Compressive Strength of Concrete Containing Expanded Polystyrene Styrofoam (EPS) Concrete and Partial Cement Replacement of Fly Ash and Silica Fume

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ABSTRACT

Expanded polystyrene (EPS) waste is generated by industry and post-consumer products. This is non-biodegradable, but is often disposed of by incineration or landfill, resulting in environmental pollution. Fly ash (FA) is a waste product from coal-fired power plants, and silica fume is a by-product of the smelting process in the production of silicon and ferrosilicon alloys. Both materials cause environmental pollution. Instead of disposing of them, there is a better way to put them to good use, such as EPS concrete (EPSC), by using EPS as a coarse aggregate and a mixture of fly ash and silica fume as a partial cement replacement. In this study, different mixes were investigated in which 100% of the coarse aggregate was replaced by EPS beads and the cement was replaced by a mixture of FA and SF at 20%, 25%, and 30%. Several laboratory tests were performed, including a slump test, a density test, a compressive strength test, and an ultrasonic pulse velocity (UPV) test. Based on the data

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obtained, the optimum EPSC mix is EPSC3 (20% FA,5% SF) with 25% cement replacement and a compressive strength of 12.8 MPa at 28 days. The total slump of EPSC ranges from 65 mm to 173 mm and the total density ranges from 1562.6 kg/m3 to 1619.4 kg/m^3.

Keywords: *Fly Ash; Silica Fume; EPS; Lightweight Concrete*

Introduction

Alternative ecological and cost-effective materials are becoming increasingly popular. Due to its low density, hydrophobic properties, excellent thermal insulation, low absorption and low cost, expanded polystyrene (EPS) is widely used as a packaging material. More than fourteen million tons of polystyrene are produced worldwide each year, and a significant portion of it ends up as waste in landfills with limited capacity [1]. Normal concrete used with its density between 2200-2400 kg/m^3, higher dead load used on structure and this would cause more manpower used to carry to the site construction due to heavyweight [2]. EPS concrete is increasingly used in many applications in the construction sector and other industries due to its light weight, good thermal insulation, and acoustic insulation [1], [3]. It can be used as a coarse foundation material for sidewalks, cladding panels, lightweight partitions, floating marine structures, marine floors, energy absorbing material for underground military buildings, and fenders for offshore oil platforms. Nowadays, the demand for lightweight concrete is rapidly increasing around the world due to its lower dead weight and maintenance cost compared to conventional concrete.

Among the various types of lightweight concrete proposed, expanded polystyrene lightweight concrete (EPSLC) is intriguing because it can be customized by changing some of the properties of its constituents, such as the particle size and volume fraction of polystyrene [4]. EPSLC is produced by fully replacing the normal aggregates (fine and coarse) with EPS beads. In addition, EPSLC can be manufactured on site, which is an immense advantage over materials such as autoclaved aerated concrete. EPSLC is a type of lightweight concrete with a wide range of densities from 1000 to 2000 kg/m^3, which can be produced by incompletely replacing coarse aggregates in the reference concrete mix (normal weight) with a parallel volume of artificially wrapped polystyrene spheres. Low weight, great thermal properties, incredible sound insulation, increased strength, and ecological compatibility are some of the advantages of EPS concrete, which is suitable for both auxiliary and non-basic applications, depending on the amount of polystyrene used [4]-[5].

In general, the addition of 5 to 25% silica fume to concrete increases the compressive strength by 6 to 81.25% percent [5]-[8]. However, at a level of 10% is considered the optimum compressive strength of concrete [9]. Dixit et al. [10] developed ultra-high performance concretes by replacing aggregates with EPS beads between 0-45% and the cement replacement of silica fume at 40% level. A previous study conducted with 3%, 5%, 7.5%, 10% and 12.5% silica fume had shown that the replacement of 7.5% gave higher compressive strength than the replacement of 10% [11]. However, it was concluded that no more than 15-20% of cement replaced by silica fume positively affects the concrete performance [12]-[13]. According to Abd-ElAziz [14], the cement replacement of 5% silica fume in EPS concrete improves the compressive strength by 10%. It was found that structural concrete can be made with EPS beads (> 17 N/mm^2) [5]. Fly ash is one of the recycled materials suitable as a partial replacement for ordinary Portland cement (OPC). Studies have shown that when the cement component is partially replaced by fly ash, the compressive strength increases with increasing fly ash content up to the optimum value [12], [14]-[15]. The improvement in compressive strength in concrete containing fly ash is probably due to the pozzolanic reaction.

The addition of polystyrene beads to concrete decreased the concrete strength, so it was expected that the addition of fly ash and silica fume would compensate for the strength loss. In this study, an experiment was conducted to determine whether the addition of polystyrene beads to fly ash-silica fume concrete can reduce its density. Various EPS concrete mixtures were prepared by replacing 100% of the volume of aggregates with EPS beads and replacing cement with a total of 20%, 25%, and 30% of the FA and SF mixtures. The slump, density, compressive strength and ultrasonic pulse velocity (UPV) of these mixes were evaluated. The objective of this work is to develop a mix design for EPSLC with a density lower than 1800 kg/m^3 and a sufficiently high compressive strength so that it can be used for construction purposes.

Methodology

Materials

Ordinary Portland Cement OPC) meeting the requirements of ASTM C150-07 [16], and two types of supplementary cementitious materials; i.e. fly ash (FA) and silica fume (SF) were used as in the production of concrete mixtures as shown in Figure 1. The chemical composition of these materials is presented in Table 1.

The materials used in EPS concrete consist of OPC, EPS beads as lightweight aggregate as shown in Figure 2, sand as fine aggregates, a mixture of fly ash and silica fume as a partial cement replacement and superplasticizer as water reduction. Type the mixture of EPS concrete was casted in the mould size of 100 mm × 100 mm × 100 mm. The fine aggregates were natural river sand with 4.75 mm maximum size. The fine aggregates were surface dried for a day before concrete mixing. Polycarboxylic ether-based superplasticizer namely Masterglenium ACE 8589 was used to enhance the flowability of the mixtures. FA was obtained from Sarawak Energy Coal Power Plant, Mukah, Sarawak and silica fume was obtained from OM Materials Sdn. Bhd. from Bintulu, Sarawak.

(a) (b)

Figure 1: Cementitious materials; a) fly ash, and b) silica fume

Table 1: Chemical composition of fly ash and silica fume

Elements	Fly Ash (%)	Silica Fume (%)
SiO_2	45.33	91.0
Al_2O_3	18.11	0.876
Fe_2O_3	8.89	3.39
CaO	12.42	1.20
TiO_2	0.67	0.013
K_2O	1.86	1.42
SO_3	1.69	0.352
MgO	5.77	0.409
TiO_2	0.67	0.013
P_2O_5	0.20	-
Na_2O	4.89	-
SrO	0.17	-
BaO	0.00	-

Figure 2: EPS beads

Mixture proportion

The proportions of the concrete mixtures are summarized in Table 2. A total number of forty-five (45) specimens were casted for five (5) different mixture proportions including EPS normal concrete as control. Each mixture proportions were casted at 3, 7, and 28 days. OPC, FA, and SF were mixed in dry state, and that of EPS beads and fine aggregates were mixed dry separately. All the materials were mixed together by adding about half of water while mixing goes on for 1 min. The remaining water was added to the mixture and continue mixing it for 3 minutes. After concrete specimen hardened, the specimens were cured under ambient temperature and tested on specific day.

Table 2: Mix proportion of proposed EPS lightweight concrete

Specimen	Cement kg	Fly ash kg	Silica Fume, kg	Sand kg	EPS Liter	Water kg
Normal (NEPS)	5.17	0	0	10.45	5.35	2.75
5% FA, 15% SF (EPSC1)	4.14	0.26	0.775	10.45	5.35	2.75
10% FA, 20% SF (EPSC2)	3.62	0.52	1.03	10.45	5.35	2.75
20% FA, 5% SF (EPSC3)	3.88	1.03	0.26	10.45	5.35	2.75
30% FA, 0% SF (EPSC4)	3.62	1.55	0	10.45	5.35	2.75

Slump test

The purpose of slump test is used to determine the workability of concrete. The test was conducted at the time that already done mixing but before fill into the mould. The procedure to conduct the test is according to BS EN 12350-2:2009 [17].

Firstly, the slump cone and base plate as shown in Figure 3 were prepared and make sure they are damped. Then, the slump cone is placed on the base plate and stand on the foot pieces to prevent spilled out of concrete. Next, the fresh concrete was filled into the slump cone by three layers with 25 blows per layer. The concrete that exceeded at the top layer is then removed by using the compacting rod and the spillage concrete to sides and base plate will also be cleaned. The slump cone is then lift slowly and carefully in straight up direction. Lastly, the slump height is measured and determined from the underside of compacting rod and the highest point of the concrete.

Figure 3: Slump value is measured after fresh EPS concrete is mixed

Casting and curing

The EPS concrete fresh mix was poured into a 100 mm × 100 mm × 100 mm cube mould for three time to form three layers. For each layer, the foam concrete was tampered with rod for 25 times. Then, the sample were left for hardening for 24 hours at non-saturated condition. After 24 hours, the mould was dissembled, and the EPS concrete cube is removed for the remaining curing period under a saturated condition by immersing into curing tank. Inside the curing tank as shown in Figure 4, the water temperature should be around 30 ± 2 ˚C.

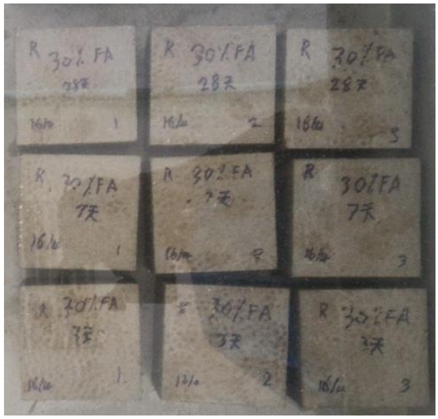


Figure 4: The EPS concrete is marked properly and placed into curing tank to undergo curing process

Compressive strength test

The compressive strength of concrete for EPS concrete specimens were tested on 3, 7, and 28 days. The specimens were cured under ambient temperature and tested on specific day. The compressive strength test was tested on the specimens according to BS EN 12390-1:2021 [18]. The cube mould size used was 100 × 100 × 100 mm. The concrete cube sample was tested by using compressive machine with capacity 3000 kN of compression load and the applied load rate is 13.50 kN/s. The compressive strength test is shown in Figure 5.

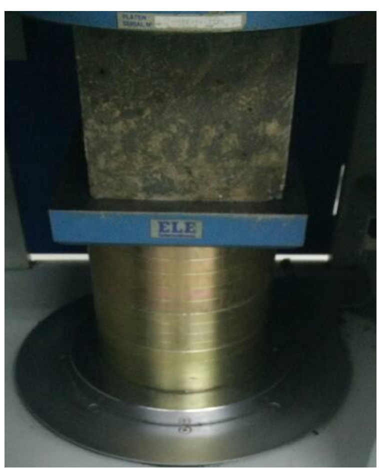


Figure 5: Compressive strength test

Ultrasonic pulse velocity (UPV) test

Ultrasonic pulse velocity (UPV) test is conducted according to BS EN 12504-4:2004 [19] to measure the concrete quality by inserting ultrasonic wave pulse through tested concrete, then followed by measuring the pulse time to pass through the concrete structure as shown in Figure 6. Through this test, concrete quality can be interpreted via the velocities results, at which lower velocities indicates the existence of cracks or voids within concrete while high velocities designate for concrete with good quality.

For the test procedure, firstly polishing stone is employed to clean the surface of test concrete thoroughly. Next, grease is applied on the concrete surface where test is to be conducted. Probes are pressed on the surface of the structural element to remove air gaps. The distance between the 2 probes is noted down. Read time is taken for ultrasonic pulse from the instrument. The test is repeated on multiple areas of the element if necessary. Different members of the structure are tested. The velocity can be calculated by using the equation below:

$$Velocity = {}^{D}/_{T} \tag{1}$$

where:

D is distance in meter, *m*
T is time in second, *s*

Density test

The unit measurement for concrete cube is in kg/m^3 was carried out the density test in lab. The experiment was carried out based on the BS EN 12390-7-2021 [18]. An electronic scale in the lab were used to obtain the weight of foam concrete specimen with volume of 0.001m^3 after curing period of 28 days.

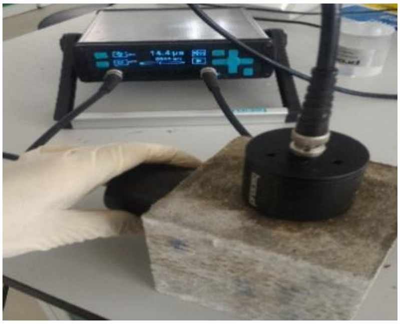
$$\text{Density}, \frac{kg}{m^3} = \frac{\text{W}_\text{i}}{\text{V}} \tag{2}$$

where:

Wi = Weight of the immersed sample after 28 days, kg
V = Volume of the foam concrete cube specimen, m^3

(a)

(b)



(c)

Figure 6: (a) Indirect transmission (b) direct transmission (c) semi direct transmission

Results and Discussion

Slump test

As shown in Table 3, the result shows that all specimens of EPS lightweight concrete have slump value of 65 mm to 173 mm. Thus, all of these specimens are adequate in quality. As shown in Figure 7, the cube specimen EPSC1 (5%FA, 15%SF) and EPSC2 (10%FA, 20%SF) have a lower slump value of 70 mm and 65 mm respectively compared to normal EPS lightweight concrete. These two (2) cubes specimens have 15% and 20% of silica fume as partial cement replacement and the silica fume will absorb water content in EPS concrete, when the higher percentage of silica fume presence in EPS concrete, the lower workability of the EPS concrete as this phenomenon can be observed addition of silica fume will make the EPS concrete had a dryer outlook.

Besides, the cube specimen EPSC3 (20%FA, 5%SF) and EPSC4 (30%FA, 0%SF) have a higher slump value of 155 mm and 173 mm respectively compared to the rest of specimens. These 2 cube specimens have 20% and 30% fly ash as partial cement replacement. According to [14], they proved that by using fly ash in concrete it can enhance the workability of EPS concrete.

Table 3: Workability of EPS lightweight concrete

Type of mix	Slump Height (mm)	Remark
Normal	88	PASS
EPSC1	70	PASS
EPSC2	65	PASS
EPSC3	155	PASS
EPSC4	173	PASS

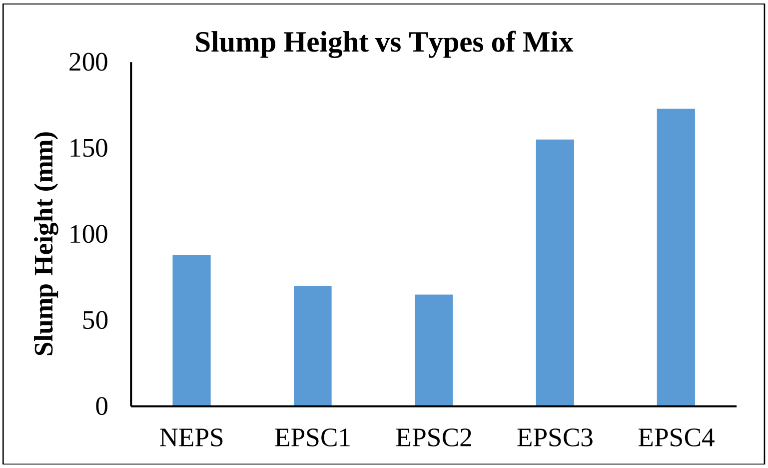


Figure 7: Density of EPS lightweight concrete with different mix proportion

According to Sadrmomtazi et al. [5] and ACI Committee 213 [20], the lightweight concrete is classified into three (3) main categories which are structural lightweight concrete, moderate lightweight concrete and insulating lightweight concrete. The strength required for each of these categories are above 17 MPa, 7-17 MPa and below 7 MPa respectively.

As shown in Table 4 and Figure 8, all of the EPS concrete specimen have an overall strength from 9.9 MPa to 12.8 MPa and can be categorized as moderate lightweight concrete. The cube specimen EPSC3 (20%FA, 5%SF) had the highest strength of 12.8MPa over other specimens. The cube specimen EPSC1 (5%FA, 15%SF) had the second highest strength of 12MPa. The higher strength of these 2 specimens is due to the presence of silica fume in EPS concrete and silica fume help to enhance the early and late strength of EPS concrete compare to the EPS concrete that only use OPC as binder which had strength of 10.2 MPa.

The mixture EPSC2 (10%FA, 20%SF) had the lowest strength of 7.9 MPa compared to normal EPS concrete. The excessive percentage of silica fume in EPS concrete leads to decreased of early strength and late strength of EPS concrete. The reason is the higher amount of silica fume added into concrete, it needs more water to let it react with cement in concrete.

The mixture EPSC2 (30%FA, 0%SF) also had slightly lower strength of 9.9 MPa compared to normal EPS concrete. This is due to high amount of carbon content in fly ash make it require more water content in concrete [14].

Table 4: Compressive strength of EPS lightweight concrete at 3, 7, and 28 days

Types of Mix	Compressive Strength (N/mm^2)		
	3 days	7 days	28 days
NEPS	7.3	8.4	10.2
EPSC1	8.1	11.4	12.0
EPSC2	7.0	7.4	7.9
EPSC3	5.5	9.2	12.8
EPSC4	5.7	5.9	9.9

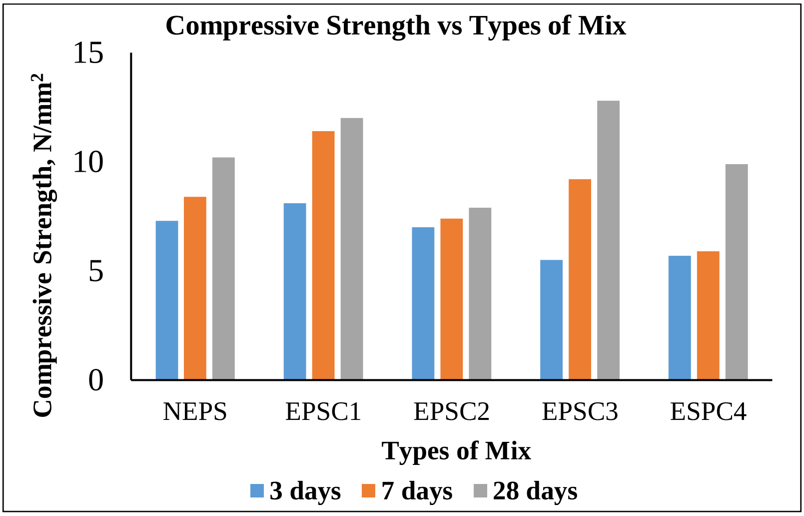


Figure 8: Compressive strength of different type of EPS lightweight concrete mix at 3, 7, and 28 days

Ultrasonic pulse velocity (UPV) in semi direct transmission

In order to carry semi direct UPV measurement, the sensor need to place at the adjacent faces of concrete specimen. As shown in Table 5 and Figure 9, it shows the relationship between UPV semi direct transmissions and mixture types of EPS lightweight concrete. It can be observed that EPSC4 (30%FA, 0%SF) had the highest average pulse velocity with 6320 m/s. In turn, the normal EPS concrete (0%FA, 0%SF) had the lowest average pulse velocity with 4572 m/s.

Table 5: UPV in semi direct transmission for 28 days

Types of Mix	Pulse Velocity (m/s)			Average Pulse Velocity (m/s)	Compressive Strength (N/mm^2)
	1	2	3		
Normal (NEPS)	4785	4916	4016	4572	10.2
5% FA, 15% SF (EPSC1)	5747	6711	4274	5577	12.0
10% FA, 20% SF (EPSC2)	6711	7194	4184	6030	7.9
20% FA, 5% SF (EPSC3)	5917	4274	7274	5822	12.8
30% FA, 0% SF (EPSC4)	6944	6098	5917	6320	9.9

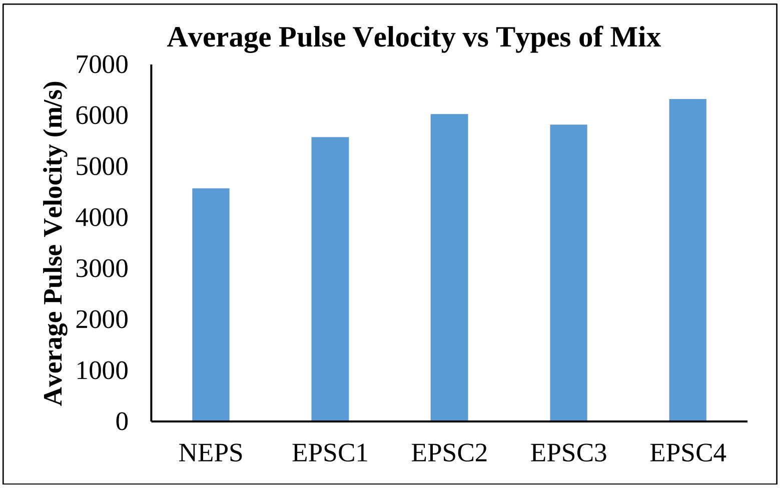


Figure 9: Relationship between average semi direct pulse velocity and type of EPS lightweight concrete mix

Ultrasonic pulse velocity (UPV) in indirect transmission

In measurement of indirect UPV transmissions, the sensors need to place indirectly at the one surface only of the cube specimen. As shown in Table 6 and Figure 10, it shows the relationship between UPV indirect transmissions and mixture types of EPS lightweight concrete. It can be observed that EPSC4 (30%FA, 0%SF) had the highest average pulse velocity with 6095 m/s. In turn, the EPSC3 (20%FA, 5%SF) had the lowest average pulse velocity with 3093 m/s.

Table 6: UPV in indirect transmission for 28 days

Types of Trial Mix	Pulse Velocity (m/s)			Average Pulse Velocity (m/s)	Compressive Strength (N/mm^2)
	1	2	3		
Normal (NEPS)	4184	3861	6494	4846	10.2
5% FA, 15% SF (EPSC1)	4274	4019	3788	4027	12.0
10% FA, 20% SF (EPSC2)	6711	5155	2415	4760	7.9
20% FA, 5% SF (EPSC3)	3436	2865	2979	3093	12.8
30% FA, 0% SF (EPSC4)	7752	4785	5747	6095	9.9

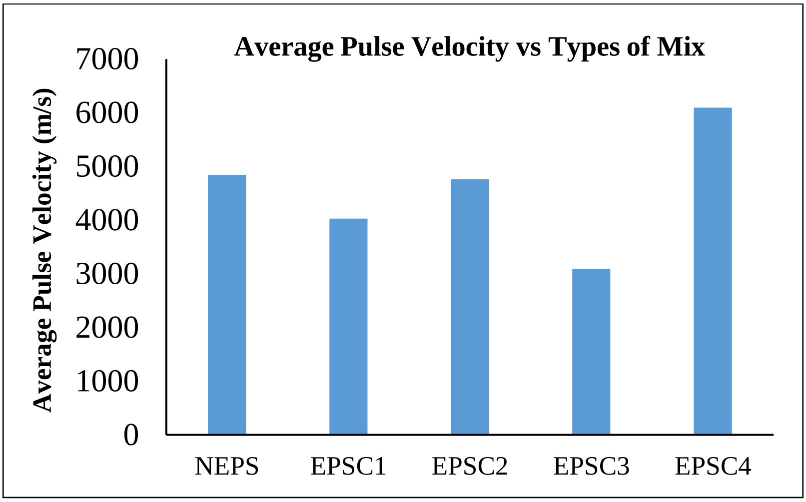


Figure 10: Relationship between average indirect pulse velocity and type of EPS lightweight concrete mix

Density test

As shown in Table 7 and Figure 11, it shows that the overall density of EPS lightweight concrete ranged from 1562.6 kg/m^3 to 1619.4 kg/m^3. All of the EPS concrete cube specimens was properly cured by using clean tape water.

According to Ligia et al. [21], lightweight concrete density is considered between 400 kg/m^3 to 2000 kg/m^3. Thus, from the density result of EPS lightweight concrete obtained from this experiment is considered as in acceptable range.

In this particular test, there are some observations that can be observed such as:

i. The density of EPS lightweight concrete decrease when there is presence of silica fume and fly ash.

ii. The higher content of OPC inside EPS lightweight concrete, the higher density it is.

Table 7: Density of EPS lightweight concrete at 28 days

Types of Trial Mix	Density (kg/m^3)			Average Density (kg/m^3)
	1	2	3	
NEPS	1628.5	1618.7	1610.9	1619.4
EPSC1	1604.9	1599.1	1622.9	1609.0
EPSC2	1557.0	1591.0	1583.0	1577.0
EPSC3	1543.9	1571.2	1572.6	1562.6
EPSC4	1564.4	1572.5	1590.8	1575.9

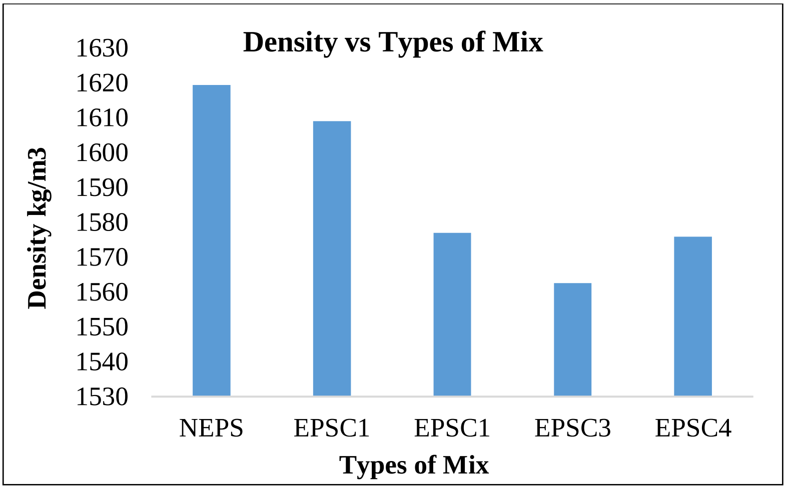


Figure 11: Density of EPS lightweight concrete with different mix proportion

Conclusion

In order to produce environmentally friendly concrete by utilizing FA and SF in EPS lightweight concrete, the conclusions can be drawn to fulfill the research objectives are as follows:

i. The density of EPS lightweight concrete can be further reduced by adding silica fume and fly ash.
ii. Fly ash and silica fume can help improve the fresh concrete properties of EPS lightweight concrete.
iii. The optimum mix proportion of EPS lightweight concrete is 20%FA, 5%SF, which gives the compressive strength at 12.8 N/mm^2.
iv. The compressive strength of EPS lightweight concrete can be improved by adding both fly ash and silica fume.
v. Both fly ash and silica fume can be used as partial cement replacement in concrete.
vi. EPS beads can be used as lightweight aggregate in the production of lightweight concrete.
vii. The use of fly ash and silica fume can help reduce environmental problems.

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