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Digital Image Correlation for the Determination of Mechanical Properties of Concrete with Modified Expanded Polystyrene

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Abstract. Modified Expanded Polystyrene (MEPS) has emerged as a promising material obtained by heating and shredding Expanded Polystyrene (EPS) to enhance its specific gravity and strength. This study investigates the suitability of MEPS as a partial replacement for coarse and fine aggregates in non-structural lightweight concrete. The substitution levels of MEPS were set at 10%, 20%, and 25% of the total aggregate volume. Cylindrical concrete specimens (10 x 20 cm) and concrete cubes (15 x 15 x 15 cm) were used for the experimentation. Ultrasonic Pulse Velocity (UPV) and Digital Image Correlation (DIC) were performed to evaluate the mechanical properties of the concrete under compressive stress test. Through DIC, the approach to obtain the concrete's properties, including compressive strength, stiffness, elastic modulus, and poisson's ratio, were obtained. The results demonstrated that the concrete mixture with 20% MEPS substitution exhibited the most favorable performance. Overall, the use of MEPS as a replacement for aggregates in non-structural lightweight concrete shows promise for optimizing the material's mechanical properties. This study provides valuable insights into sustainable construction practices and contributes to the ongoing research in utilizing innovative materials for enhancing concrete performance.

Keywords: Digital image correlation; Innovative material; Lightweight Concrete; Modified expanded polystyrene; Ultrasonic pulse velocity

1. Introduction

The utilization of expanded polystyrene (EPS) in concrete mixtures has been investigated in various research studies. Research has shown that the inclusion of expanded polystyrene can reduce the density of concrete, making it lightweight and providing potential benefits in construction applications (Gamal *et al.*, 2023; Purnomo, Baskoro, and Muslim, 2021; Kan and Demirboga, 2009). The thermal insulation properties of polystyrene concrete have also been investigated, indicating its potential to enhance energy efficiency in buildings (Chung, Elrahman, and Stephan, 2018).

Furthermore, studies have examined the mechanical properties and structural performance of polystyrene concrete to assess its suitability for different engineering applications. Research findings suggest that this type of concrete can exhibit favorable structural behavior and resistance to specific loading conditions (Kulkarni and Shete, 2022; Vinod, Surendra, and Shobha, 2022). Its lightweight nature also contributes to improving

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some advantages in civil engineering applications (Rishith, Kumar, and Kiran, 2021; Hussein, 2021; Sjah *et al.*, 2018; Sulong, Mustapa, and Rashid, 2018).

The manufacturing process and mix design of polystyrene concrete have been investigated to optimize its properties and performance (Zhang, 2021). Researchers have investigated different additives, mix proportions, and curing methods to improve the strength, durability, and workability of the material (Shabbar, Al-Tameemi, and Alhassani, 2022; Ulhaq and Andayani, 2021; Mwero and Onchaga, 2020; Patidar *et al*., 2019; Xu *et al.*, 2012).

The use of Expanded Polystyrene (EPS) material in everyday life has increased EPS waste. Essentially, EPS waste is highly resistant to decomposition and becomes a major issue in waste management. As a form of environmental concern, concrete with a mixture of partial fine/coarse aggregate EPS can be a viable and considerable answer to this issue. This research aims to explore an innovation by examining the mechanical properties of concrete with a mixture of partial fine/coarse aggregate with Modified Expanded Polystyrene (MEPS). MEPS is a material resulting from the modification of EPS (Kan and Demirboga, 2009). This modification is carried out by heating the expanded polystyrene using an oven at a specific temperature, which slightly alters the shape and characteristics of the material compared to EPS, but the differences are not too significant. The most notable difference lies in the volume and density of this material. MEPS has a smaller volume than EPS, thereby increasing its density, which in turn affects the strength of the concrete produced. It is indicated that the density of MEPS concrete will increase while the volume of MEPS will decrease (Kan and Demirboga, 2009). By replacing a portion of the fine/coarse aggregate with MEPS, the lightweight concrete manufacturing standards can be met while gradually addressing the issue associated with EPS waste.

2. Methods

2.1. Preparation and Material Properties of Aggregates

Before casting the concrete, it is necessary to prepare and test the material properties of the aggregate. The types of aggregate used in this study were natural coarse aggregate, natural fine aggregate, and MEPS material as a partial substitute for natural coarse/fine aggregate.

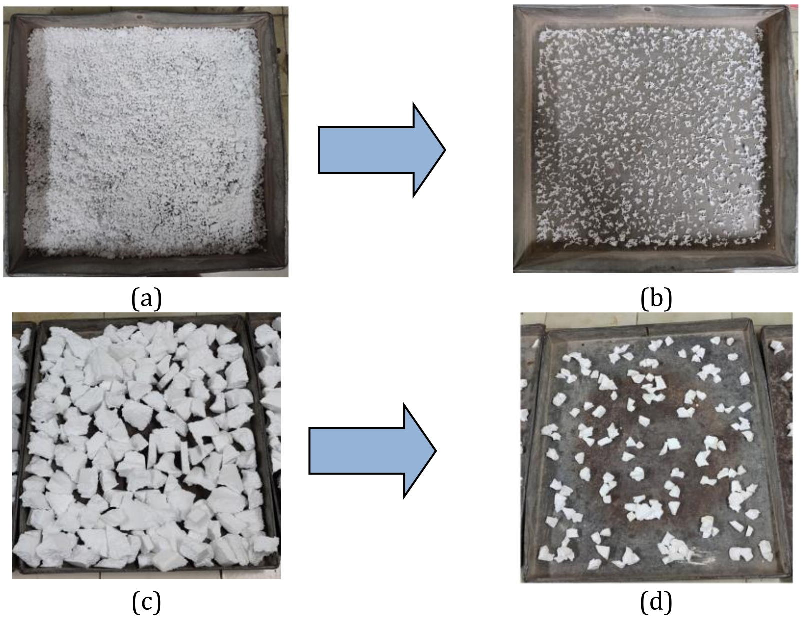

Figure 1 Transformation of EPS to MEPS material before and after oven-dry for (a, b) fine aggregate (FA); (c,d) coarse aggregate (CA)

Preparation to obtain MEPS material needs to be done to be used as a partial substitute for aggregate in concrete. Expanded polystyrene (EPS) obtained from waste of electronic equipment packaging is prepared. This EPS waste will then undergo treatment by being heated in an oven at a temperature of 130°C for 15 minutes to become a new material called Modified Expanded Polystyrene (MEPS). For fine aggregate composed of MEPS, the first step is to grate the EPS to form granules of a size like fine aggregate (≤ 4.75 mm), then oven-dry them at a temperature of 130°C for 15 minutes. When producing coarse aggregate with MEPS, the initial step involves cutting the EPS into randomly sized pieces using a cutting tool or by hand. Subsequently, these pieces are oven-dried at a temperature of 130°C for 15 minutes (Kan and Demirboga, 2009). The transformation of EPS material into MEPS for fine and coarse aggregate is illustrated respectively in Figure 1.

Table 1 Material properties of natural fine aggregate, natural coarse aggregate, and MEPS material as a partial substitute for fine and coarse aggregate

Material Properties	Natural Fine Aggregate (Sand)	MEPS as a partial substitute for Fine Aggregate (MEPS-FA)	Natural Coarse Aggregate (Stone)	MEPS as a partial substitute for Coarse Aggregate (MEPS-CA)
Specific Gravity (SG) (g/cm^3)	2.63	0.24	2.37	0.24
Absorption (%)	3.52	-	8.6	-
Bulk Density (Compacted)	1.64	-	1.362	-
Size Max. Aggregate (inch)	0.187	0.187	1	1
Fineness Modulus (f_m)	2.18	3.06	4.39	4.76
Abrasion (%)	-	-	54.86	-
Organic Content Test	No.8	-	-	-

The condition of natural coarse and fine aggregates used at the time of casting the concrete were in saturated surface-dry condition. The material properties of natural coarse and fine aggregates can be seen in Table 1.

2.2. Mortar Mix and Testing Result

The compressive strength of mortar with variations in the proportion of using MEPS as a partial substitution of fine aggregate was evaluated. Three cases are studied involving normal mortar, MEPS FA-25% mortar (mortar with MEPS material as a substitute for fine aggregate with 25% of the total weight of fine aggregate), and MEPS FA-50% mortar (mortar with MEPS material as a substitute for fine aggregate with 50% of the total weight of fine aggregate). The normal mortar mix design was conducted following ASTM C109/C109M Standard (ASTM C109/C109M, 2020). For each case, 60 samples will be cast and tested at ages 1, 3, 7, and 28 days.

Figure 2 shows the compressive strength and density results of normal mortar, MEPS FA-25% mortar, and MEPS FA-50% mortar. The higher the density of the mortar, the higher the compressive strength of the mortar tends to be. The use of MEPS material as a substitute for fine aggregate causes the density of the mortar to decrease, resulting in a lighter sample than normal mortar. The density of the mortar sample was reduced by 7% and 18% for case MEPS FA-25% and case MEPS FA-50%, respectively. The MEPS FA-25% mortar exhibits better compressive strength than MEPS FA-50%. Therefore, in this research, MEPS material from 0% to 25% will be utilized as a substitute for aggregate in concrete.

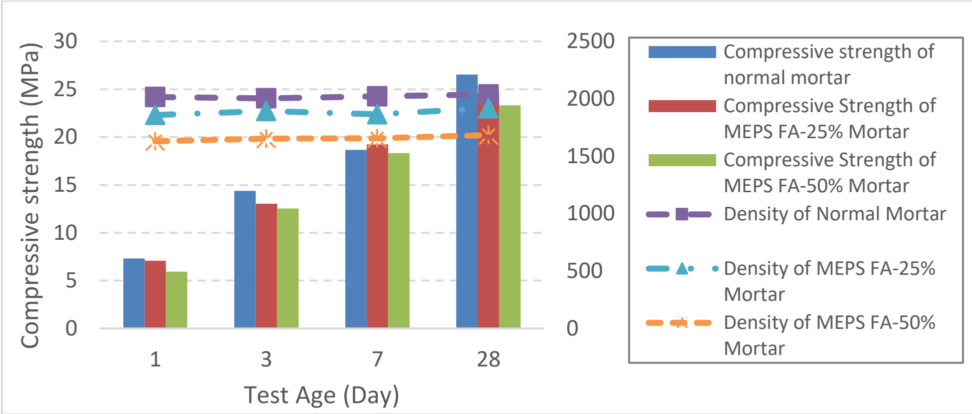

Figure 2 Compressive strength and density of "Normal Mortar", "MEPS FA-25% Mortar", and "MEPS FA-50% Mortar"

2.3. *Concrete Mix Design*

The concrete mix design will be conducted using the ACI 211.1 Standard. The water-to-cement ratio is 0.424, with a normal concrete density of 2400 kg/m^3, and the target slump for each composition is 7 - 8 cm. The specimens are 120 cylinders (diameter of 10 cm and height of 20 cm), which will be tested at the ages of 7, 14, and 28 days, and 80 cubes (15 cm x 15 cm x 15 cm), which will be tested at the ages of 7 and 28 days. A total of 5 samples will be made for each day and each composition. The average will be taken from the results of testing all these samples to ensure that the generated data is more representative.

The research will investigate the effects of incorporating MEPS material at proportions of 10%, 20%, and 25%, serving as a substitute for both fine aggregate (FA) and coarse aggregate (CA) in the concrete.

Table 2 Concrete mix design

Specimen	Material weights per unit volume (kg/m^3)					
	Water	Cement	Fine Aggregate (Sand)	MEPS as a partial substitute for Fine Aggregate (FA)	Coarse Aggregate (Stone)	MEPS as a partial substitute for Coarse Aggregate (CA)
Normal	192.8	454.7	596.8	-	997.5	-
FA-10%	192.8	454.7	537.1	5.5	997.5	-
FA-20%	192.8	454.7	477.4	11.1	997.5	-
FA-25%	192.8	454.7	447.6	13.8	997.5	-
CA-10%	192.8	454.7	596.8	-	897.8	10.3
CA-20%	192.8	454.7	596.8	-	798.0	20.5
CA-25%	192.8	454.7	596.8	-	748.1	25.7

2.4. *Digital Image Correlation, Ultrasonic Pulse Velocity, and Compressive Test Set-Up*

DIC is a method that can be used for non-contact optical analysis of concrete. It involves capturing digital images of the surface of the test object to analyze the deformation of that plane through the related images (Ernawan *et al.*, 2023; Deltanto, Handika, and Sentosa, 2021; Ghani *et al.*, 2016; Pan and Li, 2011). Digital Image Correlation (DIC) testing is performed using a camera with a setting of 3 fps and in black and white. Before conducting DIC, the test object is painted with white paint and then sprayed with black points to create a speckle pattern that can be read by the GOM Correlate application. The image capturing is performed before the compressive strength testing begins, capturing the failure pattern.

Ultrasonic Pulse Velocity (UPV) testing is conducted using the UPV Pundit Lab+ instrument, following the ASTM C597 standard (ASTM C597, 2016). Before the UPV testing, the instrument needs to be calibrated according to the desired settings. Then, the test object is coated with grease on each side to be tested, which acts as a medium for transmitting ultrasonic waves through the specimen (Zarate *et al.*, 2022).

Compressive strength testing is performed following the ASTM C39/C39M standard (ASTM C39/C39M, 2014). For cylindrical test specimens, capping of the specimens is processed using gypsum to ensure a flat surface and a loading direction parallel to the axis of the cylinder.

3. Results and Discussions

3.1. Compressive Strength and Density

The results of concrete compressive strength and bulk density for cube and cylinder specimens are shown respectively in Figure 3(a) and Figure 3(b). In this figure, the average compressive strength results of cylindrical concrete specimens at ages 7, 14, and 28 days, as well as cubic concrete specimens at ages 7 and 28 days, can be observed. The use of MEPS as a substitute for fine aggregate and coarse aggregate shows better results than normal concrete in the variation of 20% composition. The substitution of 20% MEPS for fine aggregate increases compressive strength by 14%, while the substitution of 20% MEPS for coarse aggregate shows an increase in compressive strength of 5.6% compared to normal concrete. These results indicate that the optimal composition of MEPS material as a substitute for both fine and coarse aggregate is 20%, regardless of the shape of the tested specimens (cube or cylinder). The obtained bulk density decreases as the amount of MEPS increases. This is due to the lightweight nature of the MEPS material, which reduces the bulk density of the concrete.

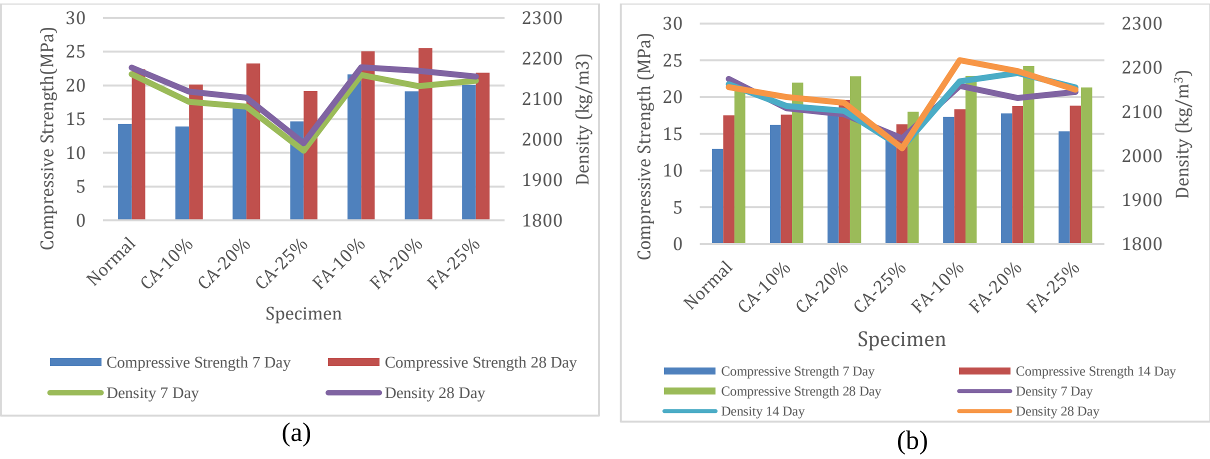

Figure 3 Compressive strength and density of using MEPS material as a substitute of fine (FA) and coarse aggregate (CA) in concrete for (a) cube and (b) cylinder specimens

3.2. Correlation of Compressive Strength and Ultrasonic Pulse Velocity

Ultrasonic pulse velocity (UPV) testing is used to determine the density of concrete based on the results of the ultrasonic wave propagation velocity within the concrete. The results of the UPV test will be compared with the compressive strength test results to determine the relationship between them. The correlation between compressive strength and wave propagation velocity for cube and cylinder specimens can be seen respectively in Figure 4(a) and Figure 4(b).

The results of the relationship between compressive strength and wave propagation velocity are expressed in both linear and exponential trendlines, as shown in Figure 4(a,b). The results indicate a direct proportional relationship between compressive strength and wave propagation velocity. However, some samples show significant differences and are considered outlier data. These outlier data are still included and are considered phenomena that may occur during the data collection process. These phenomena can be caused by various factors, including operators or measurements of temperature, accuracy of instrument usage, and variations in the mixture content among different samples.

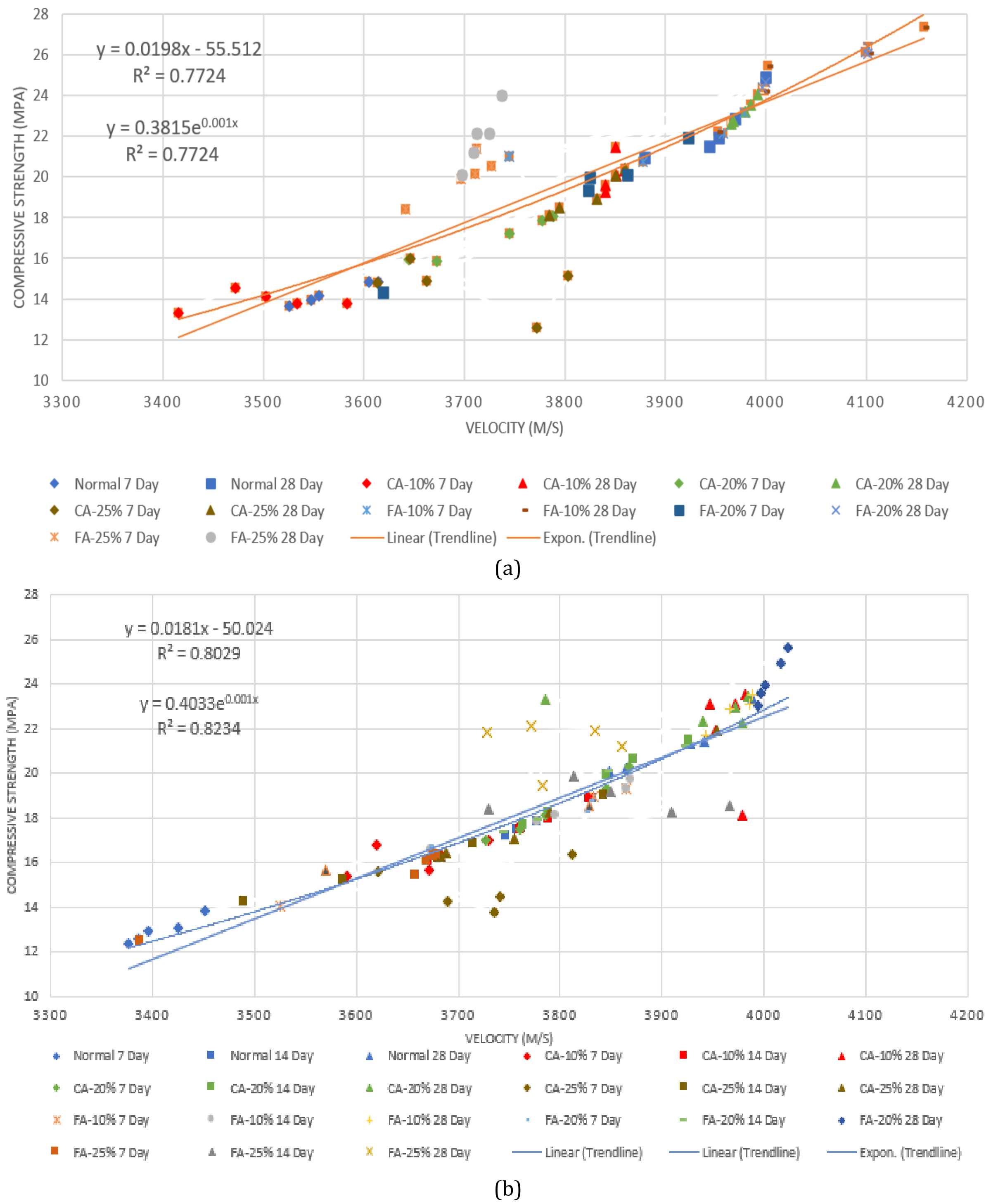

Figure 4 Compressive strength and UPV of using MEPS material as a substitute for fine (FA) and coarse (CA) aggregate in concrete for (a) cube and (b) cylinder specimens

3.3. Digital Image Correlation (DIC)

DIC testing is conducted using the GOM Correlate Pro application to obtain results, such as displacement, stiffness, elastic modulus, and Poisson's ratio for each sample.

3.3.1. Load - displacement

The relationship between load and displacement is obtained through DIC (Digital Image Correlation) testing, as shown in Figure 5 and Figure 6. In this figure, the magnitude of deformation of the test specimen can be observed for each applied load captured by the camera at a speed of 3 fps. This image can be used to identify the vertical and horizontal displacement directions of the test specimen. The deformation results can be influenced by factors such as the strength of the test specimen, the placement of the test specimen in the compression testing machine, and the speckle pattern applied prior to testing.

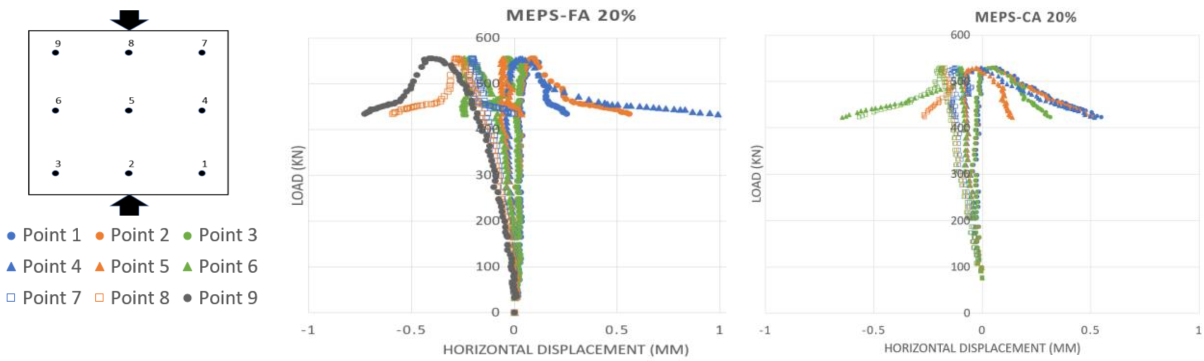

Figure 5 Load – *u* displacement (horizontal displacement) response of using 20% MEPS material as a substitute for fine aggregate (FA) and coarse aggregate (CA) in concrete

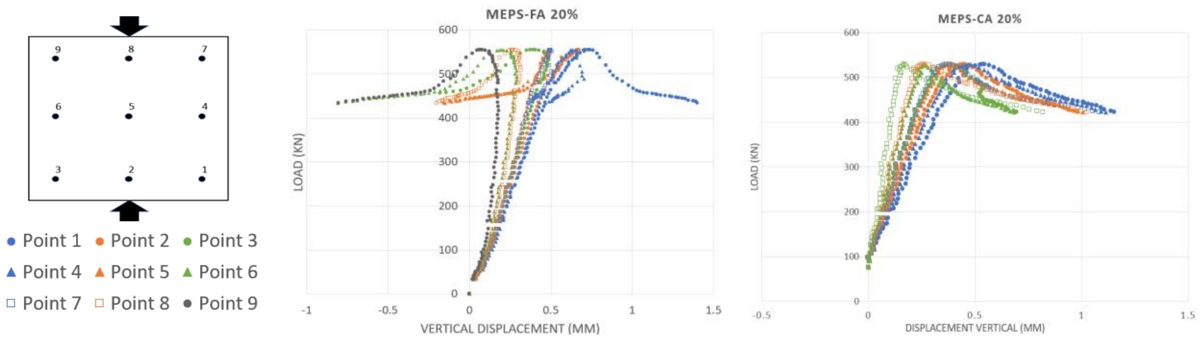

Figure 6 Load – *v* displacement (vertical displacement) response of using 20% MEPS material as a substitute for fine aggregate (FA) and coarse aggregate (CA) in concrete

3.3.2. Stiffness, Poisson's ratio, and modulus of elasticity

The displacement data obtained can be processed into mechanical properties data of concrete, including stiffness, elastic modulus, and Poisson's ratio. It's important to note that these values are considered approximate as they are derived through digital image correlation processing. These results are then used for analysis for each variation of concrete using MEPS (Modified Expanded Polystyrene) mixtures.

The magnitude of stiffness using MEPS as a mixture in concrete shows better results compared to normal concrete. It indicates that concrete using MEPS has a higher level of stiffness, as evidenced by smaller vertical deformations compared to normal concrete for each applied load.

The Poisson's ratio values obtained for each variation still meet the criteria of normal concrete Poisson's ratio, which is 0.15 - 0.2. However, Poisson's ratio value for the FA-25% composition does not yet meet the existing standards, indicating that the 25% composition has a less optimal mixture proportion.

The magnitude of elastic modulus obtained through the DIC approach is significantly different from the theoretical elastic modulus values. This may be due to factors during the DIC imaging process. The elastic modulus values produced by concrete using MEPS are better than those of normal concrete. Based on the results shown in Table 4, the conclusion is that concrete with MEPS mixtures has better mechanical properties than normal concrete, especially in the 20% mixture, which has the most optimal mechanical properties.

Table 4 Stiffness, Poisson's Ratio, and Modulus of Elasticity

Specimen	Average Stiffness (kN/mm)	Average Poisson's Ratio	Average Elastic Modulus (MPa)
Normal	1784.1	0.18	7666.4
FA-10%	2763.7	0.16	12283.1
FA-20%	2751.2	0.19	12227.6
FA-25%	2058.0	0.36	9146.3
CA-10%	2132.9	0.17	9570.4
CA-20%	3595.4	0.18	16569.0
CA-25%	1345.5	0.16	10709.4

3.3.3. Failure pattern

The failure pattern is related to the displacement values obtained. The higher the displacement value, the greater the likelihood of failure occurring. The failure patterns of each sample can be clearly observed using the GOM Correlate application, and the failure patterns are then analyzed. The top failure patterns from each variation can be seen in Figure 7. Each failure pattern is compared to the failure pattern provided by BS-EN-12390-2019, and the MEPS-FA10%, MEPS-FA10%, and MEPS-FA10% patterns fall into the "satisfactory" category.

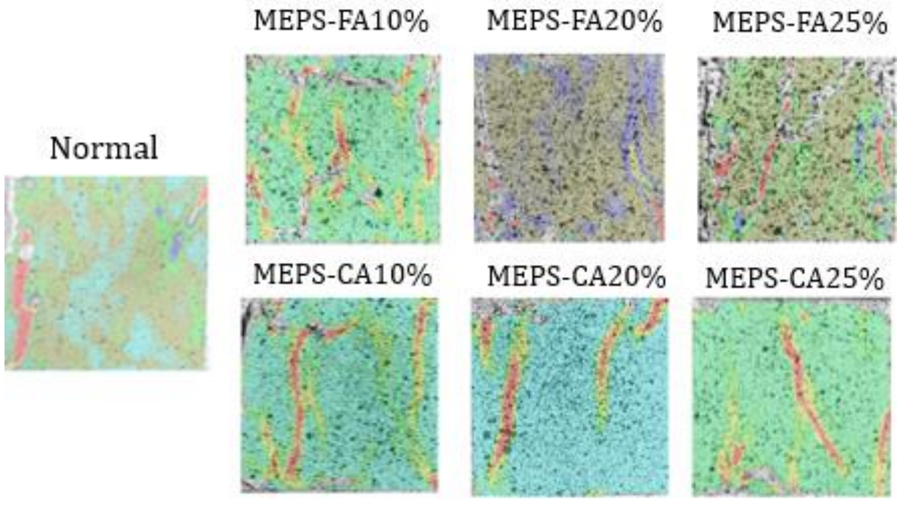

Figure 7 Failure pattern of specimens

4. Conclusions

The substitution of MEPS-FA results in a reduction in both compressive strength and bulk density of the mortar. By introducing MEPS-FA and MEPS-CA at a 20% content in concrete effectively enhances its compressive strength. However, it is important to note that the use of 20% MEPS-FA/CA substituted concrete can be deemed suitable for non-structural applications; although it does not reduce the bulk density, it does not qualify as lightweight concrete. Conversely, the application of 25% MEPS-FA/CA substituted concrete meets the criteria for lightweight concrete, but its mechanical properties are inferior to those of normal concrete. The stiffness magnitude, when MEPS is incorporated into the concrete mixture, demonstrates superior results compared to conventional concrete. Moreover, the Poisson's ratio values obtained for most variations still conform to the specified criteria for normal concrete (0.15 - 0.20). Additionally, the elastic modulus values produced by concrete utilizing MEPS surpass those of normal concrete. Lastly, the failure patterns observed, specifically for MEPS-FA10%, MEPS-CA10%, and MEPS-FA10%, align with the "satisfactory" category as per the standards outlined in BS-EN-12390-2019. The use of MEPS as an aggregate substitute in concrete can be considered a good alternative because it has mechanical properties that are relatively better than concrete without MEPS. The utilization of MEPS as an aggregate substitute meets the criteria for non-structural lightweight concrete with a minimum compressive strength value of 17.24 MPa, but it does not meet the criteria for the density of non-structural lightweight concrete. So, for further research it is necessary to investigate further to increase the amount of MEPS as a substitute for aggregate so that it can meet the criteria for non-structural lightweight concrete.

Acknowledgments

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