Behaviour of dry mix EPs mortar panel under axial eccentric loading

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Abstract. Lightweight mortar panel has been an alternative wall in the construction. However, the unsteady distributions of loads to the panel due to disorder alignment during construction affect the capability of the wall to reach the optimum load capacity. The inclusion of expanded polystyrene (EPs) that less in density and strength also was contributed the factor to achieve cohesiveness the properties of mortar panel. Therefore, this study aimed to determine the load capacity of the panel under axially eccentric loading that comply with the design of plain wall in BS8110-1. Due to this type of loading, the deformation was investigated through the load-strain, buckling profile and failure mode. This research involves laboratory experimental work for the different panel’s height. Four variables of EPs proportion were designed in a dry-mix mortar and constructed into the panel. From the result, the panel failed in compression stress where the wall deflected in single and double curvature at the vertical position. The high slender panels were failure at the joint of panels with the maximum deflection of 3.96 mm. Meanwhile, the low slender panel tended to crack and bend at the top. The ultimate eccentric load obtained for the panel at 45% EPs replacement was 587.76 kN.

1. Introduction

The industrial of lightweight panel for building construction leads to the favourable advantages that include better site management, cost efficient and speeding time construction. The use of lightweight panels has extended to structural member; and previous studies have investigated this panel on the strength performance and properties behaviour [1][2][3]. It is desirable to meet the proper design of panel that compatible with certain development such as high-rise construction, commercial building and factory. Recently, the lightweight panel has been designed for strengthening member such as load bearing system [4][5]. The panel of load bearing system has offered carrying load that includes roof and floor to the foundation. This type of panel has received greater acceptance by practicing engineers as load carrying structural element [6]. Practically, load on the panel are distributed by the axial load and also for those subjected to lateral load. However, in order to obtain perfect alignment of the panel during the construction works, it is important to investigate the effect of eccentric loading towards the structural performance of panel [6][7][8]. In this scenario, the slenderness ratio gained was affected by the eccentric loading toward the panel due to non-uniform loading applied to this structural element.

In fact, using lightweight material leads to the reduction of density and substantially reducing its strength [9]. The types of lightweight aggregate are classified in natural (pumice, diatomite, volcanic cinders, etc.) and artificial (perlite, clay, sintered fly ash, expanded shale, etc.) [10][11]. It had indicated that using lightweight materials in panel provide gravity load that represents a small total load. Thus,
the lightweight panel reduce of self-weight and promotes saving in dead load to the foundation [12]. Expanded polystyrene (EPS) is a type of artificial ultra-lightweight polymeric materials wastes which are widely used as a lightweight material in concrete that presented with good behaviour, suitable as materials embedded into concrete and mortar [10][11]. Besides, the density of EPS was less than 30 kg/m³ and EPS possess quite inert favourable properties including having non-absorbent water, chemical resistance to frost, pollutants, dilute acids and alkalis [13]. According to the previous researchers, EPS wastes have been used in lightweight concrete that subjected to axial compression loading [4][10][14].

In the production of the EPS concrete, it was found out that the lightweight aggregate of EPS tends to float and formed a weak thin layer at the surface of concrete, hence has a tendency to segregate during casting [15][16][17]. Therefore, to improve the mechanical properties and bonding between cement with EPS in concrete, silica fume or other additives were added into the concrete matrix [10][18]. Meanwhile, superplasticizer was utilized to prevent the segregation and thus, improve adherence of EPS [18][19]. To author’s knowledge, no study has been investigated for casting EPS mortar without additional chemical and other materials as to keep the EPS tabulate uniformly in the mixture. Therefore, this present study carried out design of dry mix mortar method and compression with a pressure to form as a panel. This research investigated the potential of mortar panel to achieve the minimum strength as load bearing panel for application in structural member. A limited design mix mortar ratio between cement and sand (C:S) was achieved as structural grade mortar with specific strength ranges between 20 to 50 N/mm² and satisfied workability [20]. The economic and friendly waste material such as EPS used as lightweight aggregate for sand replacement by volume of 0, 40, 45 and 50 % proportion. It is noticeable that EPS able to incorporate into the mix more attractive up to 50% [21]. Therefore, the present study aimed to determine the eccentric load capacity of the panels that made of dry mix EPS mortar as plain wall. To understand the failure behaviour of the dry mix EPS mortar lightweight panel under through eccentric loading, the load capacity with strain, buckling profile and failure mode was evaluated upon failure.

1.1. Analysis using BS8110-1:1997

In this experimental program, the panel was constructed into four category involves single stack without reinforcement panel (URS), single stack reinforcement panel (RS), double stack without reinforcement panel (URD) and double stack reinforcement panel (RD) respectively. The compressive strength $f_{cm}$ was determined earlier was resulted in range between 15 to 20 N/mm². As given from BS8110-2:1985 the structural member use of concrete below grade 20 (C20) should be limited to plain walls [22]. Since the panel considered as lightweight of grade 15 and above, it also considered related to BS8110-1:1997 [23]. According to Clause 3.9.4 the design ultimate axial force in a plain wall may be calculated on the assumption that the members transmitting forces into it are simply supported. The arrangement of vertical forces, the resultant force in every plain wall should be assumed to have a transverse eccentricity of not less than $t_w/20$ or 20 mm as mentioned in Clause 3.9.4.5 [23]. In this experimental works, the distance of eccentricity, $t_w/6$ (16.67 mm) was decided complying with the American Concrete Institute (ACI 318) [24].

Since the determining of forces on a single plain wall as according to Clause 3.9.4, the slenderness ratio $L/t_w$ should not exceed 30 for the wall is braced or unbraced. In this research, guidance as given in BS8110-1:1997 Clause 3.9.4.17 the maximum unit axial load for unbraced plain walls should satisfy the following:

$$n_w \leq 0.3(t_w-2e_{x,1})f_{cu} \tag{1}$$

Where $n_w$ is the maximum design ultimate axial load per unit length on wall, $f_{cu}$ is the characteristic strength of concrete, $t_w$ is the thickness of wall and $e_{x,1}$ resultant eccentricity calculated at the top of the wall [23].
2. Experimental program

2.1. Materials

The binder used in mortar mixtures was Type I Ordinary Portland Cement (OPC) which comply with the requirement as BS EN 197-1:2000 [25]. The particle size distribution was performed using sieves analysis for EPs and river sand as according to the BS EN 933-1:2012 [26]. In this experiment, EPs wastes were collected from Industry Foam E&E, Klang, Malaysia and these EPs were crushed into fine granule. The physical properties of cement, sand and EPs are given in table 1.

| Materials | Density (kg/m$^3$) | Passing sieve size | Fineness modulus | Particle geometry |
|-----------|-------------------|-------------------|------------------|------------------|
| OPC       | 3150              | -                 | -                | Powder           |
| Sand      | 2650              | < 5 mm            | 2.6              | Irregular        |
| EPS       | 18                | < 5 mm            | 1.4              | Irregular        |

2.2. Mix proportion

A total of 72 samples were prepared as panel units with size 500 mm (h) height x 500 mm (L) length x 100 mm ($t_w$) thickness. In this study, the mortar composed of 1:3.0 by cement to sand (C:S) was adopted. Water to cement (w/c) ratio of 0.37 with the amount of water at 203 kg/m$^3$ and amount of cement content of 550 kg/m$^3$ were fixed for this investigation. One layer of reinforcement mesh (BRC) Y10 was employed at the central section of the sample and the plain panels were tested as a control panel. The details of the mix proportion and the category of panels prepared are as presented in table 2. The numbers following after each panel designation represent as percentage proportion of EPs incorporated in the mixtures. The dimensions of the EPs mortar panel are shown in figure 1(a).

| ID   | Stack of panel | Height, (h) mm | Sand kg/m$^3$ | EPS kg/m$^3$ | Aspect ratio h/L | Slenderness ratio h/t$_w$ |
|------|----------------|----------------|--------------|--------------|------------------|--------------------------|
| URS0 | Single         | 500            | 1649         | -            | 1.0              | 5                        |
| URS40| Single         | 500            | 990          | 4.48         | 1.0              | 5                        |
| URS45| Single         | 500            | 907          | 5.04         | 1.0              | 5                        |
| URS50| Single         | 500            | 825          | 5.60         | 1.0              | 5                        |
| URD0 | Double         | 1000           | 1649         | -            | 2.0              | 10                       |
| URD40| Double         | 1000           | 990          | 4.48         | 2.0              | 10                       |
| URD45| Double         | 1000           | 907          | 5.04         | 2.0              | 10                       |
| URD50| Double         | 1000           | 825          | 5.60         | 2.0              | 10                       |

Figure 1. Fabrication of samples (a) single and double stack EPs mortar panel (dimensions are in millimetre) and (b) casting of panel made of dry mix EPs mortar compressed and demoulded.
2.3. Fabrication of samples

Procedures in making the dry mix method initially started with the mixing of cement and sand to ensure the materials were evenly dispersed before water is added. Then, the EPs were added into the matrix and mixing was continued until the mortar was uniformly distributed. The panels were cast and moulded using a steel mould size 500 mm x 500 mm x 150 mm (t). The mould height was made higher than the size of the specimens in order to fill up the fresh mortar until the top of the mould. A square size of 495 mm x 495 mm of reaction steel platen required as a top load to compress the fresh mortar until 100 mm (t_w) to form a panel. A pressure of 700 psi (4.826 N/mm²) was applied during the compression process to produce the sample. The specimens were demoulded immediately after casting and curing to 28 days of air-dried. The process of casting panel was demonstrated in figure 1(b). For panels with Y10 reinforcement, compression was performed two times. Firstly, when the thickness attained 45 mm and secondly when the panel attained 100 mm. One layer of Y10 BRC with size 475 mm x 475 mm was placed on the top of the 45 mm where the panel was subjected to the first compression and the balance EPs mortar was poured immediately and subjected to the second compression. Meanwhile, the double stack panel required mild steel (R10) at 300 mm length as a stiffener to support top and bottom panel with standard mortar layering between the panels.

3. Testing program

3.1. Experimental set up and loading protocol

EPs mortar panels were prepared for compression under axial eccentric loading until failure using 1000 kN Universal Testing Machine at Heavy Structure Laboratory of the Faculty of Civil Engineering. The panel was set up vertically and pin-end type support was applied to the panel connection as shown in figure 2. A distance of the axial load acting on the panel have been offset from the center to the front is referred to as eccentricity (e) using roller type support for top and bottom panel. Grooves in V-shape were machined on bearing plate to match the roller shape loading edge, hence the eccentricity could be precisely controlled. The instruments of strain gauges with size 67 mm and displacement transducer (LVDT) was set up as shown in figure 3. The pace rate was set up at 0.03 mm/second and all the specimens were loaded to failure. The results were analyzed in terms of load deformation profile and the data were depicted graphically.

![Diagram](image)

**Figure 2.** Experiment set up: (a) support set up condition, (b) same top and bottom set up and (c) arrangement of LVDT and strain gauges on panel.
4. Results and analysis

4.1. Ultimate load

The total of 16 panels with reinforcement and without reinforcement were successfully tested until failure subjected to single stack and double stack position. Figure 4 shows the ultimate load with an eccentricity of $t_w/6$ loading recorded at 586.76 kN for URS45 panel, which this ultimate load was 60% developed from 366.84 kN for URS0 panel. However, the ultimate eccentric load that can be sustained by the panel was found to decrease for the panel with reinforcement. The eccentric load of the RS45 panel decreased 15.16% compared to URS45 panel. The failure of the RS45 panel occurred because of the large pore entrapped, which is found in the reinforced panel that contributed to this reduction of load capacity. Some pores appeared during compression of the panel at casting process, which the reinforcement mesh shifted upward after unloading the compression machine. Consequently, the binder between mortar and reinforcement mesh tended to split and became a weak bonding.

Figure 4. Eccentric load incorporates with axial displacement: (a) EPs mortar panels with reinforcement and (b) EPs mortar panels without reinforcement (plain walls).

However, the eccentricity loading capacity for the panel at the slenderness ratio of 10 decreased compared to that with the slenderness ratio of 5. The dropped of eccentricity loading by 15.93% loads from RS45 to RD45 panel and 17.19% loads from UR545 panel to URD45 panel was recorded. The loading capacity reduced because the effect of high slenderness ratio and the crack at mortar joint occurred between double stack panels contributed to the failure of the panel. It was deduced that load bearing capacity under compression test reduced due to the factor of slenderness ratio [7]. In this study, the load capacity for eccentric loading decreased in reference to the axial load at the center section of the panel.
that was tested earlier in uniformly distributed type loading for the same design of the panel. In fact, the practice of axial eccentric loading previously have shown the decrease of load bearing capacity, while the stress value reached is slightly higher in the walls if the load is centered [7].

The EPs mortar panel were seen to have densities varying from 1700 to 2000 kg/m$^3$ and the ultimate eccentric loading ranges between 200 to 600 kN as shown in table 3. In this investigation, the load increased in mortar panel with contains fine granule EPs size below 5 mm. Previous study proved that the compressive strength of EPs lightweight concrete increase with a decrease in EPs bead size [10][11][27]. Besides, the density of this research decreased with increased in volume of EPs aggregates as accordance to recent researchers [18][28]. But the load of panel increased thus found to be indirectly proportional to the reducing of density. It can be observed that the panel that made of EPs replacement of 0%, 40% and 45% gained the eccentric load. Meanwhile the loading dropped to 50% for all design panels. The 0% EPs replacement in the mortar panel was less hydration between the aggregates and cement binder. The binding properties of mortar panel improved at 40% to 45% of EPs because of the non-absorbent characteristics of EPs providing sufficient water to have proper hydration with the binder. For a panel that contained 50% EPs, the eccentric load capacity decreased due to excess of water contained cement flowed out from the mould during the compression at the casting process. The observation is consistent with the fact that the water of cement ratio is the main factor affecting the workability of concrete, whereby the increase in water content resulted in higher workability of the mix [29].

### Table 3. Results of densities, maximum lateral displacement and percentage ratio of ultimate load.

| ID   | Density $\rho$, kg/m$^3$ | Displacement $\Delta_{um}$, mm | Ultimate load (Test) $P_{ul}$, kN | BS8110-1 $n_u$, kN | Percentage ratio $P_{ul}/n_u$ | Eyes observation of EPs in mortar |
|------|--------------------------|-------------------------------|---------------------------------|-----------------|-------------------------|-------------------------------|
| URS0 | 1948                     | 1.63                          | 366.84                          | 74.49           | 79.69                   | No segregation                |
| URS40| 1856                     | 1.52                          | 511.95                          | 100.35          | 80.39                   | No segregation                |
| URS45| 1798                     | 1.42                          | 586.76                          | 149.88          | 74.45                   | No segregation                |
| URS50| 1714                     | 2.97                          | 544.75                          | 90.39           | 83.41                   | No segregation                |
| URD0 | 1954                     | 1.44                          | 242.84                          | 74.49           | 69.33                   | -                             |
| URD40| 1828                     | 3.96                          | 240.59                          | 100.35          | 58.29                   | No segregation                |
| URD45| 1798                     | 3.09                          | 485.90                          | 149.88          | 69.15                   | No segregation                |
| URD50| 1788                     | 2.32                          | 372.23                          | 90.39           | 75.72                   | No segregation                |
| RS0  | 1929                     | 0.39                          | 349.32                          | 74.49           | 78.68                   | -                             |
| RS40 | 1886                     | 0.81                          | 429.96                          | 100.35          | 76.67                   | No segregation                |
| RS45 | 1796                     | 1.06                          | 497.80                          | 149.88          | 69.90                   | No segregation                |
| RS50 | 1760                     | 0.85                          | 377.17                          | 90.39           | 76.03                   | No segregation                |
| RD0  | 1982                     | 1.54                          | 308.66                          | 74.49           | 75.87                   | -                             |
| RD40 | 1852                     | 2.03                          | 249.58                          | 100.35          | 59.80                   | No segregation                |
| RD45 | 1852                     | 1.24                          | 418.50                          | 149.88          | 64.20                   | No segregation                |
| RD50 | 1779                     | 2.00                          | 318.31                          | 90.39           | 71.60                   | No segregation                |

### 4.2. Load strain

The strain elongation data was measured in micro strain unit ($\mu$e) and the characteristic behaviour load versus strain of the panel are demonstrated as in figure 5 at loading condition $e = \Delta_{um}/6$. The samples designated as H-0, H-40, H-45 and H-50 represent the horizontal positioned direction, while V-0, V-40, V-45 and V-50 as the vertical positioned direction of strain gauge that placed at the middle of the sample. For double stack panel, the term HT and VT denoted for top panel, while the term HB and VB denoted for the bottom panel. It can be seen that all the strain gauges, which were vertical positioned were in negative value because the loading is in compression force state. The strain gauges that located horizontal were in positive value because in tension force state. The RS45 panel with reinforcement for single stack exhibited higher strain under tension force as that of the unreinforcement panels. The strain under the tension force was lower than that under compression force. All the panels experienced strain increment until failure.
4.3. Buckling profile and failure mode
The buckling profile and failure mode are presented in figure 6. The deformation and lateral displacement was measured by using LVDT to monitor the deflection curve of panel after failure. In the experimental work, the eccentric load and LVDT was positioned at front panel from the center. The curved at positive value as illustrated in figure 6 shows the rear side of panel, meanwhile the curved in negative value presents as front panel. Due to eccentric loading, it is obviously shown that the panels failed after bend towards the rear side. From the demonstration, the URS and RD panels were deflected in double curvature while URD panels deflected in the single curvature at lateral direction, hence continues to bend until the failure by flexure. Buckling profile as illustrated in the figure 6 shows that the panels failed by buckling except the RS panels. The over limit load capacity in the actual structural wall experienced buckling damage since reaching the upper limits stress to the slender wall [7]. The URS and URD panels showed the high buckling mode at 2.97 mm and 3.96 mm deflection at the ultimate eccentric load. Respectively, the lines of failure for RS panels lied nearest to the center of the panel as shown in figure 6(b). From observation, the curvature for panel at slenderness ratio h/tw=5 shows it failed by major buckled at the top. While panel at slenderness ratio h/tw=10 has the major curvature at middle span due to cracked at the joint between the top and bottom panel.

Figure 5. Eccentric load incorporated with strain characteristic of EPs mortar panel: (a) single stack without reinforcement, (b) single stack with reinforcement, (c) double stack without reinforcement and (d) double stack with reinforcement.
Figure 6. Deflection curve for lateral displacement at effective height: (a) single stack without reinforcement (URS), (b) single stack with reinforcement (RS), (c) double stack without reinforcement (URD) and (d) double stack with reinforcement (RD) panel.

Figure 7 shows type of crack pattern for the panels upon failure mode. The URD and RD panels tended to fail and brittle at joint between the panels before collapsed, while URS and RS failed by crushing. Those panels that were reinforced influence the failure mode. This might be due to the weak bonding between the reinforcement and mortar in the panel section. It was observed that when the ultimate load is achieved, most of the panels exploded and failed in a brittle mode [30]. The high slender wall subjected to compression loading contributes to collapsing failure.

Figure 7. Cracking at the reinforcement: (a) void appear between mortar and reinforcement, (b) failure double stack panel and (c) buckle at top single panel.

5. Conclusion
The EPS was distributed uniformly in the panel section and promote a good bonding between EPS and mortar after applied with dry mix method. Therefore, the objective of this study was achieved since loading capacity form panel testing is higher than analysis calculation BS 8110 but still not fulfil the requirement as load bearing member due to less in strength. The density of panel is decrease with increased volume proportion of EPS. The loading capacity found to be increased by influence increased of water and affected by workability in mortar. As the eccentricity load increased, the panel bends to rear side position and crushed at the mortar joint between the panels. The mortar panel behaviour has been observed through increment of strain, buckling profile and failure mode were determined. The double curvature appeared in the buckling profile due to failure in shear stress. Since the economic waste...
material from EPs still under practicing in industrial lightweight panel, it is able to establish as construction member with minimum design required.

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