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Cement and Concrete Research 35 (2005) 1218–1223

Cement and Concrete Research

Properties of lightweight expanded polystyrene aggregate concretes containing fly ash

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Received 23 January 2004; accepted 1 November 2004

Abstract

Lightweight concretes can be produced by replacing the normal aggregates in concrete or mortar either partially or fully, depending upon the requirements of density and strength levels. The present study covers the use of expanded polystyrene (EPS) beads as lightweight aggregate, both in concrete and mortar. The main aim of this programme is to study the mechanical properties of EPS concretes containing fly ash and compare the results with these in literature on concretes containing OPC alone as the binder. The effects of EPS aggregate on the green and hardened state characteristics of concretes containing fly ash were evaluated. The compressive strength of the EPS concretes containing fly ash show a continuous gain even up to 90 days, unlike that reported for OPC in literature. It was also found that the failure of these concretes both in compression and split tension was gradual as was observed earlier for the concretes containing plastic shredded aggregates. The stress–strain relations and the corresponding elastic modulus were also investigated.

Keywords: Expanded polystyrene; Fly ash; Compressive strength; Splitting tensile strength; Modulus of elasticity; Stress–strain behavior

1. Introduction

Historically, lightweight concrete is used for both structural and non-structural applications. As a structural material it should have specific characteristics to meet the strength and performance requirements for the application. Thus, naturally, before recommending any material for a specific application (whether structural or non-structural) there is a need to study the mechanical characteristics to establish its suitability. In the case of lightweight aggregate concrete it was recommended that the compressive strength should be above 17 MPa for it to be useful as a structural concrete. Also, if the concrete is required for insulation purposes, the density of the concrete should be 800 kg/m^3 or lower [1].

Expanded polystyrene is a stable low density foam of non-absorbent, hydrophobic, closed cell nature [2,3]. It was reported that this can be used as ultra lightweight aggregate suitable for developing concretes for both structural and non-structural applications by varying its volume percentage in mortar or concrete [2–6]. Moreover the use of high volume fly ash as a supplementary cementitious material in concrete applications is very much preferred for economy and durability apart from the advantages that are related to the environmental aspects. At present block making industries are consuming reasonably higher volumes of fly ash to make it economical. But these blocks are highly absorbent, brittle and heavier having higher densities of around 1200 kg/m^3. The above drawbacks can be overcome by using the EPS concretes in the block making industry.

Presently a comprehensive investigation on the mechanical behavior of the EPS concretes containing a low cost mineral admixture like fly ash is not available, particularly, over a wide spectrum of concrete densities. In this study EPS concretes having a high volume fly ash content of 50% and with different percentages of EPS volume were developed to obtain concretes of different densities. Also

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doi:10.1016/j.cemconres.2004.11.015

literature suggests the hydrophobic nature of EPS aggregates in these mixes has to be compensated through bonding additives [4] or through the use of chemically treated aggregates [5]. However, in the present study no bonding additives were used. This paper provides new information on the strength characteristics of concretes of densities ranging from 550 to 2200 kg/m^3 through EPS replacement of the normal weight aggregate.

2. Mix proportions

2.1. Materials

Cement conforming to ASTM Type I which will also confirm to IS:12269 (C53 grade) and Class F fly ash were used as cementitious materials in the concrete mixes. The chemical characteristics of the cement and fly ash are given in Table 1. Sand finer than 2.36 mm with a fineness modulus of 2.8 was used. Normal coarse aggregate (crushed blue granite) passing through 8 mm sieve and retained on 2.36 mm sieve was also used in concretes of higher density. The normal weight aggregates were either sand alone or a combination of sand and normal coarse aggregate. Two types of beads Type A (4.75–8 mm) with mostly 6.3 mm size beads and Type B (1–4.75 mm) with mostly 4.75 mm sizes were used in concretes. The bulk density and specific gravity of these beads were 9.5 kg/m^3 and 0.014 for Type A and 20 kg/m^3 and 0.029 for Type B, respectively. A naphthalene-based superplasticizer and an air-entraining admixture were used to obtain a better workability and to avoid bleeding and segregation in the fresh state of the mix and also to produce mixes of flowable or flexible nature for the hand compaction adopted.

2.2. Mix proportions

Concretes were initially designed as per the recommendations of ACI-211.2 [7] and were modified by incorporating fly ash [8]. All the EPS concretes were designed with a fly ash replacement of 50% by weight of the total cementitious material. The details of the concrete mixes studied are presented in Table 2. The concretes were designed over a wide range of densities ranging from 550 to 2200 kg/m^3 with corresponding EPS replacements of the total aggregate ranging from 0 to 95%. Also, the mixes E13 and E22 have the same mix proportions (with 50% fly ash), except for the fact that E22 has 0% EPS and is used as reference concrete with fly ash for comparison. In addition, a normal concrete without fly ash (NC) made with 20 mm, graded normal coarse aggregate was also used for a comparison.

Table 1
Characteristics of the cement and fly ash

Chemical characteristics	Cement	Fly ash
Silica (SiO_2)	21.78	58.29
Alumina (Al_2O_3)	6.56	31.74
Ferric oxide (Fe_2O_3)	4.13	5.86
Calcium oxide (CaO)	60.12	1.97
Magnesium oxide (MgO)	2.08	0.14
Sodium oxide (Na_2O)	0.36	0.76
Potassium oxide (K_2O)	0.42	0.76
Sulphuric anhydride (SO_3)	2.16	0.15
Loss on ignition (LOI)	2.39	0.31

2.3. Production and casting

All the concretes were mixed in a planetary mixer of 100 l capacity in the laboratory. The mixing of materials was done in a specific sequence, by placing a part of the water with superplasticizer in the mixture and adding the dry EPS beads, which was thoroughly mixed for about 2 min to get the aggregates wetted with water and plasticizer. Then the remaining materials were added to the mixer and the remaining water was gradually added while the mixing was in progress. The mixing was continued until a mix of uniform and flowing nature was achieved. The fresh concrete densities and flow values were measured immediately after mixing for all the concretes. The flow table spread for all the concretes varied between 45 and 61 cm. The test specimens were cast with hand compaction only. The specimens were covered with wet gunny bags 10 h after casting, demoulded after 24 h and stored in water for curing until testing.

3. Experimental procedures

The unconfined compressive strength was obtained from 100 mm cube, at a loading rate of 2.5 kN/s at the age of 1, 3, 7, 28, and 90 days. The ultrasonic pulse velocity (UPV) and rebound hammer studies were conducted on 100 mm cubes tested at 90 days. Cylinders of 100×200 mm were used for splitting tensile strength study at the age of 28 days. Cylinders of 150 mm diameter and 300 mm height were used for stress–strain behavior and modulus of elasticity studies that were conducted at the age of 60 days. The specimens were fixed with a longitudinal compressometer, placed vertically between the platens of the compression testing machine and tested. This test confirms to ASTM C-469-94 for static modulus of elasticity of concrete in compression. All the specimens were kept in water until the time of testing and tests were carried out on saturated surface dry specimens.

4. Results and discussions

A comprehensive summary of compressive strength, split tensile strength, stress–strain behavior and elastic modulus of all these concretes is presented in Table 3. The performance characteristics of these concretes were reported elsewhere [9].

Table 2
Details of the fly ash—EPS mixes investigated

S. no.	Name[a]	Cement, c (kg/m^3)	Fly ash, f (kg/m^3)	$w/(c+f)$ ratio	Percentage wt. of aggregates in TA			% of EPS in total volume	CA size (mm)	Flow values (cm)
					Sand (%)	CA (%)	EPS (%)			
1	E57	142	142	0.651	5.5	–	94.5	66.5	–	–
2	E76	190	190	0.487	10	–	90	58	–	45
3	E95	224	224	0.413	20	–	80	49	–	53
4	E124	247	247	0.434	20	16	64	38	8	61
5	E153	274	274	0.412	20	30	50	28.5	8	55
6	E182	309	309	0.396	20	50	30	16.3	8	54
7	E220	247	247	0.455	20	80	0	0	8	56
8	NC	319	0	0.58	31	69	0	0	20	43.5

CA—normal coarse aggregate; TA—total aggregate.
[a] E representing the EPS mix and the number (s) representing density of the concrete.

4.1. Fresh concrete

All the EPS mixes showed better flow values compared to the normal concrete at similar water cement ratio and also no segregation was observed in any mix even though the concretes were made without the addition of bonding additives. No flow value was observed in the E5 mix, it may be due to lack of cementitious paste to flow. Also, it was noted that the EPS aggregates are compressed during the mixing operation and the resulting densities of concrete are generally higher than the designed densities by about 50–100 kg/m^3. This effect was noted more in mixtures containing normal coarse aggregate. The flow values of all these concretes are given in Table 2.

4.2. Compressive strength

The variation of the compressive strength with age shows that there is a continuous increase in the compressive strength up to 90 days. A comparison of the variation of compressive strengths with different volume percentages of EPS at the age of 7, 28 and 90 days were given in Fig. 1. It is to be noted that in 50% fly ash mixes, the percentage increase of strength at 7 days is about 50% of 28 days strength (with about 50% and 75% of 90 day strength in 7 and 28 days). In contrast, Cook reported (1983) that EPS concretes develop almost 95% of the 28 day strength in 7 days, compared to the 70% for normal weight concrete. The rate of strength gain with age for silica fume concretes was increasing with increase in silica fume percentage reported elsewhere [10] as reported for OPC concretes by Cook. This lower rate of strength may be due the effect of slow reactivity of fly ash at early ages.

The low density mixes showed higher strength gain rates at later ages (28 to 90 days), whereas in the higher density mixes the strength increase at the initial ages (7 to 28 days) is higher. This variation may be due to the higher cement contents in the higher density mixes than the low density mixes. Also it was observed that the strength is decreasing with the increase of EPS percentage and with an increase in water cement ratio, similar to the normal concretes. The variation of compressive strength at 90 days with fresh density was given in Fig. 2. It can be seen that the compressive strength is increasing with an increase of density and these concretes showed power relationship unlike the linear relationship reported for the EPS concretes containing silica fume [10].

Table 3
Strength characteristics of EPS concretes

Sl. no.	Name[a]	Fresh density (kg/m^3)	Compressive strength (MPa)					$f_t^{b,c}$ 28 days (N/mm^2)	UPV[d] (km/s)	RN[e]	Depth[f] of com. (mm)	E^c (MPa)
			1 day	3 days	7 days	28 days	90 days					
1	E57	582	–	–	0.62	1.1	1.5	–	–	–	–	–
2	E76	779	–	1.50	1.9	2.3	3.6	0.64	2.29	–	–	2.100
3	E95	984	–	2.30	2.9	3.83	5.9	0.89	2.67	16.8	82	4.33
4	E124	1304	1.00	2.60	3.7	6	7.4	1.15	2.84	20.4	151	8.45
5	E153	1484	1.30	2.70	4.2	7.8	11.6	1.40	2.968	24.6	200	9.00
6	E182	1723	1.60	4.20	5.96	12.5	16	2.04	3.257	27.8	260	16.00
7	E220	2215	4.00	5.20	11.6	18.4	23.4	2.34	3.61	30.2	300	23.43
8	NC	2578	12.6	21.8	31	43	44.5	3.63	3.84	42.6	–	–

[a] E representing the EPS mix and the number (s) representing density of the concrete.
[b] Split tensile strength.
[c] Modulus of elasticity.
[d] Ultrasonic pulse velocity.
[e] Rebound number.
[f] Average depth of compression from top surface.

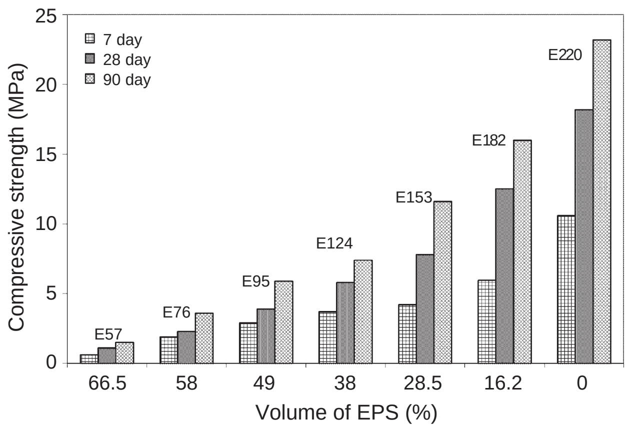

Fig. 1. Variation of compressive strength with age and EPS volume.

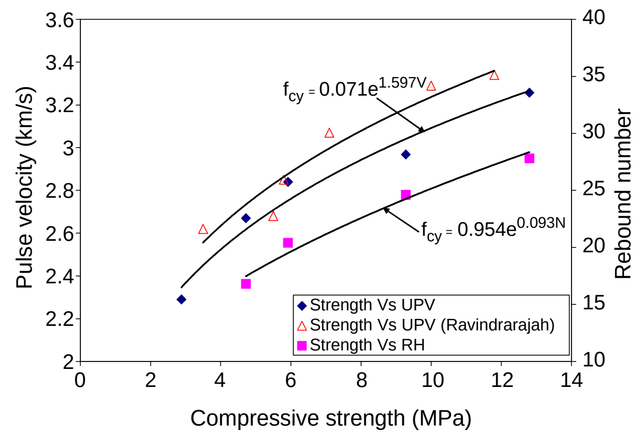

Fig. 3. Variation of compressive strength with pulse velocity and rebound number.

4.3. Compressive strength vs. ultrasonic pulse velocity and rebound number

The variation of the cylinder compressive strength (assumed as f_{cy}=0.8 times the cube compressive strength) and UPV is given in Fig. 3. The relation between the cylinder compressive strength and UPV (V) for the EPS concretes (having the densities ranging from 1150 to 1350 kg/m^3 and the strengths ranging from 3.5 to 12 MPa) made with BST coated aggregates (f_{cy}=0.12e$^{1.36V}$) suggested by Sri Ravindrarajah and Tuck was also incorporated in the same plot. It can be observed that, in general, the suggested equation is slightly over estimating the pulse velocity values for a given strength and, in particular, for the higher density concretes compared to the results of EPS concretes containing 50% fly ash. The proposed equation based on the results of the present study, the relationship between the cylinder compressive strength and the UPV (r=0.973) is given by

$$f_{cy} = 0.071e^{1.597V} \tag{1}$$

The variation of cylinder compressive strength and rebound number (N) was also given in Fig. 3. The proposed equation for the relationship between the cylinder compressive strength with the rebound number (r=0.989) is given by

$$f_{cy} = 0.954e^{0.093N} \tag{2}$$

The results indicate that both the UPV and the rebound values increase as the strength of the concrete increases.

4.4. Split tensile strength

The variation of splitting tensile strength (f_t) with both cube compressive strength was plotted in Fig. 4. It can be observed that as the tensile strength is increasing the compressive strength is also increasing. It was also observed that the equations suggested for relationship between splitting tensile strength compressive strength of the normal weight concrete (f_t=0.2$f_{cy}^{0.7}$) [11] and lightweight concrete (f_t=0.23$f_{cu}^{0.67}$) [12] were underestimating the splitting tensile strengths for the EPS concretes. The proposed equation (r=0.995) based on the results of these concretes is given by

$$f_t = 0.358 f_{cu}^{0.675} \tag{3}$$

While testing it was observed that the concretes with higher EPS volumes showed that there was no splitting like

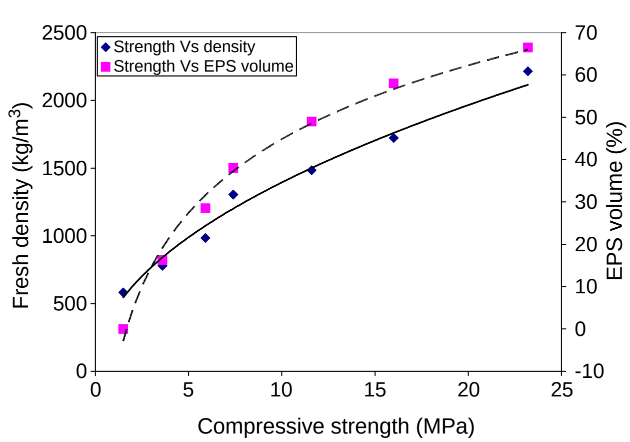

Fig. 2. Variation of compressive strength with density and EPS volume.

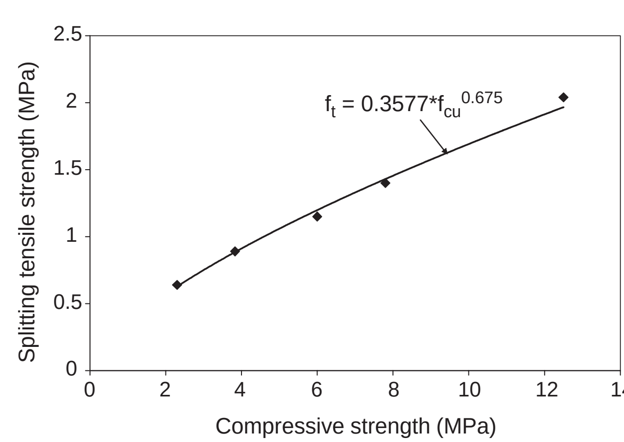

Fig. 4. Variation of splitting tensile strength with compressive strength.

that for normal concretes and indicated only a local failure. In case of normal concrete, the testing specimen was separated into two pieces after splitting, whereas in EPS concretes separation was not observed in any concrete.

4.5. Stress–strain behavior

The results of the studies on stress and strain are plotted in Fig. 5. The variations show that as the strength level increases the concretes fail at lower strain levels (i.e., the deformability of these materials were lower). Also, the steepness of the stress–strain curve increases, when the percentage volume of EPS decreases. While testing it was observed that the failure was more gradual, depending on the EPS aggregate content in the concretes. In case of the higher EPS aggregate concretes (lower density concretes) the failure was more ductile compared to the lower EPS concretes. It was also observed that the ultimate load was sustained by the specimen with increasing strain for some time.

The failure modes of the EPS aggregate concretes for different EPS volumes are given in Fig. 6. It can be seen that the concrete with 0% EPS volume (E220) exhibited cracks for full height of the specimen (300 mm); whereas E95 concrete containing about 50% EPS aggregate affected only 82 mm height from top surface of specimen. It can also be observed that the length of propagation of cracks increases with decrease in EPS volume. The average propagation length of cracks for different concretes is given in Table 3. The failure modes of these concretes indicate that EPS aggregate concretes show only local failure and behave like cushioned and energy absorbing materials. While testing the lateral bulging was observed in the failure zone of the specimens.

The resulting failure was found to be more ductile (more compressible manner) in compression, splitting tensile and

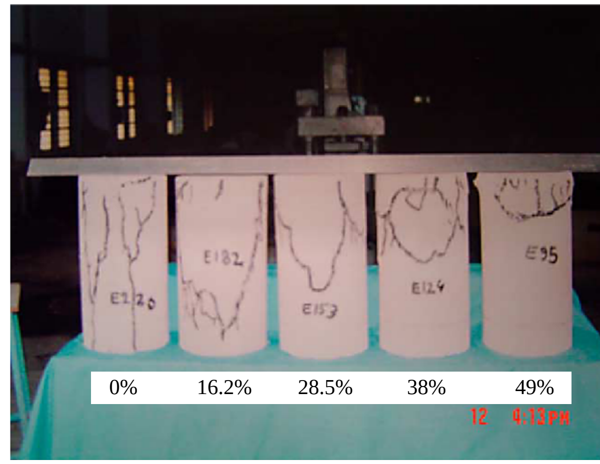

Fig. 6. Failure modes of EPS concretes containing different volumes of EPS.

stress–strain tests when the percentage of EPS aggregate was increased, as were earlier reported for EPS concretes [10] and for plastic shredded aggregate concretes [13].

4.6. Modulus of elasticity

The relationship between modulus of elasticity and cylinder compressive strength of the EPS concretes is shown in Fig. 7. It can be observed that the modulus of elasticity increases with an increase in cylinder strength. The secant modulus value was seen to be decreasing and this decrease was found to be about 40% for every 10% increase in the EPS volume.

Pauw [14] suggested a generalised equation for secant modulus (for both lightweight and normal weight concretes) as $E\!=\!0.043\gamma_{\mathrm{w}}^{3/2}f_{\mathrm{cy}}^{1/2}$ where γ_{w} is the air dry density (kg/m^3) and f_{cy} is the cylinder compressive strength (MPa). Later Perry et al. (1991) and Sri Ravindrarajah and Tuck reported that for concretes with EPS aggregates the above relation underestimates the modulus and gave the relations to be $E\!=\!0.07\gamma_{\mathrm{w}}^{1.53}f^{1/4}$ and $E\!=\!1.146\gamma_{\mathrm{w}}^{1.1}f_{\mathrm{cy}}^{1/2}$, respectively.

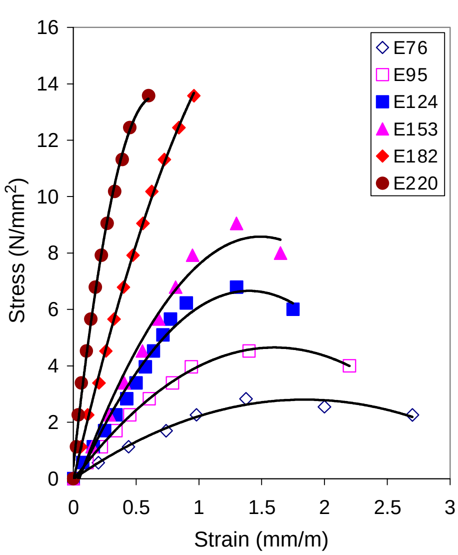

Fig. 5. Stress–strain variation of EPS concretes containing 50% fly ash.

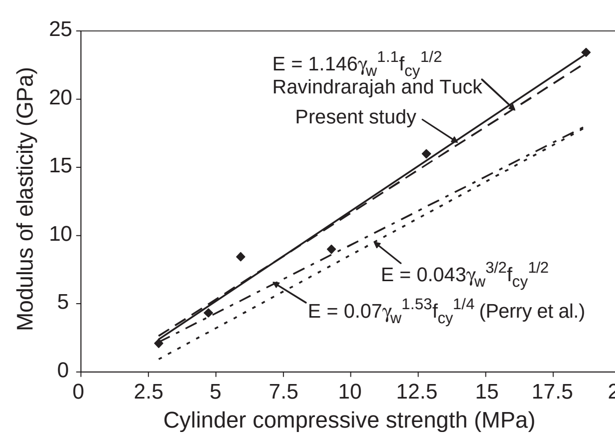

Fig. 7. Relationship between modulus of elasticity and compressive strength.

The secant modulus of the concretes in the present investigation (as calculated with the cylinder strengths and air-dry densities) for the above equations are also plotted in Fig. 7. It was observed that the equations proposed by Perry et al. and Pauw were found to be underestimating the secant modulus of EPS aggregate concretes (containing fly ash). The secant modulus values of the present study were almost similar to the empirical equation proposed for by Sri Ravindrarajah and Tuck for BST coated polystyrene aggregate concretes. Thus the equation was acceptable for the EPS aggregate concretes in the present investigation, containing 50% fly ash (with low effective cementitious contents). It was also observed that the modulus of the EPS concretes in the present study (containing fly ash) were higher than the values reported by Bagon and Yannas for similar concrete densities (made with higher cement contents and higher density of smaller size EPS aggregates).

5. Conclusions

All the EPS mixes showed better flow and no segregation was observed in any mix even in these concretes made without the addition of bonding additives. Also, the EPS aggregates are compressed resulting in slightly higher densities than the designed densities by about 50–100 kg/m^3. This effect is more in mixtures containing normal coarse aggregate.

The compressive strength showed an increasing trend as the age increases and also the percentage of increase in almost all the mixes at 7 days to 28 days and 28 days to 90 days was even higher than 35%. The strength decreases with the increase of EPS percentage (i.e., varying linearly with the density of the concrete). The variations of UPV and rebound values increase as the compressive strength increases. The proposed equations for the relation between the UPV and rebound number with the cylinder compressive strengths are $f_{cy}=0.071e^{1.597V}$ and $f_{cy}=0.954e^{0.093N}$, respectively.

The splitting tensile strength decreases with increase in the EPS volume percentage and with higher EPS concretes showed the gradual splitting whereas in the lower volume of EPS concretes the splitting was somewhat sudden, though not like normal concretes. The proposed equations for the relation between splitting tensile strength and compressive strength is given by $f_t=0.3577f_{cu}^{0.675}$.

The ultimate strains observed in the lower density mixes were higher and the stress–strain relations showed higher steepness as the percentage of EPS decreased. The length of propagation of cracks is increasing with decrease in EPS volume.

The modulus of elasticity values increased with an increase in the compressive strength and decreased with increase in percentage volume of EPS. The secant modulus value was seen to be decreasing and this decrease was found to be about 40% for every 10% increase in the EPS volume.

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