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Combined Effects of Modified Polystyrene and Unprocessed Fly Ash on Concrete Properties Produced by a Novel Technique of Densification

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Abstract: The present study evaluated the effects of two types of waste materials of expanded polystyrene (EPS) and unprocessed fly ash (FA) on different properties of concrete. A novel technique of densifying waste EPS is used to produce a novel lightweight aggregate (LWA). The resistance to segregation of EPS particles improved in concrete by coating them with a binder. Nine different concrete mixtures with water to binder ratio (W/B) of 0.8 with varying amounts of waste materials as partial replacement of natural aggregates and Portland cement were prepared and tested. The properties of concrete investigated were workability, density, compressive strength, ultrasonic pulse velocity (UPV) and water absorption (WA) at different curing times. The results indicate that there is a decrease in compressive strength and UPV with increasing amounts of waste materials in concrete. However, with appropriate concrete mix design, the utilisation of these two waste materials is possible.

Key words: Compressive Strength · Concrete · Densification · Fly Ash · Recycling · UPV · Waste Expanded Polystyrene

INTRODUCTION

Research Background: Normal concrete is basically made of natural coarse aggregates, natural fine aggregates, Portland cement and water. Each one of these concrete primary ingredients, to a different extent, has an environmental impact [1]. Many by-products and solid recyclable materials can be used in concrete mixtures as aggregates or cement replacement, depending on their chemical and physical characterisation; thus concrete can become an environmentally sustainable material [2].

Most research [3-7] on concrete containing unmodified expanded polystyrene (EPS) has shown a decrease in the durability performance and the engineering properties of concrete with increasing the amount of EPS particles in concrete and an increase in strength with smaller EPS bead size in concrete. The studies [8, 9] on EPS concretes have also shown that mixtures produced using the ordinary vibration method will lead to a large number of particles floating upward and serious concrete segregation, resulting in EPS lightweight aggregate concrete (LWAC) with reducing its various performances. This is due to the ultra-light (up to 95% air) EPS particles and being quite weak. A great deal of research [6, 10, 11] has used superplasticisers to increase the workability of the concrete containing EPS particles; additives like these may not be environmentally friendly materials and readily available in developing countries.

In previous study [12], a new technique has been developed to achieve the recycling of waste EPS, with the aim of reusing the densified waste EPS called stabilised polystyrene (SPS) as aggregate in concrete. Also, the effects of SPS on different engineering properties of concrete have been investigated. The present experimental study was aimed at investigating the combined effects of the increasing incorporation of SPS as LWA and unprocessed FA as cementitious material on the workability, density, compressive strength and water absorption of different concretes. The correlations between the compressive strength and various investigated concrete properties are also presented.

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Table 1: Chemical composition of Portland cement and FA

	Values (%)	
Constituent	Fly Ash	Cement
Loss on ignition	23	1.5
Insoluble residue	-	0.5
Brightness	-	43
SiO_2	45.06	22.8
Al_2O_3	16.94	3.8
Fe_2O_3	9.04	1.4
CaO	1.96	66.5
MgO	1.02	0.8
SO_3	-	3.3
K_2O	1.40	0.7
Na_2O	0.34	0.1
Cl	-	<0.1
Flexural tensile strengths (28Days)	-	9.9(MPa)
Compressive strengths (28 Days)	-	75.5(MPa)

Table 2: Properties of natural and SPS aggregates

Properties	SPS aggregate	Natural aggregate
Bulk density (Kg/m^3)	457	1673
Specific gravity (SSD)	0.80	2.67
Water absorption 24h (%)	13.0	1.1

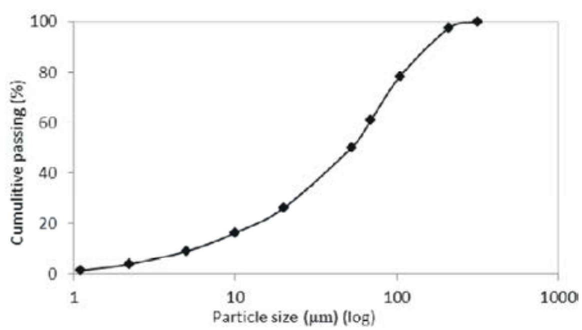

Fig. 1: Particle size distributions of unprocessed FA

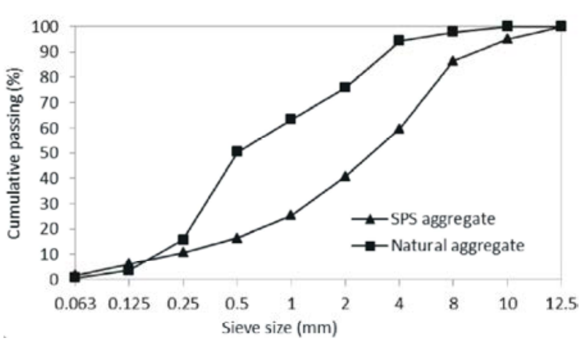

Fig. 2: Particle size distributions of natural and SPS aggregates

Experimental Details

Materials: The cement used was ordinary Portland cement Type I. The FA used was obtained from a local power station in the UK and was an unprocessed FA with high Loss-On-Ignition (LOI) of approximately 23%. LOI increases with the increase in unburned carbon content in FA. Unburned carbon particles have more surface area and porosity; hence, increase in water demand of the mixtures is expected. The chemical compositions of cement and FA are given in Table 1. The particle size distributions of FA are shown in Fig. 1. The natural aggregate used was a low-cost crushed limestone ranges between 0 and 8 mm in size conforming to the British standard requirements. The particle size distributions (sieving) details of natural and modified polystyrene called stabilised polystyrene (SPS) aggregates according to BS EN 933-1 [13] are presented in Fig. 2. The properties of natural and SPS aggregates are presented in Table 2. It is worth to mention here that, generally LWAs have high porosity resulting in higher water absorption (WA) compared with natural aggregates. In the case of SPS aggregate, due to the coating (10% clay & 20% cement) of EPS particles, WA of SPS is higher than natural aggregate and when mixed with water the value of volumetric paste content is increased.

Manufacturing Process of SPS Aggregate: The general description of the manufacturing process of this novel LWA is shown in Fig. 3. In order to improve the resistance to segregation of EPS particles, a new technique [12] has been used. The crushed waste polystyrene, clay and cement were mixed with water then formed into a "cake", which was then dried (cured in the controlled laboratory environment of 20 ± 2°C and 60-70% relative humidity (RH) for 14 days) and re-crushed into a novel LWA called SPS. A volume ratio of 7:2:1:1.5 (70% waste EPS: 20% Portland cement: 10% clay powder: water) was adopted. Although no detailed study was conducted on the effect of bond between binder (coating) and EPS; it was found that the aforementioned proportion has given the best results in terms of working with the materials and increasing the utilisation of waste EPS (i.e. maximises the amount of EPS for a suitable coating thickness, capable of enhancing bond strength, without using too much cement). The water to cement + clay ratio (W/(C+C)) was 0.75. The great cohesiveness of the binder at the time of wet mixing avoided the segregation of EPS aggregates.

Concrete Mixtures: Total of nine different concrete mixtures were made for this investigation. The control mixture (Mix 1) had a proportion of 1 (cement): 6 (Natural aggregate). The natural aggregate was replaced with 0, 60 and 100% (by volume) of SPS aggregate.

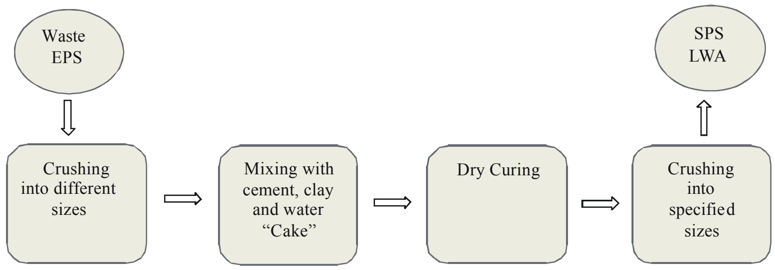

Fig. 3: Manufacturing process of SPS LWA

Table 3: Details of mixtures

W/B	Mix NO.	SPS (%)	FA (%)	Mixture Constituents Cement + FA (kg/m^3)	Water (kg/m^3)	NA (kg/m^3) + SPS (kg/m^3)	Slump (mm)
0.8	1	0	0	320+0	256	1920 + 0	8
	2	60	0	320+0	256	768 + 345	44
	3	100	0	320+0	256	0 + 575	25
	4	0	20	256+64	256	1920 + 0	5
	5	60	20	256+64	256	768 + 345	35
	6	100	20	256+64	256	0 + 575	20
	7	0	40	192+128	256	1920 + 0	3
	8	60	40	192+128	256	768 + 345	25
	9	100	40	192+128	256	0 + 575	15

The Portland cement was replaced with 0, 20 and 40% (by mass) of fly ash. The water to binder ratio (W/B) of 0.8 was used for all mixtures and no adjustment to the water content was made for mixtures incorporating FA. Superplasticiser has not been used in the present study to minimise cost. Further details about the mixtures are presented in Table 3.

Concrete was mixed in a planetary mixer of 100-litres capacity. First, SPS aggregate was wetted with 1/3 of the mixing water before adding the remaining materials. The workability of the fresh concretes was measured by slump-test according to BS EN 12350-2:2009 [14]. After casting, specimens were covered and left in the laboratory for 24 hours. Then, demoulding took place and specimens were placed in water for different curing times.

Testing Procedure

Compressive Strength: Cubes of 100mm size were used for the determination of compressive strength in conformity with BS EN 12390-3:2009 [15] at 1, 7, 28 and 360 days. A compressive strength test was carried out using a testing machine of 3000kN capacity at the loading rate of 0.6 MPa/s according to BS EN 12390-4:2009 [16].

Ultrasonic Pulse Velocity (UPV): Cubes of 100mm size were used for the determination of UPV values at 1, 7, 28 and 360 days. A UPV test was carried out according to BS EN 12504-4:2004 [17]. The pulse velocity was calculated from the formula:

$$V = L / T \qquad \text{(Eq. 1)}$$

where:

V is the pulse velocity, in km/s
L is the path length, in mm
T is the time taken by the pulse to transverse the 100mm length, in μs

Water Absorption: Prisms of 100×100×50mm size were used for the water absorption (WA) test. These specimens were cured in water until testing. Saturated surface-dry (SSD) prisms were kept in an oven at a lower temperature of 80 °C until a constant weight was attained. This is because EPS is extremely sensitive to thermal degradation when subjected to relatively high temperatures. These were then immersed in water and the weight gain was measured at regular intervals until a constant weight was reached. This normally took 48 hours. The absorption at 30 minutes and the final (total) absorption (at a point when the difference between two consecutive weights at 12h interval was almost negligible) were reported to assess the concrete quality. The WA is given by:

$$WA (\%) = 100 \times (W_s - W_d)/W_d \qquad \text{(Eq. 2)}$$

where W_s and W_d are the saturated and dry weight of specimens, respectively.

RESULTS AND DISCUSSIONS

Workability: The slump values for concretes containing varying amounts of SPS aggregates and FA is presented in Table 3. The slump values were between 3 and 44mm.

Effect of SPS Aggregate: The workability for the mixtures 1, 4 and 7 was just enough to be compacted and could also be finished, but all other mixtures were flexible and easy to work with and compaction and finishability were easy. The workability of the concretes increased with increasing the replacement level of SPS aggregate in concrete up to 60% then decreased for 100% SPS replacement. This was mainly due to the SPS aggregates high water absorption and lack of any superplasticiser, which would have improved the workability [8, 18 - 20]. It is worth to mention here that lightweight (low-density) concrete does not show as much slump as normal-weight (normal density) concrete with the same workability. The reason for this is that the effect of gravity is lower in the case of lighter aggregate [21-24].

Effect of FA: The slump values were in the range of 8-44mm for concrete without FA and decreased to the range of 3-25mm with 40% FA. It is well established that the use of FA in concrete reduces the water demand for a given workability and concrete containing FA will cause an increase in workability at a constant water-to-binder ratio [25]. However, due to the high unburned carbon content in FA used in the present study, which has more surface area and porosity and increases the water demand, the concrete's slump values decreased with an increase in unprocessed FA.

Density: The dry density of concretes which complies with BS EN 12390-7:2009 [26] containing varying amounts of SPS aggregates and FA is presented in Fig. 4. The density values were in the range of 1354-2185 kg/m^3.

Effect of SPS Aggregate: According to the results reported in Fig. 4, the density of concretes decreased with increasing the replacement level of SPS aggregate with natural aggregates [12]. This is because the density of SPS aggregates was much less than that of natural aggregates. According to BS EN 206:2000 [27] the LWC must have a dry density of not less than 800 kg/m^3 and not more than 2000 kg/m^3. Thus, the concrete containing 60% SPS and more can be considered as LWC depending on SPS replacement levels in concrete.

Effect of FA: Increasing the replacement level of FA with Portland cement had little effect on the density of concretes. The density of SPS concretes appears to decrease with an increase in the FA content. For example, the density of control mixture (0% SPS + 0% FA) was 2171 kg/m^3, which decreased to 2161 kg/m^3 with 40% FA content in concrete. A recent research [28] observed that the low density of LWAC containing FA is probably related to the higher air content and also partly to the amorphous structure of FA.

Compressive Strength: The compressive strength of concretes containing varying amounts of SPS and FA at different curing times is shown in Fig. 5. The compressive strength was in the range of 3-16 MPa at 28 day curing time and 6-20 MPa at 360 day curing age.

Effect of SPS Aggregate: There is a systematic decrease in compressive strength as the amount of SPS aggregate in concrete is increased. For example, at the age of 28-day of curing the strength for the control mix (0% SPS + 0% FA) is 16 MPa and this drops down to 11 MPa for the mix containing 60% SPS + 0% FA, which the decrease in strength is about 31%. The decrease in compressive strength of the concretes may be due to the lack of natural coarse aggregate. A previous research [4] reported that the concrete mixes containing coarse aggregate show increase in strength and slight increase in density. The decrease in compressive strength of the concrete may also be due to the replacement of natural aggregates with SPS and the resulting increase in the surface area of fine particles, which can lead to weakening of interfacial transition zone (ITZ) between the aggregates and the cement paste. Similar results have been reported elsewhere [7, 29]. A previous study [30] reported that the strength of LWAC depends on the strengths of the LWA used and the hardened cement paste, as well as the bonding of the aggregate/cement paste in the ITZ [31, 32]. As we know the density of concrete significantly affects the strength. The strength of SPS concretes increased with increasing the concrete density. A previous investigation [10] attributed the strength loss in EPS concrete to the lack of adhesion between EPS aggregate and the paste; unmodified EPS has almost zero strength but in the case of SPS (i.e. present work) and due to the coating of EPS particles the strength of SPS may be higher than unmodified EPS [12].

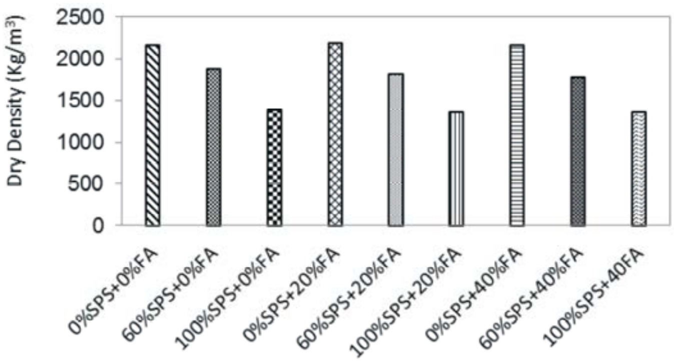

Fig. 4: Effect of SPS aggregate and FA on density of mixtures

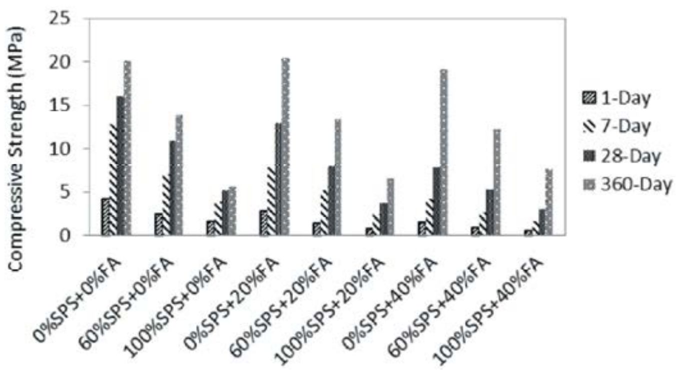

Fig. 5: Compressive strength of concretes containing varying amounts of SPS aggregate and FA

Table 4: Functional classification of lightweight aggregate concrete (Cylinder) (RILEM, 1978) [35]

Class	I	II	III
Type of lightweight concrete	Structural	Structural and Insulating	Insulating
Compressive strength (MPa)	>15.0	>3.5	>0.5
Oven-dry density (kg/m^3)	<2000	not specified	not specified
Coefficient of thermal Conductivity (W/mK)	-	<0.75	<0.30

Effect of FA: Similar to the results reported [33], the strength of control and SPS concretes in the present study decreased with an increase in the FA in concrete. For example, at the age of 28-day of curing the strength for the control mix (60% SPS + 0% FA) is 11 MPa and this drops down to 8 MPa for the mix containing (60% SPS + 20% FA), which the decrease percentage in strength is about 27%. Another study [34] reported that strength gain is expected to be lower in concrete containing a non-standard FA, as no processing has been undertaken. According to the compressive strength obtained in the present study, LWAC made with 60% SPS aggregates and up to 40% FA can comply with the Type II structural and insulating strength requirement of RILEM classification presented in Table 4. LWAC made with 100% SPS aggregate can comply with Type III concrete strength and insulating requirements.

Effect of Age: The percentage of 28 days' strength gain of concrete containing varying amounts of SPS aggregate and FA at different curing periods is presented in Fig. 6. The 100% SPS concretes containing 0, 20 and 40% FA have shown 75, 65 and 55% of 28-day compressive strength, respectively after 7 days. Furthermore, strength gains of almost 8, 44 and 60% more than that of 28-day strength for 100% SPS mixes containing 0, 20 and 40% FA respectively, have been obtained after 360 days' curing. That means the rate of strength gain at an early age decreased and after a long curing period increased as the FA content in SPS concretes increased (Fig. 6). The lower rate of strength gain in concretes containing FA may be due to the effect of FA's slow reactivity at early ages. Similar results have been reported earlier [5, 36, 37]. This is due to the typically low fineness of FA compared to cement and low pozzolanic activity of FA, which delays

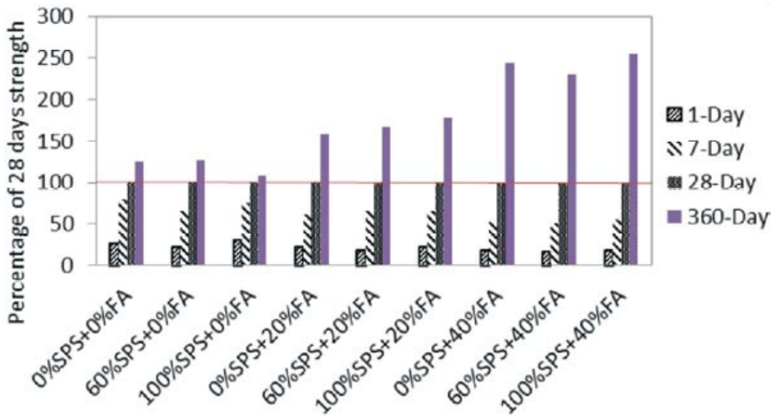

Fig. 6: Percentage of 28-day compressive strength gain with age

Fig. 7: Failure mode of control (left) and 100% SPS (right) concretes

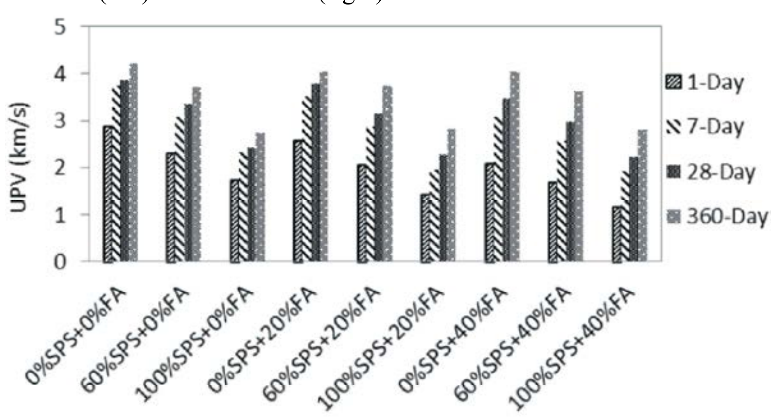

Fig. 8: UPV values of concrete containing varying amounts of SPS aggregate and FA

strength development [34]. The low pozzolanic activity is attributed to the high proportion of organic content as suggested by the high value of Loss of Ignition (23%). FA decreases the heat of hydration of concrete and needs a long curing period [33]. Calcium Silicate Hydrate (C_3S) is responsible for early strength development in cement. Therefore, when Portland cement is replaced with any pozzolanic material, the quantity of C_3S is reduced, resulting in lower early strength development.

Failure Mode: The failure mode of the concrete specimens containing SPS aggregates under compressive loading did not exhibit the typical brittle failure normally associated with control concrete. The failure observed was more gradual and compressible and the specimens were capable of retaining the load after failure without full disintegration (Fig. 7). This clearly shows the high energy absorption capacity of these concretes that was suggested earlier (4, 5, 11, 32, 38]. A recent research [39] reported that the compactness of between 15-35% reduction in thickness under compressive strength and dimensional recovery after load removing are two innovative aspects of waste plastic concrete. This is another advantage, for example, in joints where a certain amount of flexibility is necessary to absorb small load movements.

UPV: The UPV values of concrete containing varying amounts of SPS aggregates and FA at different curing times is presented in Fig. 8. The UPV values were in the range of 2.2-3.9 km/s at 28 days age and 2.8-4.2 km/s at 360 days age.

Effect of SPS Aggregate: The trend is similar to that of compressive strength, in that an increase in SPS aggregate in concrete leads to a decrease in UPV. The UPV values of the concrete containing 60% SPS + 0% FA at 28-day age decreased by 14% compared to the control mixture (0% SPS + 0% FA). It has been stated [40] that concrete with UPV values within the range of 3.5–4.5 km/s are considered as concrete with ''good'' quality. In the present study, concrete mixes 1, 4 and 7 can be considered as concretes with good condition and concrete mixes 2, 5 and 8 can be considered as concrete with satisfactory condition; while concrete mixes 3, 6 and 9 are of poor quality based on the UPV data.

The concrete mixes without FA exhibited an increase in UPV over time, the rate of which was higher in early ages of hydration and then started to stabilise. For example, the increase in UPV value for concrete (60% SPS + 0% FA) between the ages of 1 and 7 days was of 25% and between the ages of 28 and 360 days the increase was of 10%. The physical-chemical changes that occur in the concrete as a consequence of the hydration reactions over time progressively increase the strength and density of the material, favouring the propagation of the ultrasonic wave [41].

Effect of FA: As shown in Fig. 8, an increase in FA leads to a decrease in UPV. At 28-day age, control mixture achieved a pulse velocity of 3.9 Km/s, whereas concrete mixes (0% SPS + 20% FA) and (0% SPS + 40% FA) achieved a pulse velocity of 3.8 and 3.5 Km/s, a decrease of 3 and 10% respectively, in comparison with the pulse velocity of control mixture. The concrete mixes containing FA exhibited an increase in UPV over time, the rate of which was higher in early ages of hydration and then started to stabilise. For example, the increase in UPV value for concrete (60% SPS + 40% FA) between the ages of 1 and 7 days was of 35% and between the ages of 28 and 360 days the increase was of 17%.

Water Absorption: The 30 minutes and total WA of concrete containing varying amounts of SPS aggregates and FA at different curing times are presented in Table 5. The WA values at 30 minutes and total varied between 2.8-32.5% and 9.5-44.8% respectively, at 28 days of curing.

Effect of SPS Aggregate: The concrete with a higher volume of SPS aggregate, showed higher absorption. Since the non-absorbent EPS is the main material in SPS aggregate production, it mainly increased as a result of the combination of two factors: the highly porous ITZ between the EPS and the stabilising coating and; the highly porous coating of SPS aggregates in comparison to the new cement paste. This can be confirmed from the higher water absorption of low density concretes. In the case of SPS aggregate, due to the EPS coating (10% clay & 20% cement), WA of SPS is higher than natural aggregate and when mixed with water the value of volumetric paste content is increased.

According to the 30 minutes WA values and compared with the CEB [42] assessment criteria, LWAC containing 60% SPS aggregates, indicating an "average" quality concrete. In addition, mixes with 100% SPS percentages showed higher absorption values at the initial stage (30 minutes) and higher total absorption compared to the lower SPS percentage mixes.

A previous study [43] reported that the total WA for 28 days' age concretes incorporating diatomite natural LWA was between 30-65%. Another investigation [44] reported WA of 35% for LWAC containing 80% perlite aggregate content. In contrast, WA for the concretes made with SPS aggregate in the present study varied between 9.5-44.8%. Similar to the present study, the water absorption obtained at 30 minutes varied between 2.2-11.5% and total WA varied between 6.7-28.8% for concretes incorporating unmodified EPS aggregate [10]. This comparison was made only for LWACs with similar densities and cement content as in the present study.

Table 5: WA of concrete containing varying amounts of SPS and FA

	WA (%)							
	1 day		7 days		28 days		360 days	
Mix No.	30 min.	Total	30 min.	Total	30 min.	Total	30 min.	Total
1	8.45	9.59	4.22	9.72	2.82	9.46	2.63	8.49
2	17.29	18.53	11.56	20.09	7.54	18.55	7.06	16.16
3	36.09	37.87	34.97	41.48	28.49	40.12	19.35	35.86
4	9.41	10.15	7.46	10.39	5.05	10.08	3.54	7.89
5	18.75	20.09	15.01	20.16	10.93	19.83	7.91	14.71
6	39.98	42.65	39.52	43.70	30.98	42.89	18.37	31.08
7	10.03	10.67	9.00	10.72	6.44	10.52	2.60	6.75
8	19.61	20.94	18.53	21.26	13.11	20.67	5.99	13.64
9	41.84	45.02	42.70	46.27	32.49	44.78	16.99	29.97

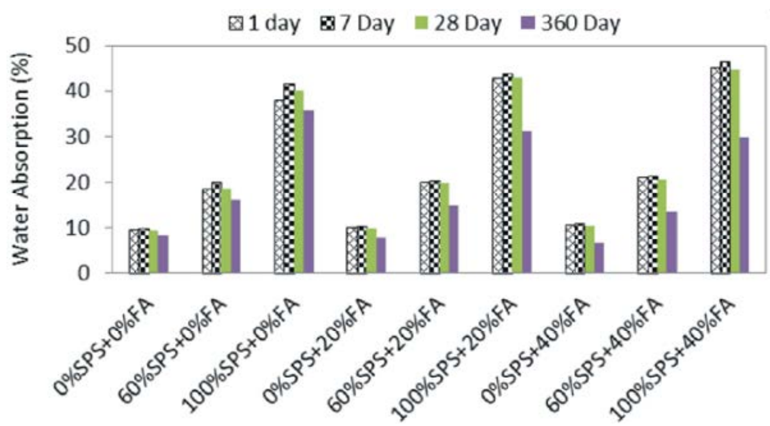

Fig. 9: WA at different curing periods

Effect of FA: The concrete containing FA showed considerably higher WA than the control mixture. The initial WA (30-minute) decreased with age. However, the total WA slightly increased at 7 days' age then slightly decreased at 28 days' age but sharply decreased at 360 days' age as shown in Fig. 9 and Table 5. At 28 and 360 days' ages, concretes containing different percentages of SPS aggregate and FA showed absorption ranging from 2.8 to 32.5% and from 2.6 to 19.3% at 30 minutes, respectively. The maximum reduction in WA was for concrete containing 100% SPS + 40% FA at long-term curing of 360 days' age. The WA of concretes increased with an increase in FA replacement levels at early ages and decreased after long-term curing. That means the rate of absorption at an early age increased and after a long curing period decreased as the FA content in SPS concretes increased. The higher rate of absorption in concretes containing FA may be due to the effect of slow reactivity of FA particles at early ages as has been reported earlier [36]. They reported that a high quality (classified or processed) FA can make positive changes in the pore structure of hydrated cementitious systems but in the case of unprocessed FA (i.e. present work) the results may be different.

The durability of concrete incorporating EPS particles may be comparable to the durability performance of higher density LWC produced by different types of porous LWA [11]. However, low density LWC with high WA may not be suitable for applications where durability and high resistance to water penetration, chloride performance and chemicals is required.

Correlation

Strength-Density-Volume: The correlation of compressive strength with density and percent volume of SPS + FA of 360 days' age concrete containing varying amounts of SPS aggregate and FA is presented in Fig.10. The strength of concrete containing varying amounts of SPS + FA appears to increase linearly with the increase in concrete density, or with the decrease in the SPS + FA volume.

$Y = 61.73X + 938.74$ $R^2 = 0.98$ (strength-density) (Eq. 3)

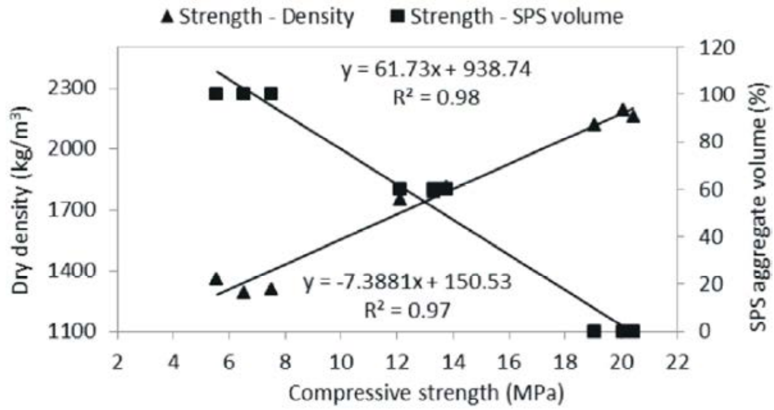

Fig. 10: Correlation of compressive strength with density and percent volume of SPS

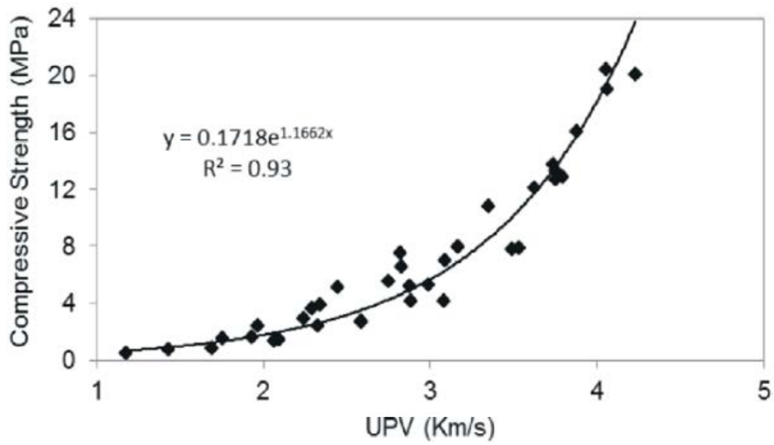

Fig. 11: Correlation between compressive strength and UPV

$Y = -7.3881X + 150.53$ $R^2 = 0.97$ (strength-SPS + FA volume)

(Eq. 4)

where Y is the density (kg/m^3) in strength-density correlation and SPS volume (%) in strength-volume correlation and X is the compressive strength (MPa).

The values ($R^2 = 0.98$ and 0.97) represent a very strong positive correlation between the two compared parameters of strength and density and a very strong negative correlation between strength and SPS + FA volume respectively.

Strength-UPV: The correlation between the compressive strength and UPV of concrete containing different amounts of SPS aggregate and FA is given in Fig. 11. Similar to the case of SPS concretes (without FA), an increase in UPV leads to an increase in compressive strength. An exponential function seems to better describe the correlation between strength and UPV for all concrete mixtures containing different replacements of SPS aggregate and FA at all curing times.

$Y = 0.1718e^{1.1662x}$ $R^2 = 0.93$

(Eq. 5)

It indicates a very strong positive correlation, where X is the UPV (km/s) and Y is the compressive strength (MPa). The proposed equation is based on the 36 experimental points from the present study. The previous study [33] suggested the relationship between the compressive strength and UPV of concrete incorporating FA with UPV values between 2.7-4.1km/s as $f_{cu} = 0.0142e^{0.0018V}$ with $R^2 = 0.96$. Another study [25] proposed the relationship between compressive strength and UPV values of concrete as $f_{cu} = 0.003e^{0.00217V}$ with $R^2 = 0.97$. However, he reported that the relationship seems to be independent of the FA content.

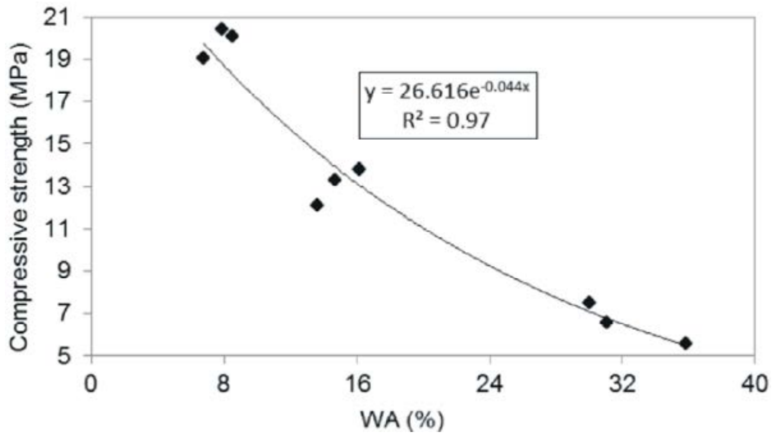

Fig. 12: Correlation between compressive strength and WA

Strength-Water absorption: The relationship between compressive strength and WA of 360 days' age concrete containing varying amounts of SPS aggregate and FA is presented in Fig. 12. The compressive strength of concretes appears to decrease with an increase in concrete water absorption as can be seen in Fig. 12. However, the experimental results obtained in the present research show that due to the slow reactivity of FA in concrete at early ages, the rate of absorption at an early age increased and decreased after a long curing period (360 days' age) as the SPS + FA content in concretes increased.

$$Y = 0.1718e^{1.1662x} \quad R^2 = 0.97 \qquad \text{(Eq. 6)}$$

where, Y is the compressive strength (MPa) and X is the water absorption (%).

The value (R^2 = 0.97) represents a very strong negative correlation between the two compared parameters of compressive strength and WA for the concrete incorporating different amounts of SPS aggregate and FA.

CONCLUSIONS

According to the literature there has been no studies that have investigated waste EPS using this original recycling technique of densification. The resistance to segregation of expanded polystyrene (EPS) particles in concrete improved by coating them with a binder. There is a tendency for the compressive strength, UPV and density to decrease and for the WA to increase when natural aggregate and Portland cement are replaced with the increasing amounts of SPS aggregate and fly ash, respectively. The level of decrease depends upon the replacement level of SPS aggregate and FA. For example at 28-day age the decrease percentage in strength and UPV for the mixture (60% SPS + 20% FA) is 50% and 19% respectively, in comparison with control mixture.

- LWAC made with 60% SPS aggregates and up to 40% FA can comply with the Type II structural and insulating strength requirement of RILEM (1978) classification presented in Table 4;
- LWAC made with 100% SPS aggregate can comply with Type III concrete strength and insulating requirements;
- LWAC containing SPS and FA can be used in different applications of the construction industry for low grade concretes and may be used to produce lightweight concrete bricks with low thermal conductivity.

If SPS aggregate is manufactured correctly, with appropriate concrete mix design, the utilisation of this novel lightweight aggregate made from waste Polystyrene and FA in lightweight concrete production is possible. However, more engineering testing needed to be done before the materials could be proven OK for use in civil engineering applications.

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