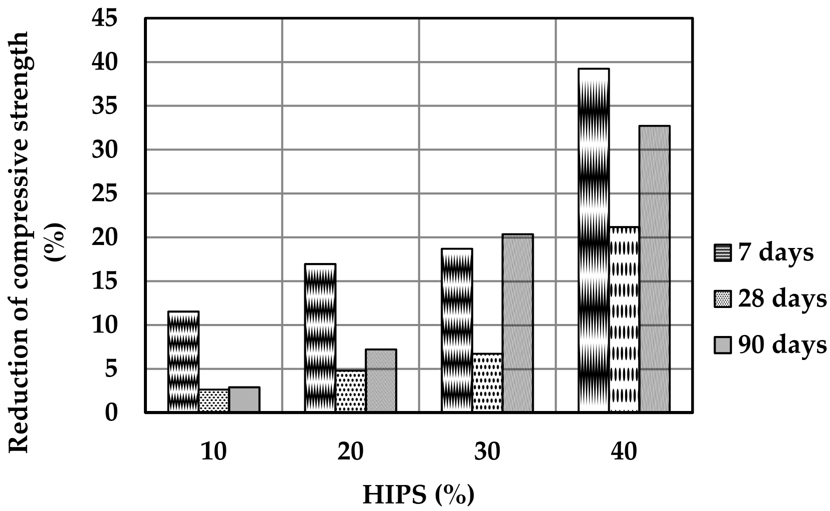

Figure 10. Graph represents % of reduction in compressive strength with varying % of HIPS.

3.2.3. Split Tensile Strength

Shape of the HIPS granules has a very significant effect on workability and the mechanical properties of SCC. Spherical particles improve SCC properties [24,25]. As shown in Figure 11, a descending tendency in split tensile strength is observed and it has to be considered majorly from 40% replacement. More free water gathered at ITZ and weakens bonding among the matrix. So, the poor adhesion at ITZ reduced split tensile strength because concrete fails in the tension zone [24]. HIPS separated out at the ultimate failure zone. Tensile strength with HIPS aggregates ranging from 10%–40% were compared with the reference mix and were reduced about 4.19%, 8.39%, 13.98%, and 26.57%, respectively, at the age of 7 days. Similarly, the strengths decreased by 5.73%, 8.30%, 11.46%, and 16.61%, respectively, at the age of 28 days. In addition, they were reduced about 3.61%, 9.63%, 15.66%, and 24.81%, respectively, at the age of 90 days in comparison with reference SCC mix. Material properties such as shape and size of HIPS affect the strength. However, specimens achieved the desirable strength up to 30% HIPS replacement even concrete fails in tensile strength.

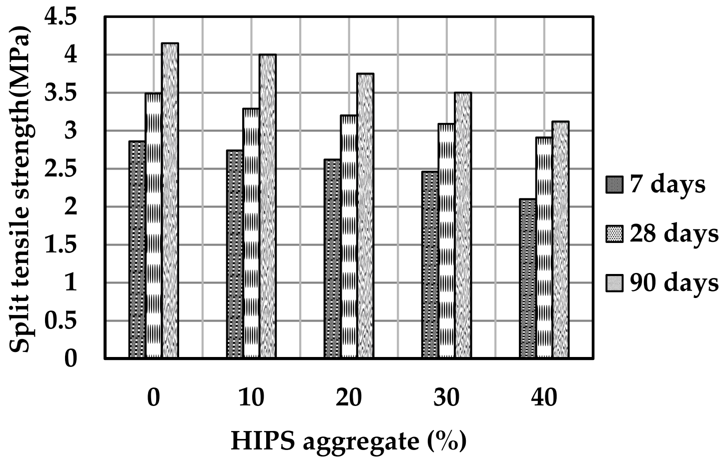

Figure 11. Split tensile strength variation with % HIPS aggregate.

Relationship between compressive strength and split tensile strength is obtained as shown in Figure 12. According to Neville, light-weight aggregate like plastic aggregate such as Polyethylene Terephthalate (PET) replaced for fine aggregate, the empirical relation is suggested as $f_t = 0.23f_c^{\ 0.67}$ at the curing period of 28 days [41]. The empirical relation obtained in this work is almost similar to the mentioned equation. The comminuted plastic waste strived for strength enhancement by attaining continuous gradation in the matrix. Hence the reduction of compressive strength is negligibly low up to 30% of HIPS replacement. The tensile strength fails through the weaker path created by poor bond between the aggregate and the paste. Therefore, the percentage of tensile strength reduction is comparatively a little higher than compressive strength reduction. The abrupt reduction of strength at 40% replacement would reduce the R square value though it is in range of fit 0.8-1.0. R square value range is replicating a good relation between compression and split tensile strength with the replacement of HIPS for fine aggregate.

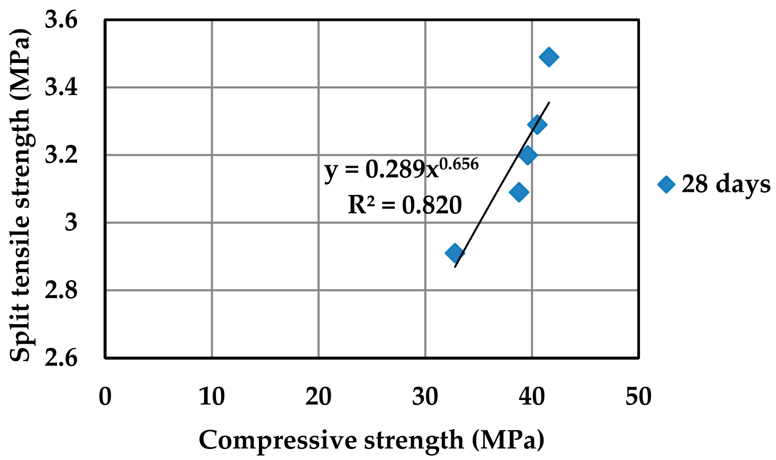

Figure 12. Correlation graph between compressive and split tensile strength.

4. Conclusions

An experimental investigation is carried out to determine the optimal percentage combination of fly ash and HIPS incorporation in SCC. The following are the conclusions drawn from the current investigation:

- All rheological properties are improved and satisfied EFNARC standards up to 30% of HIPS replacement for sand in SCC. HIPS spherical shape and smooth surface enhances the flow-ability.
- Density of SCC with HIPS is moderate, up to 30%, and reduces significantly replacing high volumes of fly ash and HIPS.
- Reduction of compressive and split tensile strengths are minimal (<20%) up to 30% HIPS replacement in SCC and achieved the desired strength of M_{30} grade concrete.
- It is a good accomplishment to say, replacement of both HIPS and fly ash up to 30% in SCC develops concrete equivalent to that of the reference concrete.

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References

1. ACI237R–07. *Self-Consolidating Concrete*; American Concrete Institute: Farmington Hills, MI, USA, 2007.
2. Al-Manaseer, A.A.; Dalal, T.R. Concrete containing plastic aggregates. *Concr. Int.* **1997**, *19*, 47–52.
3. Andiç Çakır, Ö.; Yoğurtcu, E.; Yazıcı, Ş.; Ramyar, K. Self-compacting lightweight aggregate concrete: Design and experimental study. *Mag. Concr. Res.* **2009**, *61*, 519–527. [CrossRef]
4. Aslani, F.; Ma, G.; Muselin, G. Development of high performance self-compacting concrete using waste recycled concrete aggregates and rubber granules. *J. Clean. Prod.* **2018**, *182*, 553–566. [CrossRef]
5. Guneyisi, E. Fresh properties of self-compacting rubberized concrete incorporated with fly ash. *Mater. Struct.* **2010**, *43*, 1037–1048. [CrossRef]
6. Jawahar, J.G.; Sashidhar, C.; Reddy, I.V.R.; Peter, J.A. Micro and macro level properties of fly ash blended self-compacting concrete. *Mater. Des.* **2013**, *46*, 696–705. [CrossRef]
7. Jawahar, J.G.; Sashidhar, C.; Reddy, I.V.R.; Peter, J.A. Effect of coarse aggregate blending on short term mechanical properties of self-compacting concrete. *Mater. Des.* **2013**, *43*, 185–194. [CrossRef]
8. Jawahar, J.G.; Sashidhar, C.; J, I.V.R.R.; Peter, A. Design of cost effective M25 grade of self compacting concrete. *Mater. Des.* **2013**, *49*, 687–692. [CrossRef]
9. Okamura, H.M.; Ouchi, M. Self-compacting concrete. *J. Adv. Concr. Technol.* **2003**, *1*, 5–15. [CrossRef]
10. Choi, Y.W.; Kim, Y.J.; Shin, H.C.; Moon, H.Y. An experimental research on the fluidity and mechanical properties of high strength lightweight self-compacting concrete. *Cem. Concr. Res.* **2006**, *36*, 1595–1602. [CrossRef]
11. Domone, P.L.J. Self-compacting concrete: An analysis of 11 years of case studies. *Cem. Concr. Compos.* **2006**, *28*, 197–208. [CrossRef]
12. Pineaud, A.; Cabrillac, R.; Remond, S.; Pimienta, P.; Rivillon, P. Mechanical properties of self-compacting concrete—Influence of composition parameters. In Proceedings of the Second North American Conference on the Design and Use of Self Consolidating Concrete and the Fourth International RILEM Symposium on Self-Consolidating Concrete, Chicago, IL, USA, 2 November 2005; pp. 863–868.
13. Kim, Y.J.; Choi, Y.W.; Lachemi, M. Characteristics of self-consolidating concrete using two types of lightweight coarse aggregates. *Constr. Build. Mater.* **2010**, *24*, 11–16. [CrossRef]
14. Kuroda, M.; Watanabe, T.; Terashi, N. Increase of bond strength at interfacial transition zone by the use of fly ash. *Cem. Concr. Res.* **2000**, *30*, 253–258. [CrossRef]
15. Xiong, G.; Liu, J.; Li, G.; Xie, H. A way of improving interfacial transition zone between concrete substrate and repair materials. *Cem. Concr. Res.* **2002**, *32*, 1877–1881. [CrossRef]
16. Scrivener, K.L.; Crumbie, A.K.; Laugesen, P. The interfacial transition zone (ITZ) between cement paste and aggregate in concrete. *Interface Sci.* **2004**, *12*, 411–421. [CrossRef]
17. Siddique, R. Properties of self-compacting concrete containing class F fly ash. *Mater Des.* **2011**, *32*, 1501–1507. [CrossRef]

18. Coppola, L.; Cerulli, T.; Salvioni, D. Sustainable development and durability of self-compacting concrete. In *Proceedings of the Eighth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*; American Concrete Institute: Farmington Hills, MI, USA, 2004; pp. 29–50.
19. Monteiro, P.J.M.; Maso, J.C.; Ollivier, J.P. The aggregate-mortar interface. *Cem. Concr. Res.* **1985**, *15*, 953–958. [CrossRef]
20. Sadrmomtazi, A.; Dolati-Milehsara, S.; Lotfi-Omran, O.; Sadeghi-Nik, A. The combined effects of waste Polyethylene Terephthalate (PET) particles and pozzolanic materials on the properties of selfcompacting concrete. *J. Clean. Prod.* **2016**, *112*, 2363–2373. [CrossRef]
21. Krishna, C.H.B.R.; Jagadeesh, P. Fresh and Hardened Properties of Self-Compacting Concrete Replacing Fine Aggregate with High Impact Polystyrene Plastic Granules. *Int. J. Civ. Eng. Technol.* **2018**, *9*, 831–838.
22. Krishna, C.H.B.R.; Jagadeesh, P. Compressive strength evaluation of eco-friendly concrete replacing sand partially with High impact polystyrene. *Int. J. Civ. Eng. Technol.* **2018**, *9*, 865–870.
23. Krishna, C.B.R.; Jagadeesh, P. Influence of Admixtures on Plastic Wastes in An Eco-Friendly Concrete a Review. *Int. J. Civ. Eng. Technol.* **2017**, *8*, 388–397.
24. Yang, S.; Yue, X.; Liu, X.; Tong, Y. Properties of self-compacting lightweight concrete containing recycled plastic particles. *Constr. Build. Mater.* **2015**, *84*, 444–453. [CrossRef]
25. Hama, S.M.; Hilal, N.N. Fresh properties of self-compacting concrete with plastic waste as partial replacement of sand. *Int. J. Sustain. Built Environ.* **2017**, *6*, 299–308. [CrossRef]
26. Senthil Kumar, K.; Baskar, K. Development of Ecofriendly Concrete Incorporating Recycled High-Impact Polystyrene from Hazardous Electronic Waste Journal of Hazardous. *J. Hazard. Toxic Radioact. Waste* **2014**, *19*, 04014042. [CrossRef]
27. Aslani, F.; Kelin, J. Normal and High-Strength Lightweight Self-Compacting Concrete Incorporating Perlite, Scoria, and Polystyrene Aggregates at Elevated Temperatures. *J. Mater. Civ. Eng.* **2018**, *30*, 04018328. [CrossRef]
28. Law Yim Wan, D.; Aslani, F.; Ma, G. Lightweight self compacting concrete incorporating perlite, scoria, and polystyrene aggregates. *J. Mater. Civ. Eng.* **2018**, *30*, 04018178. [CrossRef]
29. Aslani, F.; Ma, G.; Wan, D.L.Y.; Le, V. Experimental investigation into rubber granules and their effects on the fresh and hardened properties of self-compacting concrete. *J. Clean. Prod.* **2018**, *172*, 1835–1847. [CrossRef]
30. Bogas, J.A.; Gomes, A.; Pereira, M.F.C. Self-compacting light weight concrete produced with expanded clay aggregate. *Constr. Build. Mater* **2012**, *35*, 1013–1022. [CrossRef]
31. Abouhussien, A.A.; Hassan, A.A.A.; Ismail, M.K. Properties of semi-lightweight self-consolidating concrete containing lightweight slag aggregate. *Constr. Build. Mater* **2015**, *75*, 63–73. [CrossRef]
32. Gesoglu, M.; Güneyisi, E.; Ozturan, T.; Oz, H.O.; Asaad, D.S. Shear thickening intensity of self-compacting concretes containing rounded lightweight aggregates. *Constr. Build. Mater.* **2015**, *79*, 40–47. [CrossRef]
33. Saikia, N.; De Brito, J. Waste polyethylene terephthalate as an aggregate in concrete. *Mater Res.* **2013**, *16*, 341–350. [CrossRef]
34. Saikia, N.; De Brito, J. Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate. *Constr. Build Mater.* **2014**, *52*, 236–244. [CrossRef]
35. Yehia, S.; Alhamaydeh, M.; Farrag, S. High-strength lightweight SCC matrix with partial normal-weight coarse-aggregate replacement: Strength and durability evaluations. *J. Mater. Civ. Eng.* **2014**, *26*, 04014086. [CrossRef]
36. Koksal, F.; Gencel, O.; Brostow, W.; Lobland, H.E.H. Effect of high temperature on mechanical and physical properties of lightweight cement based refractory including expanded vermiculite. *Mater. Res. Innov.* **2012**, *16*, 7–13. [CrossRef]
37. Bozkurt, N. The high temperature effect on fibre reinforced self-compacting light weight concrete designed with single and hybrid fibers. *Acta Phys. Pol. A* **2014**, *125*, 579–583. [CrossRef]
38. EPA. *Advancing Sustainable Materials Management: 2013 Fact Sheet; 21 June 2016*; Environmental Protection Agency: Washington, DC, USA, 2015.
39. Alqahtani, F.K.; Khan, M.I.; Dirar, S.; Ghataora, G. Production of Recycled Plastic Aggregates and Its Utilization in Concrete. *J. Mater. Civ. Eng.* **2017**, *29*, 4016248.

40. Fredonia.IndustryStudy#3389, WorldC onstruction Aggregates. Available online: https://www.freedoniagroup.com/World-Construction-Aggregates.html (accessed on 1 March 2016).
41. Neville, A.M. *Properties of Concrete*, 5th ed.; Pearson Prentice Hall: England, UK, 2011.