Eng. Sci., 2024, **31**, 1216

Engineered Science

DOI: https://dx.doi.org/10.30919/es1216

# Punching Shear Capacity of Polystyrene Lightweight Concrete Two-way Slabs

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## Abstract

This research investigates the mechanical behavior and punching shear capacity of two-way slabs constructed using lightweight concrete incorporating Expanded Polystyrene beads (EPS). An experimental investigation has been conducted to assess the impact of incorporating EPS beads, Master Glenium 51 superplasticizer, and silica fume into the punching shear capacity of lightweight concrete slabs. The results indicate that slabs containing lightweight concrete alone exhibited the lowest punching shear capacity, approximately 22.5% less than the control sample made only from normal weight concrete. However, the incorporation of Master Glenium 51 superplasticizer and silica fume significantly improved the punching shear capacity, nearly matching the performance of the control sample made of normal-weight concrete. Additionally, it was observed that replacing 12.5% of the coarse aggregate and 25% of the fine aggregate with EPS led to a 15% reduction in the concrete's weight compared to regular concrete. The obtained results were compared with calculations based on the ACI 318-19 code to evaluate its accuracy in predicting the behavior of lightweight concrete with EPS beads, and ' 'it's noteworthy that all results for all samples showed close alignment. These findings provide valuable insights into the performance of lightweight concrete with EPS beads and highlight the potential benefits of using Master Glenium 51 superplasticizer and silica fume in enhancing punching shear capacity.

*Keywords:* Expanded polystyrene beads; Master glenium 51; Silica fume; Punching shear; Lightweight concrete.
Received: 16 January 2024; Revised: 28 May 2024; Accepted: 17 July 2024.
Article type: Research article.

## 1. Introduction

Concrete is a widely utilized building material known for its strength, durability, and sustainability. Its exceptional properties make it a preferred choice for various domestic and commercial construction needs, resulting in a growing demand for natural aggregate (NA) production.[1] However, a significant challenge lies in the fact that approximately 70% to 80% of concrete consists of NA,[2] posing hurdles for future concrete production in terms of weight and sustainability of natural aggregates. Therefore, finding an alternative to NA with lower density has become crucial to reducing the weight of concrete. This reduction in weight not only helps decrease the dead loads of structures but also contributes to the preservation of natural aggregate sources.

Researchers and engineers have been exploring alternative materials to replace a portion of the NA in concrete to address this challenge. One promising option is using lightweight aggregates (LWA), which are materials with lower density than traditional NA. LWA can be derived from various sources such as expanded clay, shale, or recycled materials like crushed concrete or fly ash. By incorporating LWA into concrete mixes, the overall weight of the resulting concrete can be significantly reduced while maintaining adequate strength and durability. This reduction in weight offers several advantages, including improved transportability, decreased construction costs, and reduced strain on supporting structures. Moreover, it contributes to sustainable construction practices by decreasing the demand for natural aggregates and minimizing the environmental impact associated with their extraction. In addition to weight reduction benefits, concrete with lightweight aggregates can exhibit improved thermal insulation properties, making it suitable for applications requiring enhanced energy efficiency. Furthermore, LWA can provide better acoustic insulation, reducing noise transmission through structures.

To ensure the successful incorporation of lightweight aggregates into concrete, it is important to consider factors such as the properties of the LWA, the appropriate mix design,

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and the compatibility with other concrete mixture components. Extensive research and testing are conducted to optimize the combination of lightweight aggregates with cement, water, and other additives to achieve the desired performance and durability of the concrete. In conclusion, finding alternatives to lower-density natural aggregates is crucial for future concrete production.

In the quest for alternative materials to natural aggregates, lightweight concrete (LWC) incorporating Expanded Polystyrene (EPS) beads has emerged as a promising solution. EPS beads, which are lightweight and thermally insulating, can be used as a replacement for both coarse and fine aggregates in concrete mixes. The utilization of EPS beads in LWC presents numerous benefits. First and foremost, the beads exhibit a notably diminished density compared to conventional natural aggregates, leading to a decrease in the overall weight of the concrete. This attribute is especially advantageous in scenarios where the reduction of weight is crucial, such as in precast elements or high-rise constructions, as it aids in the minimization of inert loads and enhancement of structural effectiveness. Additionally, the thermal insulating characteristics of EPS beads play a significant role in enhancing the energy efficiency of structures. LWC with EPS beads has the potential to offer improved thermal insulation properties, resulting in decreased heat transfer across walls and floors. Consequently, this can lead to a reduction in energy consumption necessary for heating and cooling purposes. This characteristic renders it a compelling choice for sustainable construction endeavors that emphasize the preservation of energy.

According to the ACI 318-19 code,[3] LWC concrete contains lightweight aggregate and has an equilibrium density, determined by ASTM C567, ranging from 1440 to 2160 kg/m³. The code recognizes the unique characteristics of LWC by incorporating a modification factor λ (ranging from 0.75 to 0.85) to account for the reduced mechanical properties of lightweight concrete compared to normal-weight concrete with the same compressive strength. It is noteworthy to mention that the use of polystyrene to produce LWC is not explicitly covered by building codes such as the ACI 318-19. Therefore, the behavior and structural performance of elements made of LWC with polystyrene require experimental investigation and evaluation. Experimental studies can provide valuable insights into the behavior of LWC with polystyrene and help determine appropriate design guidelines and recommendations for its use in structural applications.

Youm *et al.* focused on investigating the punching shear resistance of lightweight aggregate concrete (LWAC) slabs with low reinforcing ratios by experimental and analytical methods. This study aimed to examine the impact of LWAC on the punching shear capacity of slabs, as well as to assess the failure process of LWAC slabs with low levels of reinforcement.[4] A total of five slabs were fabricated, consisting of one conventional concrete slab and four LWAC slabs employing various lightweight aggregate materials. The results indicated that the angle of the punched shear failure surface varied based on the characteristics and origin of the coarse particles employed in the LWAC slabs. The slab designated as LWAC with clay spherical-shaped coarse aggregates (referred to as L-CL-S slab) demonstrated a relatively reduced inclination of the punched shear failure surface in comparison to slabs containing crushed-shaped coarse aggregates (referred to as L-SH-C and L-SL-C slabs). Carmo *et al.* has the intention of determining the punching resistance, angle of punching shear crack, and control perimeter in reinforced LWAC slabs. Six slabs were created with the same and longitudinal reinforcement as shear reinforcement, and constructed without shear reinforcement.[5] The experimental data that was recorded during the tests, such as cracking and maximum loads, displacements, rotations, stiffness, failure modes, and cracking patterns, were analyzed and compared with the design predictions of the most important concrete codes. These concrete codes include Eurocode 2 (EC2), fib Model Code 2010 (MC2010), and American Concrete Institute (ACI) 318. According to the research findings, the change in LWAC strength influences the punching strength, but it does not significantly impact the stiffness or angle of the primary fracture in the punching cone. The evaluation of punching shear strength attained by design approaches in the codes was greater than the experimental values.

Urban *et al.* focused on conducting tests in the Research Laboratory of the Department of Concrete Structures. These experiments aimed to assess the efficacy of shear reinforcement in the form of double-headed studs in LWAC slabs.[6] The experimental trials encompassed nine parts with dimensions measuring 2400 × 2400mm and a thickness of 200mm. The variables under investigation encompassed the longitudinal reinforcement ratio and the cross-sectional characteristics of the punching shear reinforcement. The study's findings indicated a correlation between the longitudinal reinforcement ratio and the magnitude of deformation. The slabs containing double-headed studs demonstrated shear failure without yielding in the longitudinal reinforcement, revealing the inherent brittleness of LWAC.

Shatarat & Salman carried out an experiment on thirteen reinforced concrete flat slabs to examine the behavior of punching shear. The study investigated four different configurations of punching shear reinforcement, including ordinary closed rectangular stirrups (referred to as the ST group), rectangular spiral stirrups (referred to as the RSP group), advanced rectangular spiral stirrups (referred to as the ARSP group), and circular spiral stirrups (referred to as the SP group).[7] The available sizes for each layout are 100 mm, 150 mm, and 200 mm. Additionally, a slab specimen lacking any form of punching shear reinforcement was subjected to testing. The experimental findings indicated that the circular spiral reinforcing scheme yielded the most significant improvement in punching shear capacity when compared to alternative reinforcement schemes. The SP group demonstrated a range of percentage enhancements, varying from 23% to 30%, in comparison to the reference specimen. The RSP group and ARSP group exhibited improvements ranging from 15% to 23% and 16% to 25%, respectively. The punching shear capacity of the ST group showed an increase ranging from 9% to 13% as compared to the reference specimen.

Mu'tasim Abdel-Jaber *et al.* aimed to study the possibility of obtaining lightweight concrete by using Expanded Polystyrene (EPS) beads instead of NA in concrete mixes by testing a total of 119 cubes and 118 cylinders. The results revealed that replacing normal-weight aggregates with lightweight material beads reduces the concrete mix's density and compressive strength.[8] Compared to acceptable aggregate replacement, coarse aggregate replacement significantly reduces concrete density made with EPS beads, while acceptable aggregate replacement affects compressive strength less than coarse aggregates. Also, the optimum mix was obtained for 12.5% Coarse + 25% Fine + 250ml Master Glenium 51 superplasticizer mix, where the density and compressive strength were reduced by 11.3% and 7.8%, respectively.

Mu'tasim Abdel-Jaber *et al.* experimentally investigated the effect of using EPS beads and pozzolana aggregate (PA) on the shear behavior of the reinforced concrete beams and the studies demonstrate a reduction in both the compressive strength and density of beams containing EPS and EPS with superplasticizers, with decreases of 21.7% and 24.9% for compressive strength, and 11.3% and 16.2% for density, respectively. EPS resulted in a 19.4% decrease in the ultimate shear capacity of the beams compared to the control beams. The addition of a superplasticizer to the EPS aided in partially preserving the beam's capacity. In contrast, beams subjected to a temperature of 300 °C exhibited comparable ability to manipulate beams that were not heated. Nevertheless, when subjected to a temperature of 600 °C, the beams exhibited a substantial decrease in their maximum load-bearing capability in comparison to the unheated control beams.[9]

Rouzan Samir Alhnifat *et al.* Explored the compressive strength, response to elevated temperatures, and shear performance of lightweight concrete by substituting PA with EPS. The study found that hardened concrete density and compressive strength were reduced after EPS replacement.[10] However, the mix with EPS and 250 ml of Master Glenium 51a superplasticizer had a compressive strength of 40.11 MPa at 28 days, showing EPS's promise in lightweight concrete. EPS-containing concrete mixes had less compressive strength loss at 500 °C than the control mix. Additionally, the beam constructed with EPS and superplasticizer had the best shear capacity among the others.

Raw and Al-Nsour *et al.* conducted experimental and theoretical analyses to examine the flexural behavior of rectangular reinforced concrete beams exposed to a temperature of 650 °C for 3 hours.[11] The beams were subsequently repaired using near-surface mounted (NSM) basalt fiber-reinforced polymer (BFRP) bars and NSM carbon fiber-reinforced polymer (CFRP) ropes. Out of the twelve RC beams designed, seven were fixed using NSM-BFRP bars and three were fixed using NSM-CFRP ropes to rectify flexural weaknesses. The results indicated that beams repaired with NSM-BFRP bars exhibited similar performance to beams repaired with NSM-CFRP ropes, with recovery percentages ranging from 88.2% to 127%. Theoretical results strongly agreed with empirical observations, consistent with the guidelines outlined in ACI 440.2R-08.

The world of lightweight concrete has seen many studies that enhance our understanding of this adaptable material. In these studies, Yingguang Fang *et al.* conducted a study on the mechanical properties of lightweight concrete prefabricated building structural beams.[12] Mouhammed J.Lafta focused on an experimental investigation regarding the production of sustainable lightweight concrete.[13] Mohamed K. Ismail *et al.*, delved into the flexural behavior and cracking of lightweight reinforced concrete beams containing coarse and fine slag aggregates. [14] 'Mu'tasim Abdel-Jaber *et al.* explored the thermal effect on the flexural performance of lightweight reinforced concrete beams using expanded polystyrene beads and pozzolana aggregates.[15] Stefania Grzeszczyk *et al.* presented test results of lightweight concretes obtained by introducing lightweight aggregates (Pollytag, expanded clay aggregate, and expanded polystyrene beads) in varying quantities (from 30 vol% to 60 vol%) to the reactive powder concrete (RPC) mix.[16]

## 2. Materials and methods

### 2.1 Concrete and steel reinforcement

In a study conducted by (Abdel-Jaber, Shatarat, & El-Nimri, 2023),[8] various experiments were carried out to produce lightweight concrete by replacing natural aggregates with EPS. Different percentages, of course, and fine aggregates were replaced until the optimal mix design was determined. The most suitable mix design involved substituting 12.5% of the coarse particles and 25% of the fine aggregates with EPS beads. This resulted in lightweight concrete with reduced weight while maintaining its compressive strength.

The lightweight concrete used in this study was specifically designed to decrease the total weight of the slabs while ensuring sufficient structural integrity. This particular form of concrete comprises EPS beads, wherein 12.5% of the coarse particles and 25% of the fine aggregates are substituted with EPS beads as stated before. The significance of this lightweight composition is in its ability to evaluate the influence of decreased density on the punching shear capacity. Table 1 presents the optimum concrete mix design used in this study.

During the concrete mixing and pouring process, each concrete slab required the use of three separate concrete mixes. As part of this comprehensive assessment, cylindrical samples with a height of 300 mm and a diameter of 150 mm were extracted from each concrete mix to evaluate their compressive strength according to ASTMC192/C192M:

**Table 1.** Optimum concrete mix proportions for normal & lightweight concrete.

| Mix | Coarse Aggregates ($kg/m^3$) | Fine Aggregates ($kg/m^3$) | Cement ($kg/m^3$) | Net Water ($kg/m^3$) |
|---|---|---|---|---|
| Control | 944.29 | 835.944 | 375 | 191.63 |
| 12.5% Coarse + 25% Fine | 826.25 | 626.958 | 375 | 191.63 |

**Table 2.** Compressive strength & density results for all specimens.

| Sample | 28 days Compressive Strength (MPa) | 28 days Compressive Strength (MPa) | Weight (Kg) | Density ($Kg/m^3$) | Reduction Percent (%) |
|---|---|---|---|---|---|
| T1 | 30.2 | 29.4 | 12.5 | 2357.80 | - |
|  | 29.2 |  | 12.45 | 2348.40 | - |
|  | 28.9 |  | 12.5 | 2357.80 | - |
| T1-L | 26.5 | 26.8 | 10.86 | 2048.50 | 13.12 |
|  | 27.1 |  | 10.85 | 2046.61 | 13.20 |
|  | 26.9 |  | 10.85 | 2046.61 | 13.20 |
| T1-LM | 30.5 | 30.1 | 10.88 | 2052.27 | 12.96 |
|  | 29.6 |  | 10.86 | 2048.50 | 13.12 |
|  | 30.2 |  | 10.85 | 2046.61 | 13.20 |
| T1-LMS | 31.5 | 30.96 | 10.84 | 2044.73 | 13.28 |
|  | 30.9 |  | 10.85 | 2046.61 | 13.20 |
|  | 30.5 |  | 10.86 | 2048.50 | 13.12 |

Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.[17] Consequently, for each concrete slab, three cylindrical samples were collected and tested. In addition, all these cylindrical samples were meticulously examined to ensure compliance with the American Concrete Institute (ACI318-19) requirements regarding the weight of the lightweight concrete mixture. The results of both the sample weights and their respective compressive strengths are described in Table 2.

The longitudinal steel reinforcement used in the slab specimens was high-yield strength deformed bars of grade according to ASTM A615/615M: Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement.[18] The slabs are designed to ensure that a punching shear failure occurs before a flexural failure. Accordingly, a yield-line analysis was performed to predict the flexural failure load. Then, the punching shear load was calculated using ACI 318-19 to ensure that such shear load was lower than the yield-line load. The top and bottom flexural reinforcement bars with a diameter of 16 mm were placed in two directions with a reinforcement ratio of 1.29%.

### 2.2 Cement

Ordinary Portland cement (OPC) Type I was used for this investigation. This variety of cement was chosen since it was able to satisfy all the stringent requirements outlined in ASTM C150/C150M.[19] Table 3 contains information regarding the chemical makeup of the cement that was used

**Table 3.** Chemical composition of ordinary Portland cement type 1.

| Chemical Composition | %By Mass |
|---|---|
| $SiO_2$ | 21.5 |
| $Al_2O_3$ | 5.8 |
| $Fe_2O_3$ | 3.4 |
| CaO | 63.5 |
| MgO | 1.1 |
| $SO_3$ | 2.8 |

### 2.3 Aggregates

The natural aggregates used in this study, for all specimens, were crushed limestone with a maximum aggregate size of 19 mm (retained); however, each type's specific gravity, water absorption, and density differ. All tests were performed according to ASTM C 127 and the results are illustrated in Table 4.

**Table 4.** Physical properties of coarse aggregates.

| Property | Value |
|---|---|
| Apparent Specific Gravity (ASG) | 2.58 |
| Water Absorption (%) | 1.7 |
| Density (Unit weight) ($kg/m^3$) | 1350 |

### 2.4 Expanded polystyrene beads

Expanded polystyrene (EPS) is a synthetic substance produced through chemical treatment or steam application to polystyrene foam at high temperatures.[20] This process leads to the formation of closed-cell spheres filled with air, resulting in a non-absorbent material with a density ranging from 20 to 35 kg/m$^3$. The EPS is commonly employed in nonstructural components, particularly in lightweight sandwich panels (Fig. 1). Its effectiveness has been demonstrated in improving the durability of concrete and providing enhanced fire resistance, thermal insulation, and sound insulation properties. The primary features of The EPS include the appropriate aggregate size and regularity of gradation, cost-effectiveness compared to alternative aggregate types, and its non-absorbent nature during concrete mixing, resulting in reduced water content in concrete mixtures. Table 5 presents the physical & mechanical properties of the EPS.

**Fig. 1** Expanded polystyrene beads.

**Table 5.** Physical and mechanical characteristics of EPS.

| Mechanical Characteristics | Value |
|---|---|
| Tensile Strength, Yield | 47.1-51.0 MPa |
| Flexural Yield Strength, | 0.0750-3.00 MPa |
| Modulus of Elasticity | 0.00650-2.65 GPa |
| Adhesive Bond Strength | 0.100-0.400 MPa |
| Physical Characteristics | Value |
| Density | 0.00310- 3.50 g/cc |
| Water Absorption | 0.0300 - 9.00 % |
| Viscosity | 1.65 - 1.70 cP |
| Permeability | 0.500 - 3.50 |

### 2.5 Master Glenium 51

Master Glenium 51 is a superplasticizer of high performance that effectively improves concrete workability, flow qualities, and rheological features. The additive was introduced into certain specimens to examine its impact on punching shear capacity. Table 6 offers comprehensive characteristics of the utilized type in this work:

### 2.6 Silica fume

Silica fume is a finely powdered substance that is obtained as a secondary product during the manufacturing of silicon and ferrosilicon alloys. It is composed of spherical particles with an average diameter of 150 nm. The utilization of this substance serves to enhance many characteristics of concrete, including its bond strength, compressive strength, and abrasion resistance. In this experiment, a portion of the cement with silica fume has been replaced to assess its impact on the structural performance of lightweight concrete.

**Table 6.** Master Glenium 51 properties.

| | |
|---|---|
| Appearance | Yellowish-brown liquid |
| Specific gravity @20 °C | 1.10 ± 0.03 g/cm$^3$ |
| Ph-value | 6.0 ± 1 |
| Alkali Content (%) | ≤ 5.0 (by mass) |
| Chloride Content (%) | ≤ 0.10 (by mass) |
| Water reduction | ≥ 112% of reference mix |

### 2.7 Test samples

### 2.7.1 Test matrix

In this work, an investigation was conducted on four distinct concrete samples to get insights into their behavior while subjected to punching shear stresses. All the samples exhibit the same concrete dimensions and equivalent reinforcement areas at both the top and bottom. The sole distinction among them lies in the concrete mix design. Therefore, each sample's configuration is determined solely by the type of concrete used, whether it is normal-weight concrete, lightweight concrete, or the inclusion of superplasticizer and silica fume. This enabled us to investigate the behavior of various concrete mixtures under the influence of punching shear pressures, thereby obtaining valuable insights into their performance.

Detailed descriptions of these four concrete samples are provided in Table 7, in which a unique symbol denoted each sample.

**Table 7.** Details of test specimens.

| Symbols | Denoting |
|---|---|
| T1 | Control slab- Normal weight concrete |
| T1-L | Only lightweight concrete |
| T1-LM | Lightweight concrete + Master Glenium 51 |
| T1-LMS | Lightweight Concrete + Master Glenium 51 + Silica Fume |

### 2.7.2 Slab reinforcement details

All four slabs had dimensions of (1800×1800×150) mm and (200×200×200) mm column stub was placed at the center of each slab for load application. The slabs were designed using the requirements of the "American Concrete Institute's Code ACI "318M-19[3] to fail in punching, as shown in Fig. 2.

### 2.7.3 Test setup

The specimens underwent a four-point load testing procedure, which is a frequently utilized approach for assessing the

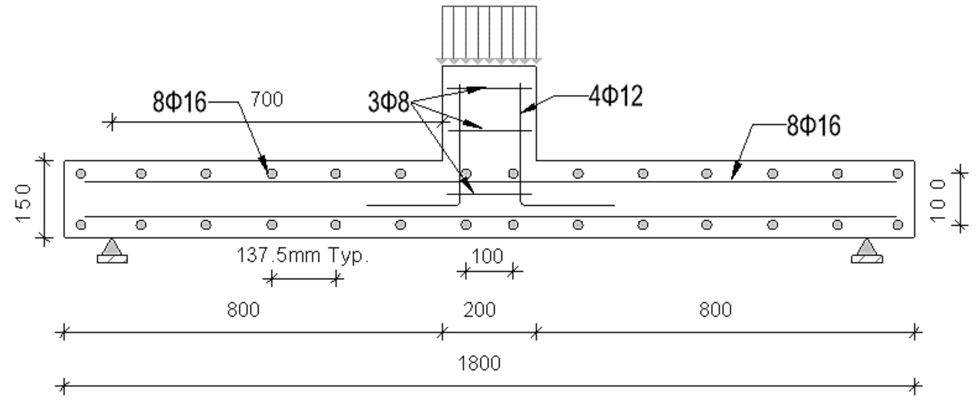

**Fig. 2** Reinforcement details of the slab.

mechanical properties and punching shear strength of concrete slabs. The experimental configuration consisted of a loading frame equipped with four-point supports strategically positioned at predetermined intervals in accordance with the experimental design. As shown in Fig. 3, the flat slab specimens were supported by four steel beams on each side. Each steel beam has a tube section. The center lines of these beams will be located 100 mm from the edge of the flat slab specimen. Hence, the center-to-center support distance is 1.6 m. The steel tubes rest on rigid concrete blocks along the edges, and the load will be applied to the concrete column by a vertical hydraulic jack connected to a heavy-duty load cell. The load was applied gradually, and the force and deflection readings were recorded at a one-second time interval.

## 3. Results and discussion

### 3.1 Load-displacement test results

This study analyzes four distinct samples of concrete slabs, including both normal and lightweight concrete, to evaluate the impact of lightweight concrete, Master Glenium 51 superplasticizer, and silica fume on their punching shear capacity.

Among the samples, the T1-L specimen, made entirely of lightweight concrete, substituted 12.5% of the coarse aggregate and 25% of the fine aggregate with an Expanded Polystyrene Bead, resulting in a significantly lower punching shear capacity, approximately 22.5% lower than the control sample, T1, which utilized only from normal weight concrete. Notably, the addition of a small amount of the Master Glenium 51 superplasticizer to the T1-LM sample greatly enhanced its punching shear capability, almost matching the performance of the control sample T1. Nevertheless, the T1-LMS sample, which was provided with both Master Glenium 51 and silica fume, exhibited a modest 2% increase in shear capacity compared to the control sample, making it the most notable effect found.

This finding underscores the limited impact of adding silica fume alongside Master Glenium 51 in enhancing the shear resistance of the lightweight concrete samples, with Master Glenium 51 exhibiting a more pronounced effect, especially when comparing the results of the third sample (T1-LM) at 290.31 KN to the fourth one (T1-LMS) at 301.1 KN. Figure 4 shows that the "Load vs. Displacement" curves for the three different samples (T1-L, T1-LM, and T1-LMS) display highly similar slopes from the start of load application until reaching the maximum load, despite changes in their maximum load values. In contrast, the first sample, T1, which is composed of normal-weight concrete, behaves differently, showing a distinct slope until it reaches its maximum load.

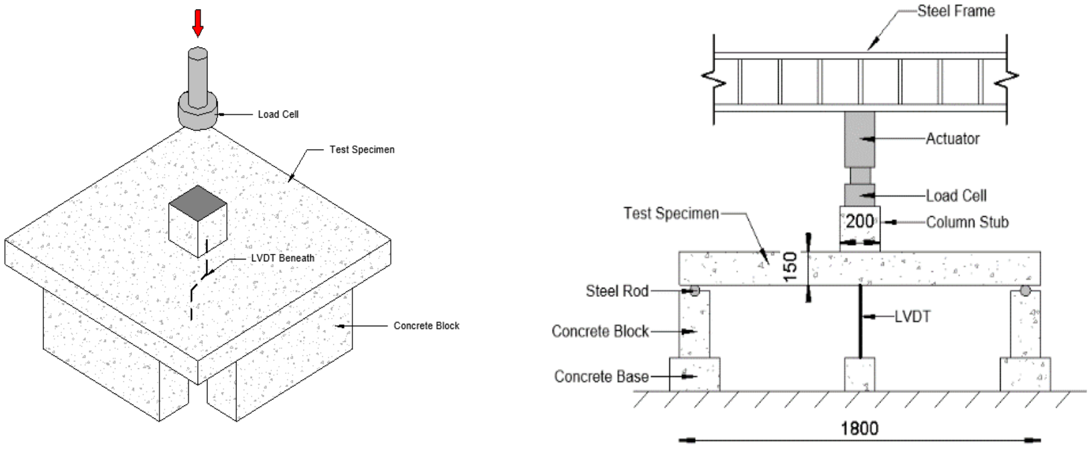

**Fig. 3** The test setup and LVDT device.

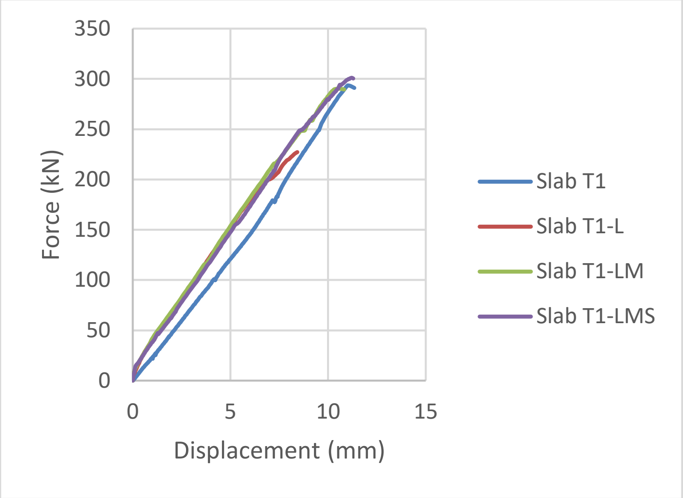

**Fig. 4** Load verses Deflection curve of all slabs.

### 3.2 Strength prediction by code provisions

The punching shear strength of the tested flat slab specimens was determined by applying the design formulas specified in the ACI 318-19 code. According to the ACI 318-19 rule, in slabs without punching shear reinforcement, the critical perimeter of the punching shear, denoted as $b_0$, must be at least half the distance (d/2) from the four faces of a column, regardless of whether the corners are rounded or straight. This is referred to as the pseudo-critical section for shear to simplify the derivation of the design equations.

The nominal shear strength, as per the ACI 318 code is given as follows[3]:

$$v_n = v_c + v_s \quad (1)$$

where the nominal shear strength, $v_c$ provided by the concrete, is calculated using the least of these expressions:

$$0.33\lambda_s\lambda\sqrt{f_c{}'}$$

$$(0.17 + 0.33\,\beta)\lambda_s\lambda\sqrt{f_c{}'} \quad (2)$$

$$(0.17 + \frac{0.083\alpha_s d}{bo})\lambda_s\lambda\sqrt{f_c{}'}$$

where λ is a factor that depends on the aggregate composition in the concrete mixture and equals 1 for normal-weight concrete, λs is a factor that modifies the effect of size, which is defined as $\lambda_s = \sqrt{\left(\frac{2}{1+0.004d}\right)} \leq 1$, f'c is the cylindrical compressive strength of the concrete in MPa, αs is 40 for inner columns, 30 for edge columns, and 20 for corner columns, while β is the ratio of the long side to the short side of the column. Table 8 outlines all samples' analytical results according to the ACI318-19 code.

**Table 8.** Analytical results of specimens.

| Specimen designation | Results by code |
|---|---|
| T1 | 275 kN |
| T1-L | 196.86 kN |
| T1-LM | 278.1 kN |
| TL-LMS | 282.07 kN |

### 3.3 Comparison between expected analytical results and test results

Figures S1-S8 present the cracking pattern on both top & bottom faces of the slabs for all specimens. Table 9 and Fig. 5 present the experimental values for the load ($V_{Exp}$) and deflection, along with the calculated load values according to the ACI code ($V_{Cal}$). The "$V_{Exp}/V_{Cal}$" ratio indicates the level of agreement between the experimental results and the code-based calculations, with values close to 1 indicating a strong alignment.

Based on the previous results, it could be noticed that for specimen T1, which is composed of normal-weight concrete, the experimental load ($V_{Exp}$) slightly exceeded the code-based calculation ($V_{Cal}$), with a $V_{Exp}/V_{Cal}$ ratio of 1.07. In contrast, the lightweight concrete specimen T1-L showed a $V_{Exp}/V_{Cal}$ ratio of 1.15, indicating that the experimental load significantly exceeded the code-based estimate.

Furthermore, when Master Glenium 51 superplasticizer was added to T1-LM, the $V_{Exp}/V_{Cal}$ ratio of 1.04 was achieved, suggesting a strong correlation between the experimental and code-based load values. Similarly, the T1-LMS sample, enhanced with Master Glenium 51 superplasticizer and silica fume, demonstrated a $V_{Exp}/V_{Cal}$ ratio of 1.07, indicating a favorable alignment with the computation based on the code. These results emphasize that the ACI code incorporates a reduction factor (0.75) for lightweight concrete, which is approximately matched in the case of T1-L (consisting solely of lightweight concrete). However, the addition of both Master Glenium 51 superplasticizer and silica fume in T1-LM and T1-LMS samples suggests that these additives mitigated the impact of this reduction factor, as indicated by a $V_{Exp}/V_{Cal}$ ratio close to 1, signifying that the experimental results closely align with the code-based calculations. This underscores the

**Table 9.** Experimental and analytical results of specimens.

| Specimen designation | Effective depth (d) (mm) | 'fc' (MPa) | Experimental Results | | Results by ACI code | |
|---|---|---|---|---|---|---|
| | | | $V_{Exp}$ (kN) | Def. (mm) | $V_{Cal}$ (kN) | $\frac{V_{Exp}}{V_{Cal}}$ |
| T1 | 120 | 29.4 | 293.45 | 11.3 | 275 | 1.07 |
| T1-L | 120 | 26.82 | 227.21 | 8.4 | 196.86 | 1.15 |
| T1-LM | 120 | 30.1 | 290.31 | 10.6 | 278.1 | 1.04 |
| T1-LMS | 120 | 30.96 | 301.1 | 11.2 | 282.07 | 1.07 |

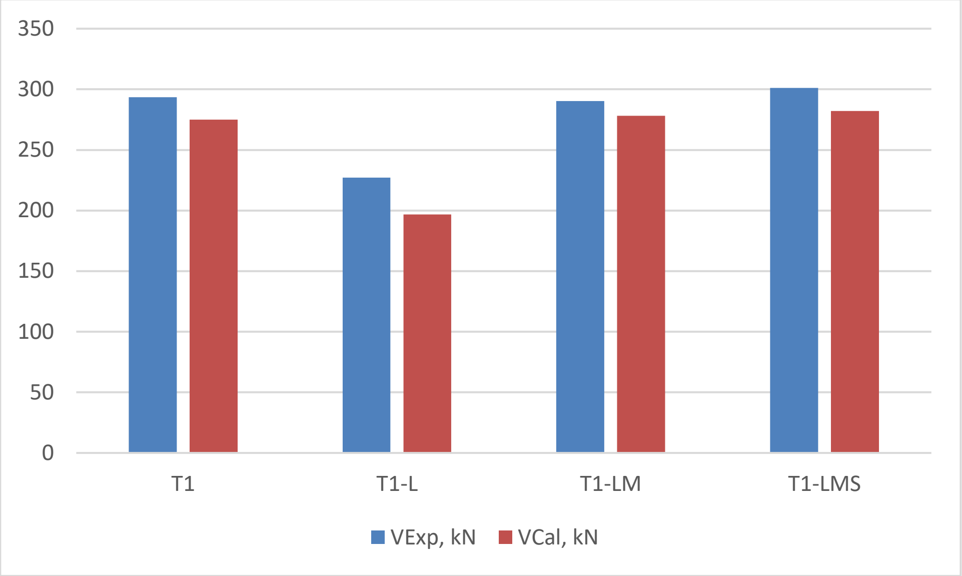

**Fig. 5** Comparison of calculated punching shear capacity as per ACI code to the experimental capacity.

effectiveness of these additives in enhancing the load-bearing capacity of lightweight concrete.

## 4. Conclusion

Four flat slabs were subjected to a punching shear loading test to assess the incorporating EPS beads, Master Glenium 51 superplasticizer and silica fume on the punching shear capacity of the lightweight concrete slabs. The punching shear behavior was investigated experimentally by monitoring the load-deflection curves, ultimate load values, vertical deflection measurements, and cracking patterns. Furthermore, the results were analytically computed using the ACI 318-19 code. The conclusions of this research can be stated as follows:

1. The utilization of EPS beads in concrete mixtures offers a promising solution to reduce concrete weight, potentially reducing the environmental impact associated with EPS waste.
2. The substitution of 12.5% of the coarse aggregate and 25% of the fine aggregate with Expanded Polystyrene beads (EPS) resulted in a 15% decrease in the weight of the concrete in comparison to normal-weight concrete.
3. The lightweight concrete slab displayed the lowest punching shear capacity, demonstrating a performance of approximately 22.5% inferior to the control samples composed solely ofnormal-weight concrete. This indicates that the incorporation of Expanded Polystyrene beads (EPS), Master Glenium 51 superplasticizer, and silica fume played a crucial role in improving the punching shear capacity of the lightweight concrete slabs.
4. The addition of Master Glenium 51 superplasticizer alone had a substantial impact on punching shear capacity, nearly matching the control normal weight concrete sample. When silica fume was also introduced, it further improved the punching shear capacity by a relatively modest 2% compared to the Master Glenium 51 superplasticizer alone.
5. The study revealed that the ACI 318-19 code is effective in predicting the behavior of lightweight concrete with EPS beads. All results are closely aligned with code-based calculations, emphasizing the code's suitability for such applications.

## Conflict of Interest

There is no conflict of interest.

## Supporting Information

Applicable.

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