Delta University Scientific Journal
Journal home page: https://dusj.journals.ekb.eg

Evaluation of Ultra-Lightweight Floating Concrete Using Polystyrene Aggregates for Non-Structural Applications

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ABSTRACT
Polystyrene concrete is a specialized lightweight concrete suitable for applications such as floating marine platforms, floating bridge components, and non-structural slabs subject to heavy vibrations. It is also ideal for light weight brick and sound insulation brick, offering significant environmental advantages as a building material. In this study, lightweight concrete mixes were designed with polystyrene aggregate replacing 2%, 4%, 6%, 8%, and 10% of the aggregate weight. Tests were conducted to evaluate compressive strength, flexural strength and density. Ultrasonic pulse velocity testing was used to determine the dynamic and elastic modulus of elasticity and Poisson's ratio.

The results demonstrated the production of lightweight concrete blocks with suitable compressive strength for light weight brick. The mix with 2% polystyrene achieved an optimal balance of density and mechanical performance, making it suitable for lightweight, non-structural insulating bricks and filler applications.
The results also showed that with an increase in the polystyrene content to 10%, the concrete reaches a state of buoyancy, accompanied by a noticeable reduction in mechanical properties with significant density reduction and floatation capability, though accompanied by reduced mechanical properties.
Therefore, attention should be directed toward utilizing polystyrene concrete as a material for producing sound and thermal insulation bricks, as well as lightweight non-structural bricks. The economic benefits of this application should not be overlooked, especially in cold regions that require insulated walls.

Keywords: *polystyrene concrete, light weight concrete, heat-resistance materials, sound-resistance materials*

1. Introduction

Concrete is one of the most widely used materials in construction, valued for its strength, durability, reflectivity, and versatility. The density of normal-weight concrete can be modified based on its intended use. In this context, the choice of raw materials, especially aggregates that form the concrete's structure, is crucial in determining its weight. Replacing fine and coarse aggregates with lightweight alternatives is the standard approach to producing lightweight aggregate concrete(Maghfouri et al. 2021)(Satish Chandra, n.d.). A lot of researchers have incorporated perlite, vermiculite, volcanic scoria, and expanded polystyrene into concrete masonry blocks to enhance their thermal insulation properties. (Al-Osta et al. 2022; Schiavoni et al. 2016; Sariisik and Sariisik 2012; Al-Tarbi et al. 2022).

A study found that non-isolated panels have 30% higher strength and better energy dissipation. They are 3-4 times lighter, with increased stiffness, minimal damage, and improved seismic performance without full failure. (Yasemi et al. 2024). Other study investigated the gas permeability and porosity of cement mortar with plastic waste aggregate (PWA) under various stress conditions. A novel LDA-tuned BAANN model outperformed conventional machine learning models, providing accurate predictions of PWA cement permeability. The research highlights the rise in permeability and porosity with increased PWA content, influenced by confining pressure, while the model offers efficient, reliable assessment tools for PWA concrete design (Chao et al. 2024). Other research developed lightweight concrete using natural Moroccan pozzolanic aggregates, optimizing thermal insulation and mechanical strength. A 40% pozzolan mix achieved ideal heat conductivity (0.78-1.5 W/mK) and mechanical balance, suitable for energy-efficient building applications such as insulating walls and tiles (Annaba et al. 2024).

In other research it has been explored the durability of structural lightweight concrete (SLWC) using Sintered Fly Ash Light weight Aggregate (SFLA) and Controlled Permeable Formwork (CPF) liners. CPF liners enhanced surface quality, reducing water absorption and penetration, and improving surface resistivity and wear resistance. Although CPF liners had minimal impact on compressive strength, they significantly reduced surface porosity, contributing to improved durability. The study suggests adjustments in AASHTO curves for SLWC with CPF liners (Gowdhamramkarthik and Arun Kumar 2023).

A seismic analysis framework was developed for lightweight Expanded Polystyrene (EPS) wall panels and energy-dissipating connectors. It utilized experimental and numerical simulations to model interactions between panels and load-bearing structures. The framework predicts seismic damage, identifying key seismic parameters and distribution patterns. Static pushover and dynamic analyses revealed differences in connector damage between panels and structures. The Maximum Information Coefficient method was used for correlating seismic parameters with damage, providing insights into predicting and preventing seismic damage in prefabricated non-structural elements(Huang et al. 2024) .Lightweight blocks made with scoria and perlite significantly reduce energy consumption, CO_2 emissions, and enhance thermal insulation (Al-Tarbi et al. 2023).

Researchers have explored the effects of perlite on the thermal conductivity and mechanical properties of lightweight concrete. Perlite, replacing natural aggregates in dosages from 20% to 100%, was mixed with Superplasticizers and air-entraining admixtures. Results indicated that 60% perlite substitution reduced thermal conductivity by 42% and compressive strength by 84%. (Al-tamimi et al. 2020). Others found that adding 30% perlite to a new concrete block design improved thermal efficiency (Hago, Taha, and Alnuaimi 2009). The researchers concluded vermiculite is unsuitable for concrete blocks due to low strength, while polystyrene proved effective for lightweight concrete with low thermal conductivity (Al-Awsh et al. 2021)

Lightweight aggregates like expanded clay, pumice, and expanded shale improve energy efficiency, thermal resistance, and reduce structural deadweight in construction. Applied in precast concrete panels, light weight aggregate decreases dead loads and costs (Ferraro and Nanni 2012; Gencel et al. 2021; Ni et al. 2020; Zaetang et al. 2013; Zhang et al. 2020; Babu, Ganesh Babu, and Tiong-Huan 2006).
Polystyrene is widely used as a replacement for aggregates to reduce concrete's weight and thermal conductivity. It is stable, low-density foam with air voids within a polymer matrix.

As a lightweight artificial aggregate, it is commercially available and can be added to mortar or concrete to create lightweight insulating concrete(Andrew Short 1963; Vėjelis and Vaitkus 2006). Its key engineering advantage over other lightweight aggregates is its lower water absorption due to reduced porosity(Asadi et al. 2018). Additionally, polystyrene has low thermal conductivity, making it highly suitable for insulation in construction (Chen and Liu 2004). Previous research has highlighted the use of EPS concrete in both structural and non-structural elements, such as precast panels, cladding, flooring systems, sub-base materials in pavements, floating marine structures, and insulation (Shaughnessy and Vavylonis 2000).

It is observed that replacing normal-weight aggregates with EPS increases drying shrinkage, raising the risk of time-dependent deformations and shrinkage-related cracking, which may affect the durability of concrete structures (Scherer 2015). The specification of physical and mechanical properties required for non-load-bearing concrete masonry units, ensuring performance and quality standards are shown in ASTM-C 129(American Society for Testing & Mater 2017)

2. Material and methods

2.1. Materials

The cement used is ordinary Portland cement produced by the Sinai cement factory complies with the requirements of the Egyptian Standards E.S.S. Initial and final setting times for cement were measured according

to BS EN 196-3. Compressive strength of cement and cement physical properties were given in Table 1. Fine aggregate was siliceous sand from North Sinai quarry, Egypt.
Sieve analysis test was done according to Egyptian Standards E.S.S. result was shown in Fig. 1. Coarse aggregate was chosen to be one size coarse aggregate 10 mm according to Egyptian code- extension III.
The polystyrene (P.S) used was ADDIPOR-55 .the material was manufactured by CMB Egypt. Fig.2. ADDIPOR-55 is expanded and extruded foam grains with special size and grading used for producing the light weight concrete.

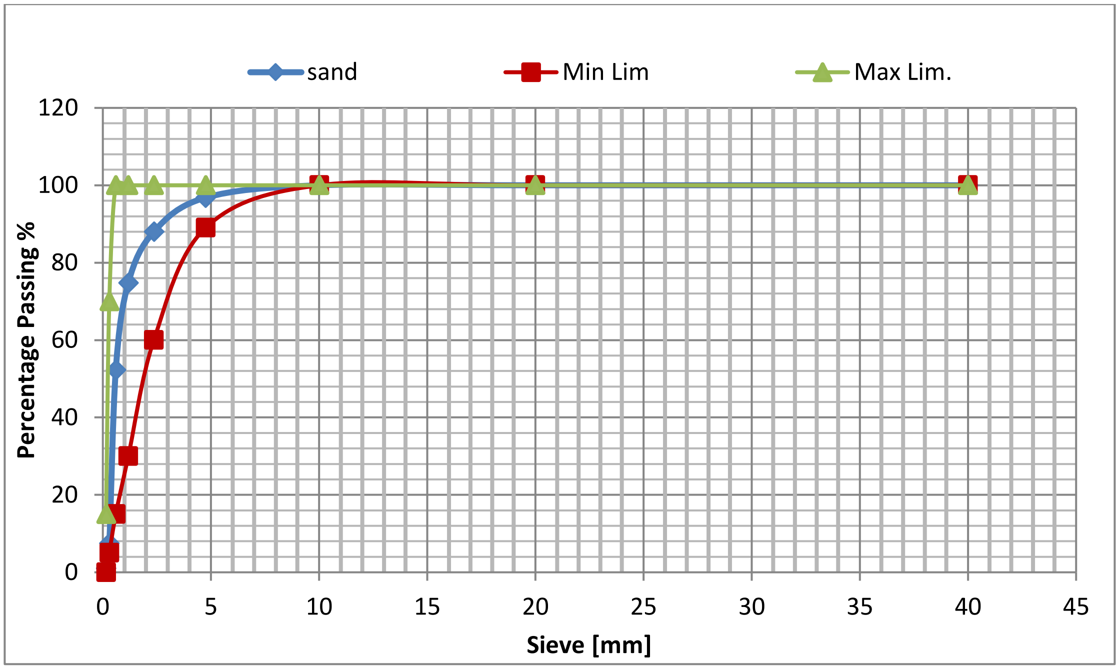

Fig.1. Sieve analysis of fine aggregate

Fig. 2. Polystyrene (P.S) used

The density of Addipor 55 was (20 – 22) kg/m³ and the grain size varies between 5 - 35 mm. according to CMB datasheet. Standard Test for determination of clay and other fine materials in fine aggregate by volume was carried out according to BS 812-124.

The ratio of clay and fine materials in sand was 1.89 %. The test was done in new Damietta higher institute of Engineering, Damietta, Egypt

Table 1: Physical properties of Portland cement

Test		Cement
Initial sitting time[Minutes]		60
Final sitting time[Minutes]		185
Specific surface area (cm^2/gm)		3500
Specific gravity		3.15
Compressive strength(N/mm^2)	7 days	28
	28 days	45

2.2. Experimental program and mix proportion

The main goal is to achieve lightweight concrete mixes that also have suitable compressive strength for use as un-structural concrete such as lightweight blocks that provide thermal and sound insulation, utilizing polystyrene aggregate. Several experimental trial mixes were conducted to find the optimal design approach. The design was finalized using the empirical method, as it is the most suitable due to the significant variation in density between the raw materials used.

The empirical approach was chosen for its ability to accommodate the extreme differences in specific gravity between cement, natural aggregates, and polystyrene. This method also offered flexibility in achieving the desired lightweight characteristics, ensuring that the concrete mix could maintain strength while providing benefits such as thermal insulation and buoyancy. Absolute volume equation of design checked for control mix design. The main governing factor in the polystyrene mixes was the concrete mix consistency according to the empirical mix design method.

After validation using the absolute volume equation, it will yield results for mixes containing polystyrene, as recorded in Table 2, with a volume greater than one cubic meter. This is one of the drawbacks of using the empirical method in designing concrete mixes. This becomes evident with the increase in polystyrene due to its very low density, unlike the control mix where this precision is achieved. Nonetheless, these represent the real mixes that give the exact strength and density.

The high cement content and water-to-cement ratio aimed to improve the hydration process, contributing to the mix's overall durability and mechanical performance. The polystyrene replacement further helped in reducing the weight.

In concrete containing polystyrene, it is crucial to pay attention to the consistency of the concrete mix and determine the ratios that provide the mix with cohesive properties between the particles. Therefore, experimental mixtures were used to achieve the optimal mix suitable for the intended purpose.

A water-to-cement ratio of 0.45 was employed to ensure proper hydration and improve the workability of the concrete. Partial replacement of fine aggregate with polystyrene was carried out at replacement rates of 2%, 4%, 6%, 8%, and 10%. Concrete mix proportions are shown in in Table 2.

Table 2. Concrete mix proportion

MIX	Cement (kg)	Coarse Agg. (kg)	Fine Agg. (kg)	Polystyrene (kg)	Water (lit)

Control Mix	889	444.5	444.5	0.0	400.05
2% P.S	٨٨٩	435.61	435.61	17.78	400.05
4% P.S	٨٨٩	426.72	426.72	35.56	400.05
6% P.S	٨٨٩	417.83	417.83	53.34	400.05
8% P.S	٨٨٩	408.94	408.94	71.12	400.05
10% P.S	٨٨٩	400.05	400.05	88.9	400.05

2.3Testing procedure

The mechanical properties were tested through compression strength and flexural strength tests, along with a density test. The tests were conducted in accordance with the British Standard and the Egyptian Code.

Forty-two standard cubes 150 *150*150 mm were used to prepare the concrete cubic specimens to measure compressive strength at 7 and 28 days of curing. After 7 & 28 days of casting compressive strength test were done and flexural strength test of concrete were conducted according to BS EN 12390-2. Compressive strength test were conducted in the laboratories of new Damietta higher institute for engineering and technology, Damietta, Egypt, flexural strength test was conducted in the laboratories of Horas University, Damietta, Egypt. Fig.3 shows a specimen weight.

Fig. 3. Concrete cube Specimen

In a typical compression strength test, cracks usually appear as an indication of the failure. However, in the case of polystyrene concrete, the failure occurs without the appearance of obvious cracks. Instead, the sample's compression is observed as a sign of failure. This behavior is an important indicator when using polystyrene concrete under machines exposed to vibrations or in structures prone to earthquakes. Additionally, the compression strength decreases significantly as the polystyrene content rises. This decrease in compression strength was with higher levels of polystyrene in the mix. The compressive strength test are shown in Fig. 4. The failure styles of polystyrene concrete are shown in Fig.5.

Fig. 4. Compression strength test

Fig. 5. specemens after failure.

Twenty-seven standard beams with dimensions of (10 mm * 10 mm * 50 mm) were prepared for the flexural strength test. All specimen preparation and curing were conducted according to BS EN 12390-5. The load was applied at the center of the beam, which is supported at both ends. The test aims to determine the polystyrene-concrete flexural strength. Flexural strength loading are shown in Fig.6.

Measuring the flexural strength of polystyrene concrete is important, even though it is not intended for structural purposes. Since polystyrene concrete is used in making insulating bricks, it must have adequate mechanical properties. Understanding its flexural performance ensures that it can withstand handling, installation, and environmental factors while maintaining its insulating properties and durability.

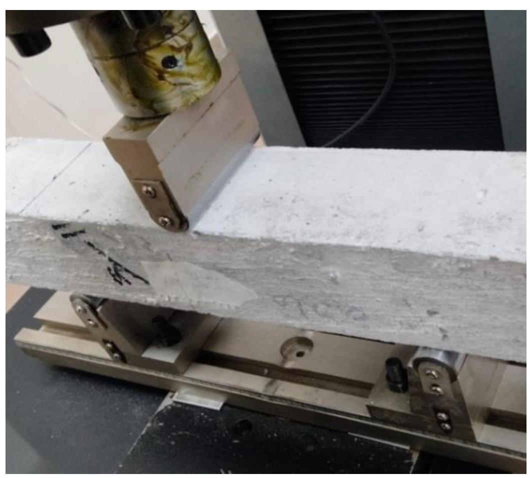

Fig. 6 flexural strength test loading

Density determination was according to BS 1881-114. A part of a standard cube from every mix was used. One of the research objectives is to develop lightweight polystyrene concrete with the ability to float. Therefore, a density test was conducted on concrete samples at the age of 28 days.

All specimen preparations were done at the New Damietta Higher Institute for Engineering and Technology, Damietta, Egypt.

The ultrasonic pulse velocity test was conducted. Standard cube samples with side lengths of 150 mm were tested directly, with the transmitter and receiver positioned face-to-face. The efficiency of the device was verified using the test standard rod at the beginning of the test to ensure the accuracy of the results as shown in Fig. 7. The test was then performed on the control mix sample and a sample from each polystyrene-concrete mix Fig.8.

Fig.7. Calibrating the ultrasonic device before starting

Fig.8. Ultrasonic-pulse waves through Polystyrene-concrete sample

3. Results

The results showed that the characteristic strength of experimental mixes. The characteristic strength decreased by 64%, 80%, 90%, and 97% in the mixes containing polystyrene at proportions of 2%, 4%, 6%, 8%, and 10%, respectively. Compressive strength results are shown in Table.3. & Fig.9.

Table .3. Mechanical properties results

Mix	Compressive Strength 7 day[N/mm^2]	Compressive Strength 28 day[N/mm^2]
Control Mix	32.5	41
2% P.S	12.0	14.5
4% P.S	6.5	8.0
6% P.S	3.0	4.0
8% P.S	2	2.5
10% P.S	1	1

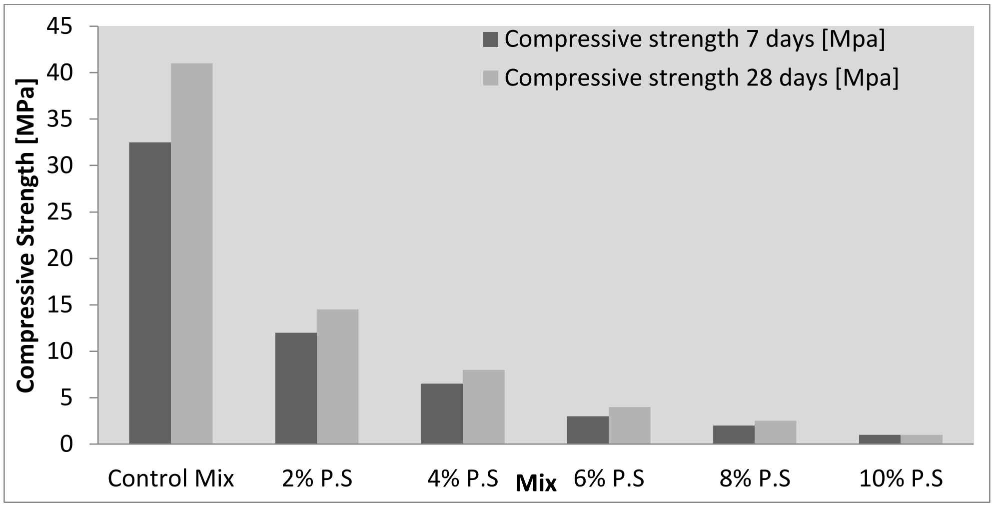

Fig.9. compressive strength results

The results of the flexural strength test were consistent with the compression strength results. The flexural strength in the mix containing 2% polystyrene decreased by approximately 50%, and in the mix containing 4% polystyrene, it decreased by about 84%. The flexural strength value almost disappeared in the mixes with higher polystyrene content. This is logical, as flexural strength typically ranges from 10% to 20% of the compression strength in normal concrete, providing a reasonable indication for ultra-lightweight concrete. The flexural strength was calculated using the equation (2) from the Egyptian Code, Appendix 3. The results are shown in Table 4. & Fig 10.

$$\text{Flexural Strength [MPa]} = \frac{3\text{FL}}{2d1\ d2} \qquad (1)$$

Where;

F= Failure load [N]

L= beam length [mm], L = 500 [mm]

d1= beam depth [mm]

d2= beam width [mm], d1= d2= 100 [mm]

Table 4. Flexural strength test results

Mix	Flexural Strength 28 day[N/mm^2]
Control Mix	5.34
2% P.S	2.11
4% P.S	0.98
6% P.S	0.0
8% P.S	0.0
10% P.S	0.0

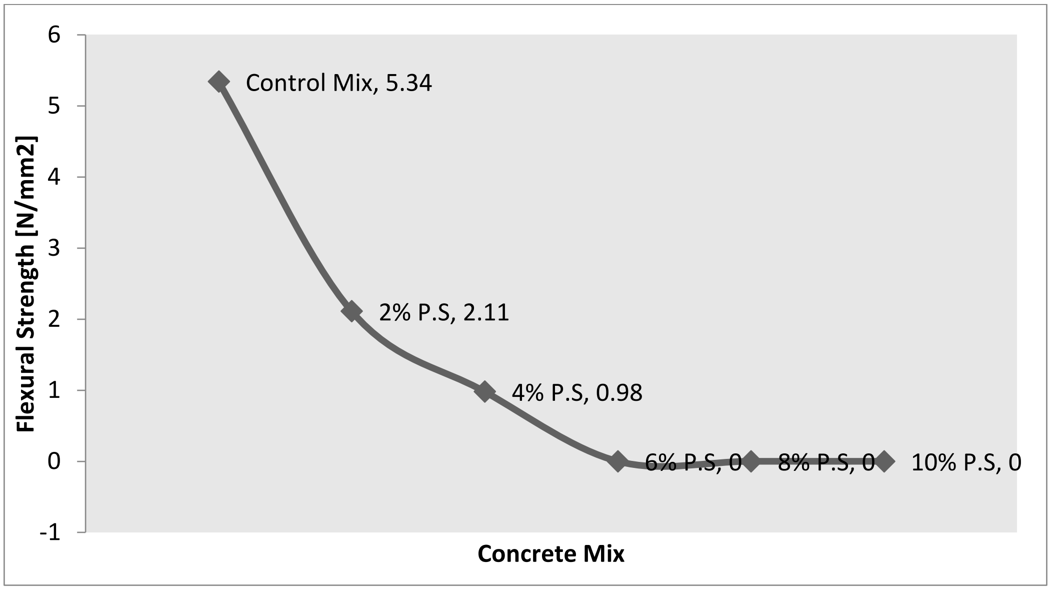

Fig. 10. Flexural Strength test results

In the density test, the density of the samples was calculated as-received. A significant reduction in density was observed as the percentage of added polystyrene increased, despite the replacement ratio ranging from 2% to 10%. However, by the end of the testing and during the curing of the samples, it was noted that the mix design successfully produced a concrete mixture capable of floating on water, while still maintaining acceptable rigidity.

This demonstrates that the use of polystyrene effectively reduced the overall weight of the concrete. The mix 10%P.S shows ultra-light weight floating concrete. Fig. 11. The results of concrete density test are shown in Table .5.

Fig. 11. Floating Specimen of (8 % P.S) Mix

Table.5. Concrete Density test results

Mix	Density [kg/m³]
Control Mix	2145
2% P.S	1189
4% P.S	835
6% P.S	645
8% P.S	510
10% P.S	430

The ultrasonic pulse test was conducted on all the mixtures. To calibrate an ultrasonic device, a reference material with known properties, such as a standard calibration block, is used. The device settings, including frequency and time-of-flight, are adjusted until it provides accurate readings matching the known values of the material. Once calibration is complete, the device is ready for testing. During testing, the calibrated device measures the properties of samples, such as thickness or defects, and the results are compared to standards. By conducting the ultrasonic pulse velocity test, the time taken for the ultrasonic pulse to pass through the material is measured (T). Using the following equation (2), the velocity of the ultrasonic pulses passing through each concrete mix can be determined.

$$V = \frac{L}{T} \qquad (2)$$

Where: L= the length of pulse 150 mm T= the time of pulse (reading) km/sec

Some of concrete properties can be determined such as Poisson's ratio, static modulus of elasticity (E_s) and dynamic modulus of elasticity (E_d) can be derived using specific formulas shown in equation (3), (4) and (5) respectively. These formulas relate pulse velocity, material density, and wave propagation characteristics to mechanical properties. It must be noted that shear waves Vs are harder to measure due to the need for specialized sensors. The assumption in equation (6) used to simplify the calculations.

$$\upsilon = \frac{Vl^2 - 2Vs^2}{2(Vl^2 - 2Vs^2)} \qquad (3)$$

$$E_s = k.E_d \qquad (4)$$

$$E_d = \sigma\, Vl^2 \frac{(1+\upsilon)(1-2\upsilon)}{(1-\upsilon)} \qquad (5)$$

$$Vs = 0.55\ Vl \qquad (6)$$

Where: υ = Poisson ratio Vl= Longitudinal (compression) wave velocity

Vs= Transverse (shear) wave velocity. E_s= static modulus of elasticity

E_d= dynamic modulus of elasticity f = compressive strength (Mpa)

σ = material density (kg/m^3) K = A conversion factor, taken 0.85

The ultra-sonic pulse wave's results are shown in Table.6. The test conducted according to ASTM-C597 in the higher institute of Engineering and technology in New Damietta.

Table.6 Ultra-sonic pulse waves results

Mix	σ [kg/m^3]	T [μ.sec]	V_l [km/sec]	V_s[km/sec]	υ Poisson.r	E_d [Gpa]	E_s [Gpa]
Control	2145	37.3	4.02	2.21	2.83	26.92	22.88
2% P.S	1189	41.2	3.64	2.0	2.83	12.23	10.4
4% P.S	835	41.8	3.59	1.97	2.83	8.36	7.11
6% P.S	645	42.3	3.55	1.95	2.83	6.31	5.36
8% P.S	510	43.5	3.45	1.89	2.83	4.71	4.
10% P.S	430	44.9	3.34	1.86	2.83	3.73	3.17

4. Discussions

The compressive strength results clearly show that increasing the polystyrene (P.S) content leads to a significant reduction in strength. The control mix (without polystyrene) exhibited the highest strength (32.5 N/mm² at 7 days, 41 N/mm² at 28 days. When 2% of the aggregate was replaced with polystyrene, the strength dropped significantly to 14.5 N/mm² at 28 days, this mix can be used as light weight brick with an acceptable compressive strength for brick and suitable weight for brick.

At 4% polystyrene, the compressive strength further reduced to 8.0 N/mm², and at 6% P.S, it fell to just 4.0 N/mm². As polystyrene content increases, it introduces voids into the concrete, making the mix more porous.

At 8% and 10% polystyrene, the compressive strengths were 2.5 N/mm² and 1.0 N/mm², respectively. At these levels, the concrete becomes extremely lightweight and porous, making it suitable for specific applications but not for structural uses.

For floating concrete plates, which prioritize lightness and buoyancy over strength, the 8% P.S mix is the most suitable. It has enough polystyrene to ensure the concrete will float while still retaining some minimal strength (2.5 N/mm²). This mix could be used for floating platforms or other buoyant structures where load-bearing isn't critical. For soundproof and thermal insulation bricks, the 10% P.S mix is ideal. The high polystyrene content (88.9 kg) makes the concrete highly porous, providing excellent thermal and acoustic insulation properties due to the trapped air in the voids. However, the strength is very low (1.0 N/mm²), making this mix suitable for non-load-bearing walls or partitions designed for insulation purposes rather than structural applications.

The flexural strength results indicate that as polystyrene (P.S) content increases, the concrete becomes unsuitable for structural applications due to its inability to resist bending stresses. However, for non-structural uses such as floating concrete and soundproof-thermal insulation bricks, this reduction in strength is acceptable. The 2-4% P.S mixes are ideal for these applications, where low weight, buoyancy, or porosity is crucial. These mixes can still meet the requirements for lightweight, floating platforms and porous insulation bricks, where strength isn't the priority. The results of mechanical properties are near to the results of most of the previous research(Babu, Ganesh Babu, and Tiong-Huan 2006) (Annaba et al. 2024).

The density results show a significant reduction as polystyrene (P.S) content increases, with the control mix at 2145 kg/m³ and the 10% P.S mix dropping to just 430 kg/m³. This substantial decrease highlights the key advantage of lightweight concrete: reduced weight, which is crucial for floating concrete and insulation bricks Lightweight concrete lowers structural load, improves buoyancy, and enhances thermal and sound insulation. These properties make the higher P.S mixes ideal for non-structural applications like floating platforms and energy-efficient bricks. Also density results are close to previous research (Chao et al. 2024)

The ultrasonic pulse velocity (UPV) test provided the dynamic modulus of elasticity E_d and Poisson's ratio, showing consistent trends across concrete mixes. These results demonstrate the effectiveness of UPV for evaluating concrete stiffness and elasticity, confirming its reliability for both lightweight and normal-weight concretes in structural performance assessments.

the calculated static modulus of elasticity from the dynamic modulus closely aligns with the values obtained from the empirical equation in ACI 318 (ACI Committee 318 2014)This consistency validates the applicability of dynamic testing methods for lightweight and normal-weight concretes while affirming the robustness of the ACI 318 equation for estimating

Disclosure

The author reports no conflicts of interest in this work

5. Conclusions

The introduction of polystyrene (P.S) aggregate into the concrete mix reduces its mechanical properties but enhances its lightweight properties, making it suitable for specific non-structural applications.

- **Compressive Strength**: Increasing the polystyrene content causes a substantial drop in compressive strength. For structural applications, this is a limitation. However, for floating concrete platforms, a mix containing 8% P.S (2.5 N/mm²) strikes a balance between reduced strength and buoyancy. For soundproof and thermal insulation bricks, the 10% P.S mix (1.0 N/mm²) is ideal, as it provides excellent insulation due to the high porosity. However, the 2% and 4% P.S mixes, with compressive strengths of 14.5 MPa and 8.0 MPa respectively, are suitable for non-load-bearing, lightweight brick applications.

- **Compressive strength**: The cube's shape under failure showed compressive deformation with minimal visible cracks, indicating a ductile failure mode. This behavior suggests its potential applicability in structures subjected to dynamic loads, such as vibrating machine foundations.

- **Flexural Strength**: The reduction in flexural strength with increasing polystyrene content makes the concrete unsuitable for load-bearing structural applications. However, the low strength is acceptable for non-structural uses like floating platforms and insulation bricks.

- **Density**: The density of the concrete decreases significantly with higher P.S content, dropping from 2145 kg/m³ (control mix) to 430 kg/m³ (10% P.S mix). This makes the high P.S mixes well-suited for applications where reduced weight is critical, such as floating concrete structures and lightweight insulation materials, particularly in soundproof and thermal insulation applications

- **Floating Concrete**: The 8% P.S mix is the most suitable for floating platforms, offering adequate buoyancy while retaining some compressive strength.

- **Dynamic modulus of elasticity**: The results, obtained through ultrasonic pulse velocity tests, confirm the decline in elasticity with higher P.S content. This reinforces the material's potential for non-structural applications, where reduced weight and insulation are prioritized over mechanical strength. These results underline the versatility of polystyrene-modified concrete for specialized non-structural applications, particularly in lightweight and insulation materials.

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