ASEAN Engineering Journal

Full Paper

PHYSICAL AND MORPHOLOGICAL INVESTIGATION OF THE UTILIZATION OF EXPANDED PERLITE AS FINE AGGREGATE FOR TYPE M STRUCTURAL LIGHTWEIGHT MORTAR

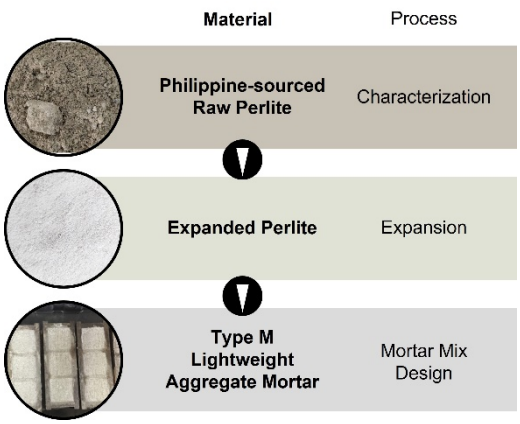
Clarence Rosario Guanzon*, Jesha Faye Torrecampo Librea, Paolo Sarmiento Valencia, Jomar Christian Jeresano Camposano, Rosabelle Louise Abad Caram, Karlo Daniel Quizon Colegio, Mathew Harvey Tongol Peralta

Institute of Civil Engineering, University of the Philippines Diliman, Quezon City, Metro Manila, Philippines

Article history
Received
16 October 2022
Received in revised form
20 February 2023
Accepted
21 February 2023
Published online
31 May 2023

*Corresponding author
crguanzon@up.edu.ph

Graphical abstract



Abstract

The study examined the influence of expanded perlite aggregates (EPA) on mortar properties and whether EPA could replace sand to produce mortar that meets the compressive strength requirement of ASTM Type M mortar. The study involved fabricating mortars wherein sand was substituted by volumes of 20%, 40%, 60%, 80%, and 100% with three types of EPA (EPA A, EPA B, and EPA Coarse). Results showed that EPA-mortars can meet the ASTM compressive strength requirement of 17.2 MPa. The sample attained its greatest compressive strength of 29.19 MPa, which is nearly equal to the control sample strength of 29.42 MPa, upon replacing sand with 60% by volume of EPA A. In comparison to the control mortar density of 2055 kg/m^3, Type M EPA mortar density can drop as low as 1422 kg/m3, which is a 30.8% decrease. Additionally, it was observed that EPA microstructure played a role in the resulting mortar compressive strength. Mortars with the highly absorbent EPA Coarse were found to have less compressive strength than mortars that used EPA A, which has a lower capacity for absorption and more intact microstructure.

Keywords: Expanded perlite aggregates, perlite, mortar, Type M mortar, lightweight mortar

1.0 INTRODUCTION

The construction industry is expected to grow along with the Philippine government's accelerated push for infrastructure development. As the construction industry experiences a surge of projects, it inevitably leaves behind a significant environmental impact [1, 2, 3]. However, the push for infrastructure is not to be vilified altogether as the United Nations even highlights how building critical infrastructure is important in supporting economic and sustainable development [4]. The United Nations listed "Industry, Innovation and Infrastructure" as one of its sustainable development goals, thereby affirming that infrastructure plays an essential role in driving industrial development, especially in emerging economies. The Updated Philippine Development Plan 2017-2022 explicitly states that infrastructure development is envisioned to be a major lever in hastening the country's recovery from the pandemic through enhancing land corridors, expanding mass transportation and investing in critical infrastructure. In order to shift towards more sustainable and resilient practices, it is imperative to evaluate the existing construction processes and identify possible approaches to minimize its impacts.

One way of increasing the sustainability of construction practices is through the use of alternative and sustainable raw materials. Raw materials that are locally sourced, lightweight, and generally environmentally inert are good alternatives to the current emission-releasing and resource-depleting construction

materials. Various alternative materials have been studied as a replacement for fine aggregates, coarse aggregates, or even cement in concrete. Fly ash and bottom ash which are byproducts of coal-fired plants are utilized as alternatives for fine aggregates and cement [5]. Waste glass used as an aggregate replacement is seen as a budding solution that repurposes old and unused glass bottles that would have gone instead to landfills [6]. However, its use in the concrete industry is still controversial because aside from the added costs and labor input in crushing glass, there are qualms within the industry with regards to the resulting mechanical properties of waste glass-incorporated concrete [7]. Recycled glass powder, on the other hand, was shown to improve the mechanical properties of mortars when used as a cement replacement. Almeshal et al. noted that mortar compressive strength increased when glass powder treated in ammonium nitrate was utilized as a partial cement substitute at 10% level [8]. Najaf and Abbasi found that mortars made with 40% cement, 15% fly ash, 15% micro-silica, 15% waste glass powder and 15% waste plastic powder produced a higher mortar compressive strength than that of a mortar with 100% cement level [9].

An alternative raw material, which is generally inert, lightweight, and with abundant reserves in the Philippines, is perlite. Perlite, as shown in Figure 1 (specifically, Figures 1a, 1b and 1c), is a glassy volcanic rock obtained from pumice, which is formed from rhyolitic and dacitic magma. Once perlite is heated at temperatures of around 760-1100°C, the trapped inherent water is converted to vapor which then causes the material to expand 4-20 times its original volume [10]. The construction industry commonly refers to heated and expanded perlite as Expanded Perlite Aggregate (EPA). Aside from construction, EPA is also used in horticulture, insulation, filtration, and other environmental applications that could make use of its high porosity, good insulating ability, and lightweight property [11].

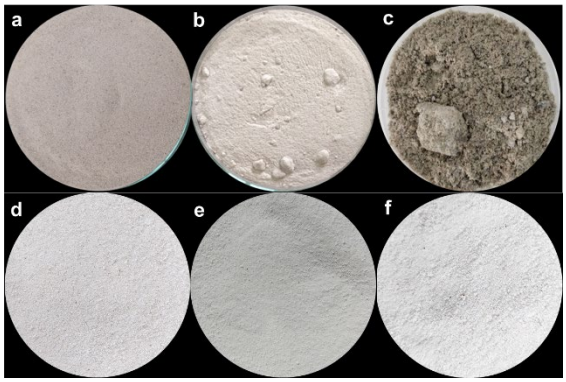


Figure 1 Images of processed, unexpanded perlite samples (a, b) and raw, unexpanded perlite sample (c) along with images of expanded perlite samples EPA A (d), EPA B (e), and EPA Coarse (f)

In the Philippines, one of the most commonly used building materials is concrete masonry units or also known as Concrete Hollow Blocks (CHB). CHBs are a preferred choice in buildings as they are relatively low-cost, durable, and are good insulators for sound and heat [12]. Along with CHBs is the use of masonry mortar to support adjacent CHBs. Masonry mortar made of cement, fine aggregates, and water acts as a binder and fills in the gaps between blocks and bricks. With masonry mortar as a vital component of walls, its strength is, therefore, an important indicator of the overall strength and durability of the wall.

ASTM C270-19AE1 standard specification covers four types of mortar mixes for use in construction of non-reinforced and reinforced unit masonry structures, namely: Type M, S, N, and O [13]. The proportions of cement, lime, and sand used in each mix differ from one another, resulting in a hardened mortar with distinct properties such as bond strength, plastic flow, compressive strength, and durability. Since compressive strength is very straightforward to measure and is frequently related to other qualities of the mortar, such as tensile strength and absorption, it is sometimes used as a primary factor for selecting mortar type [13]. In terms of compressive strength, Type M mortars are the strongest with a minimum required strength of 17.2 MPa, followed by S (12.4 MPa), N (5.2 MPa), and lastly O (2.4 MPa). Type M mortar is a high-strength mortar suggested for use in exterior load-bearing walls above grade and even in below-grade applications such as in foundation walls, retaining walls, manholes, sewers, pavements, walks, and patios [13].

Various studies, such as Jedidi et al. [14], Wadie [15], and Zulkifeli and Mohamed [16] demonstrated the use of EPA as a partial replacement of fine aggregates for cement-based mixtures. Jedidi et al. investigated the impact of EPA on the characteristics of lightweight mortar [14]. 15%, 30%, 45%, 60% and 80% replacement levels of sand by volume were considered. Their findings showed that the unit weight fell as the EPA dose was raised while the compressive strength decreased as the EPA dosage was increased. At 30% fine aggregate replacement with Menderes expanded perlite, the density of the mortar was reduced by almost 25% but its compressive strength was reduced by 65%. Another study by Wadie found that lightweight mortar with EPA as partial replacement of fine aggregates generates compressive strengths that range from 33.2 MPa to 52.5 MPa [15]. It was also noted that as the percentage of EPA increases, the mortar unit weight decreases linearly. On the other hand, Zulkifeli and Mohamed studied the insulating properties of expanded perlite aggregate mortar [16]. They observed that as the percentage replacement of EPA increases, compressive strength at below elevated temperature declines. However, the highest compressive and flexural strengths were recorded at 200°C and 20% EPA replacement with 65.52 MPa and 21.34 MPa respectively, demonstrating that EPA as an aggregate replacement improved the physical performance of mortar at elevated temperatures.

The study aimed to examine whether Philippine EPA could replace sand, a denser raw material, to produce a more lightweight Type M mortar that still adheres to the required compressive strength of 17.2 MPa as stipulated by ASTM. In order to accomplish that, the paper determined how replacing sand with EPA at 20%, 40%, 60%, 80% and 100% replacement levels affects the density and compressive strength of mortar specimen. The paper also explored how EPA of different microstructures influence the mechanical properties of the resulting mortar.

2.0 METHODOLOGY

2.1 Raw Material Properties

Mortar is produced from mixing fine aggregates, cement, and water. In this study, varying combinations of EPA and sand were used as fine aggregates to create mortar samples. Traditionally, sand is solely used as fine aggregate for mortar mixing; however, EPA was utilized in this study both as partial and full replacements to sand to investigate the physical and mechanical properties of the resulting EPA-mortars. With the use of a gas-fired vertical furnace expander, the EPA samples were produced by the researchers from thermally processing raw perlite that was sourced in Camarines Sur, Philippines. Three different kinds of EPA were investigated for the study, namely EPA A, EPA B, and EPA Coarse. EPA A and B were expanded from raw perlite that was pre-processed through washing, grinding, and sieving while EPA Coarse was expanded from raw perlite that was directly acquired from the mine using shovel sampling. Nominal maximum particle size for EPA A and EPA B are both 1.18 mm while that of EPA Coarse is 2.36 mm and as such, EPA Coarse is the coarsest of the three.

Table 1 Physical Properties of Fine Aggregates

Property	EPA A	EPA B	EPA Coarse	Sand
Loose bulk density (kg/m^3)	80	80	50	1460
Bulk density (kg/m^3)	110	110	60	1610
Voids (%)	83	86	91	35
Absorption (%)	29.8	50.9	263.9	3.3
Specific Gravity	0.63	0.78	0.67	2.46
Fineness Modulus	1.57	0.98	2.31	2.06

The physical properties of the sand and each EPA sample as determined using ASTM standard test methods are shown in Table 1. The loose bulk densities of the EPA samples were calculated to be less than 1120 kg/m^3 and were therefore deemed to be lightweight according to the loose bulk density standards of ASTM C330/C330M-17A [17]. This finding is echoed by the results of the specific gravity determination of the EPA samples. Each EPA sample has a specific gravity of less than 1.00 and is observed to float in water as opposed to sand which sinks and settles. EPA samples also show higher void contents than sand because of the porous structure created by the thermal expansion of the perlite particle. The increase in the porosity translates to an increase in the absorption capacity of EPA samples. The absorption of EPA is a particularly important property as it affects the resulting water-cement ratio of the mixture.

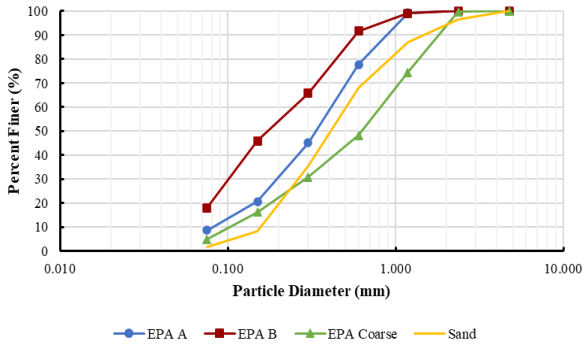


Figure 2 Particle size distribution of fine aggregates

Figure 2 presents the particle size distribution results of the fine aggregates by means of ASTM C136/C136M-19 [18] standard test method. EPA samples A and B were found to be finer than sand which as previously discussed is due to the grinding and sieving of the raw perlite prior to the expansion process. Finer particles have larger total surface area and consequently, larger contact area for water to coat. Extremely fine particles would thus necessitate more water and may also produce less workable mortar. EPA Coarse, on the other hand, contains more coarse particles at a relatively increased rate than sand, particularly in particle diameters between 2.36 mm (Sieve #8) and 0.30 mm (Sieve #50).

Aside from the fine aggregates, type IP Portland-Pozzolan cement and hydrated lime were also utilized. Although not necessary in making mortar, hydrated lime was used as it increases the workability of the mixture. Furthermore, Jedidi et al. noted that a homogeneous and workable concrete/mortar mixture is difficult to obtain due to the high absorption rate of EPA [14]; as such, a type-A (water-reducing) admixture was also used to further improve workability.

2.2 Mortar Fabrication

Figure 3 shows a flowchart of the study methodology. The cement-lime mortar type that was used for the study was Type M mortar. Type M mortar has a design strength of 17.2 MPa. Proportioning was done using the Volumetric Method and was based on the proportion stated in ASTM C270-19AE1. Type M mix proportion, as specified by ASTM C270-19AE1, has 4 parts cement, 1 part hydrated lime, and 15 parts fine aggregate mix. Twelve mortar specimens for each of the 0%, 20%, 40%, 60%, 80%, and 100% replacements were manufactured which resulted in a total of 72 specimens. It should be noted that the 0% mortar pertains to the mortar produced using only sand as fine aggregates and thus, serves as the control specimen. Water-cement ratio for mortar fabrication was set to 0.50. The inclusion and usage of plasticizer with the mix proportion was also done with the intention to increase the workability of the mixture. Plasticizer was included for all samples to increase the workability. The ratio of plasticizer to cement used per mix was calculated from the recommended dosage of the manufacturer at 60 mL per 40 kg of cement used. From the proportion requirements stated in ASTM C270-19AE1, the mix proportions for the mortars are shown in Tables 2 and 3. It should be noted that since EPA Coarse has lower bulk density, mix proportions for EPA Coarse mortars were adjusted and re-calculated accordingly.

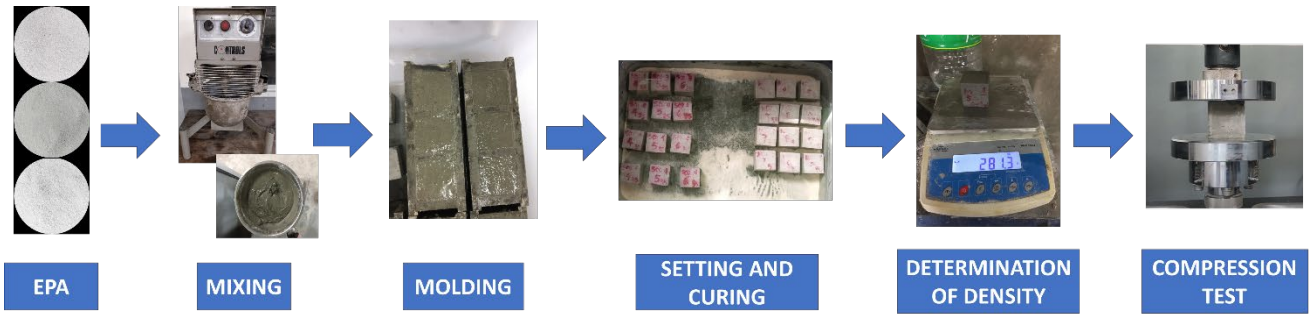


Figure 3 Flowchart of the methodology

Table 2 Mix proportion for EPA A and EPA B mortars

Material	Percentage Replacement					
	0%	20%	40%	60%	80%	100%
Cement (g)	874.2	874.2	874.2	874.2	874.2	874.2
Lime (g)	92.9	92.9	92.9	92.9	92.9	92.9
Sand (g)	2630.2	2104.2	1578.1	1052.1	526.0	0
EPA (g)	0	35.9	71.9	107.8	143.8	179.7

Table 3 Mix proportion for EPA Coarse mortars

Material	Percentage Replacement					
	0%	20%	40%	60%	80%	100%
Cement (g)	874.2	874.2	874.2	874.2	874.2	874.2
Lime (g)	92.9	92.9	92.9	92.9	92.9	92.9
Sand (g)	2630.2	2104.2	1578.1	1052.1	526	0
EPA (g)	0	26.1	52.3	78.4	104.6	130.7

The mortar mixtures were prepared and mixed in accordance with ASTM C305-20 [19]. The mixing procedure was carried out using a mechanical mixer. After mixing, the mortar mix was immediately placed into the molds that were coated with a layer of release agent. The mortar was allowed to set in the mold for at least 20 hours, but not exceeding 28 hours. The ponding method was used as the curing procedure of choice. The specimens were submerged in a water-filled container until the 28-day compressive strength test was performed. Figure 4 shows an image of the mortar specimens to be tested.

Figure 4 Mortar cube specimens

2.3 Testing

The specimens were tested in accordance with ASTM C109/C109M-21 [20]. Three specimens for each EPA type and percentage replacement were tested on the 28th curing day. The specimens were removed from the curing storage, surface-dried with a towel, and weighed before testing. A uniaxial compressive strength test was performed by the research team using an Instron Universal Testing Systems Machine. Mortar density was obtained by taking the ratio of the mortar weight after 1 day of setting in the mold to the mortar volume whose dimensions were measured with a caliper.

2.4 Morphological Characterization

The structure of EPA particles was observed through scanning electron microscopy (SEM). Scanning electron microscopy was conducted using the Hitachi SU-8230 FE-SEM. Prior to viewing under the microscope, the samples were directly dispersed on carbon tape and coated with platinum to avoid charging of the sample surface. The morphological features of the samples were viewed at increased magnifications up to 300x.

3.0 RESULTS AND DISCUSSION

3.1 Effect of EPA Replacement on Mortar Density

The 1-day densities of the mortars prepared with the 3 EPA samples are listed in Table 4. These mortar densities were used in the analysis since these specimens were weighed prior to being submerged in water for the curing procedure. Hence, the weight of the curing water most likely percolating through the mortar cube would be negligible in the calculation of density.

Table 4 1-day densities of the mortar samples using the 3 EPA samples

Material	1-day Mortar Density (kg/m^3) at EPA Percentage Replacement				
	20%	40%	60%	80%	100%
EPA A	2013	1947	1840	1659	1422
EPA B	2037	1948	1850	1651	1464
EPA Coarse	1931	1805	1623	1464	1196

Figure 5 shows the progression of the 1-day mortar density as the percentage replacement increases. The 1-day density of the control Type M sand-mortar is 2055 kg/m^3 and is displayed as the broken line in Figure 5. The density of the mortar prepared with EPA A at 100% replacement decreased by 30.8% from the control sand-mortar while the mortar with 100% EPA B attained a 28.8% decrease in density as compared to the control sand-mortar. Mortars manufactured with EPA A and B generally have similar densities which was expected as both materials have equal bulk densities. On the other hand, the use of EPA Coarse led to the most drastic reduction of up to 41.8% in mortar density at 100% replacement. This is because the bulk density of EPA Coarse is less than those of EPA A and EPA B.

It is evident that as the percentage of sand replaced with EPA increases, the mortar density decreases because of the lightweight property of EPA. Similar observation was noted in the study of Tie et al [21]. The porous structure and the low specific gravity of EPA primarily contribute to the significant reduction of mortar density. In addition, their findings pointed to the conclusion that when lightweight aggregates are utilized as full replacement for sand, lightweight mortars can be produced. Sharma et al. also echoed the same decrease in resulting density upon replacement with EPA, albeit in concrete. They reported a 23.05% decrease in concrete density upon replacing fine sand with expanded perlite at 100% replacement level [22]. However, it should be noted that despite the apparent decrease in density, mortars manufactured with EPA still need to be subjected to compression test to check if they adhere to the minimum strength requirement set by ASTM for them to be suitable for mortar applications.

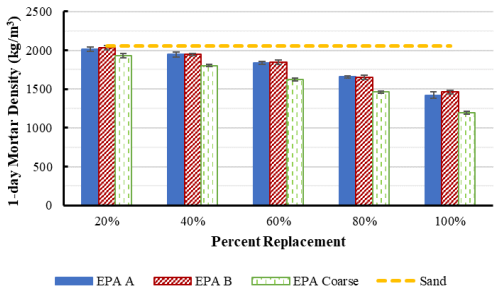


Figure 5 Variation of 1-day mortar density with EPA percentage replacement

3.2 Effect of EPA Replacement on Mortar Compressive Strength

It is shown in Figure 6 that as the replacement values increase, there is a variation in the mortar compressive strength from 29.42 MPa at 0% replacement to 24.29 MPa at 100% replacement with EPA A. EPA A-mortar has a mean compressive strength of 27.01 MPa with a standard deviation of 2.37 MPa. The graph presents a mostly downward trend as what has been described in the compressive strength results of Jedidi et al. [14] and Wadie [15]. Jedidi et al. noted a decrease in mortar compressive strength from 30 MPa at 0% replacement level to 3.4 MPa at 80% replacement level [14]. The same was observed by Wadie wherein the mortar compressive strength also reduced from 52 MPa at 0% replacement to 32.5 MPa at 75% EPA replacement [15].

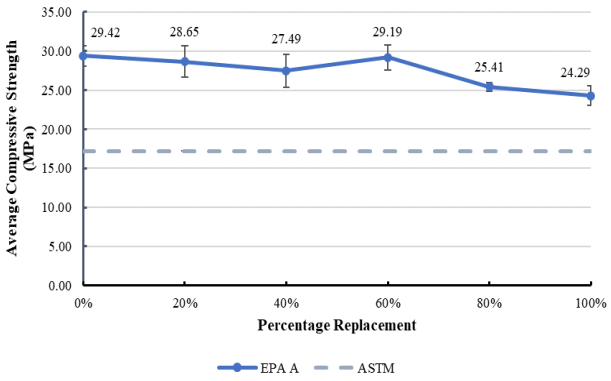


Figure 6 Variation of average compressive strengths of EPA A-mortars with percentage replacement

Table 5 Fisher LSD grouping information for EPA A-mortars

Percentage Replacement	N	Mean (MPa)	Grouping		
0%	3	29.422	A		
20%	3	28.653	A		
60%	3	29.187	A		
40%	3	27.490	A	B	
80%	3	25.414		B	C
100%	3	24.290			C

Note: Means that do not share a letter are significantly different.

A statistical analysis using a one-way analysis of variance (ANOVA) with a significance level of 95% between the average 28-day compressive strength as the response and the percentage replacement as the factor shows that not all means are equal ($p = 0.001 < 0.05$). As presented in Table 5, the grouping information using the Fisher LSD method as a comparison test shows that 0% to 60% replacement of EPA has no significant difference in the average compressive strength at the 28-day strength test. The Fisher LSD Method also showed that the 60% and 80% replacements are significantly different from each other. On the other hand, the 80% and 100% replacements showed no significant differences between their average compressive strengths at the 28-day strength tests. Though graphically, there is a minute increase in the compressive strength with increasing replacement up to 60%, the difference in values is not statistically significant as shown in Table 5. This indicates that the resulting trend is decreasing.

Despite the reduced strength relative to the control specimen, a 100% EPA A-based mortar is still above the compressive strength limit of 17.2 MPa set by ASTM C270-19AE1, as shown by Figure 6, and can be recommended for the typical applications of Type M mortars.

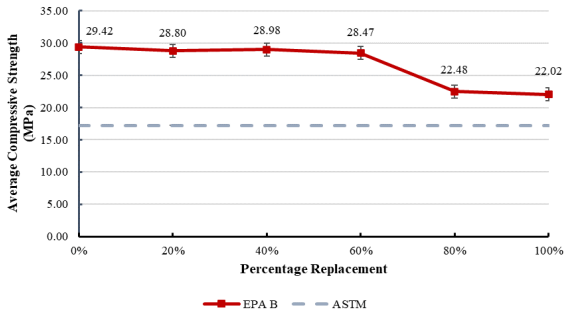


Figure 7 Variation of average compressive strengths of EPA B-mortars with percentage replacement

Table 6 Fisher LSD grouping information for EPA B-mortars

Percentage Replacement	N	Mean (MPa)	Grouping	
0%	3	29.422	A	
20%	3	28.800	A	
40%	3	28.978	A	
60%	3	28.469	A	
80%	3	22.481		B
100%	3	22.023		B

Note: Means that do not share a letter are significantly different.

For EPA B-mortars, a generally decreasing trend was observed on the 28-day mortar compressive strengths between 60% to 80% EPA replacement types as demonstrated in Figure 7. The average compressive strength of EPA B-mortar is 26.15 MPa with a standard deviation of 3.60 MPa. Analysis using one-way ANOVA presents that not all means are equal ($p < 0.001$). The Fisher LSD Method for comparison of mean as presented in Table 6 showed that there is no significant difference among the means of the average 28-day compressive strengths from 0% to 60% replacements and between the groups of 80% and 100% replacements. Results also revealed that mortars whose fine aggregates are fully replaced with EPA B pass the mortar compressive strength criteria of 17.2 MPa as stipulated by ASTM C270-19AE1. Hence, mortars formulated with EPA B and are developed using Type M specifications may be used for purposes wherein Type M is utilized.

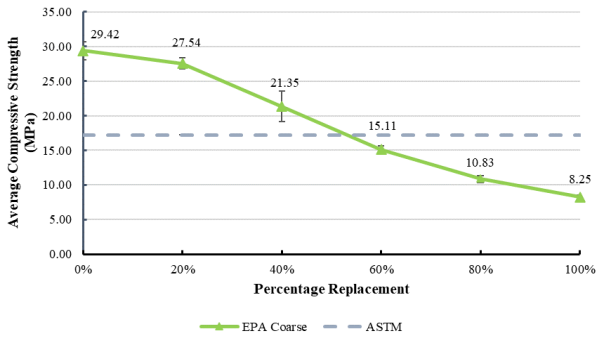


Figure 8 Variation of average compressive strengths of EPA Coarse-mortars with percentage replacement

Table 7 Fisher LSD grouping information for EPA Coarse-mortars

Percentage Replacement	N	Mean (MPa)	Grouping				
0%	3	29.422	A				
20%	3	27.539	A				
40%	3	21.350		B			
60%	3	15.112			C		
80%	3	10.833				D	
100%	3	8.247					E

Note: Means that do not share a letter are significantly different.

On the other hand, based on Figure 8, the graph of the mortar compressive strength has a clear decreasing trend with an increase in percentage replacement of sand by EPA Coarse. The trend mirrors the findings of Wadie [14] and Jedidi et al. [15] that replacing sand with EPA causes a reduction in mortar compressive strength. The results for the one-way ANOVA show that not all means are equal ($p < 0.001$). As presented in Table 7, the Fisher LSD Method for comparison of means reveals that only the control (0%) and 20% replacement show no significant difference with each other in terms of their average 28-day compressive strength, and the rest all have significantly different means. Contrary to EPA A and EPA B-mortars, only mortars formulated with 20% and 40% partial replacements pass the compressive strength specification of 17.2 MPa required by ASTM C270-19AE1.

3.3 Effect of EPA Morphological and Physical Properties on Mortar Compressive Strength

Findings in the previous section showed how the percentage replacement plays a role in mortar compressive strength. Figure 9 shows that there is a generally decreasing trend throughout the 5 EPA replacement levels, with mortars prepared using EPA Coarse deviating starkly from those using EPA A and B. Further analysis using ANOVA between EPA A and EPA B showed that there is no sufficient evidence to conclude that there is indeed a significant difference between the two types ($p = 0.398$). This finding is further strengthened by the results of the Fisher LSD method for comparison of means in Table 8 which demonstrates that mortars prepared with both EPA A and B have no significant differences in terms of their average 28-day compressive strengths.

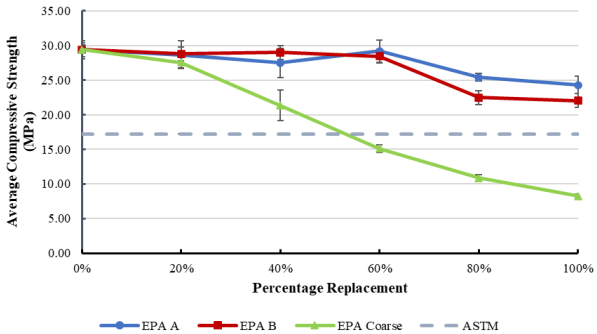


Figure 9 Compressive strengths of mortars prepared with EPA A, EPA B, and EPA Coarse at different replacements

Table 8 Fisher LSD grouping information for EPA-mortars

EPA Sample	N	Mean (MPa)	Grouping
EPA A	15	27.006	A
EPA B	15	26.151	A
EPA Coarse	15	16.616	B

Note: Means that do not share a letter are significantly different

Since varying the percentage replacement does not produce a significant difference in the compressive strength for mortars replaced with EPA A and B, another factor, such as the physical properties or the morphology of the EPA particles is likely in play. In a study conducted by Angelopoulos et al., it was observed that the lighter the perlite particle is in terms of the loose bulk density, the lower the compressive strength [23]. It could be inferred that physical properties such as the loose bulk density have an overall effect not just on the compressive strength of the particle but also on the resulting mortar. The similar trend that the mortar compressive strengths of both EPA A and B exhibit could be attributed to the fact that both EPA A and B have equal loose bulk densities (80 kg/m^3). Furthermore, Table 8 shows that the compressive strengths of mortars prepared with EPA Coarse are significantly different from those with EPA A and B. The Fisher LSD results are consistent with the drastic deviation of the graph of EPA Coarse-mortar compressive strength from those of the two other types as shown in Figure 9.

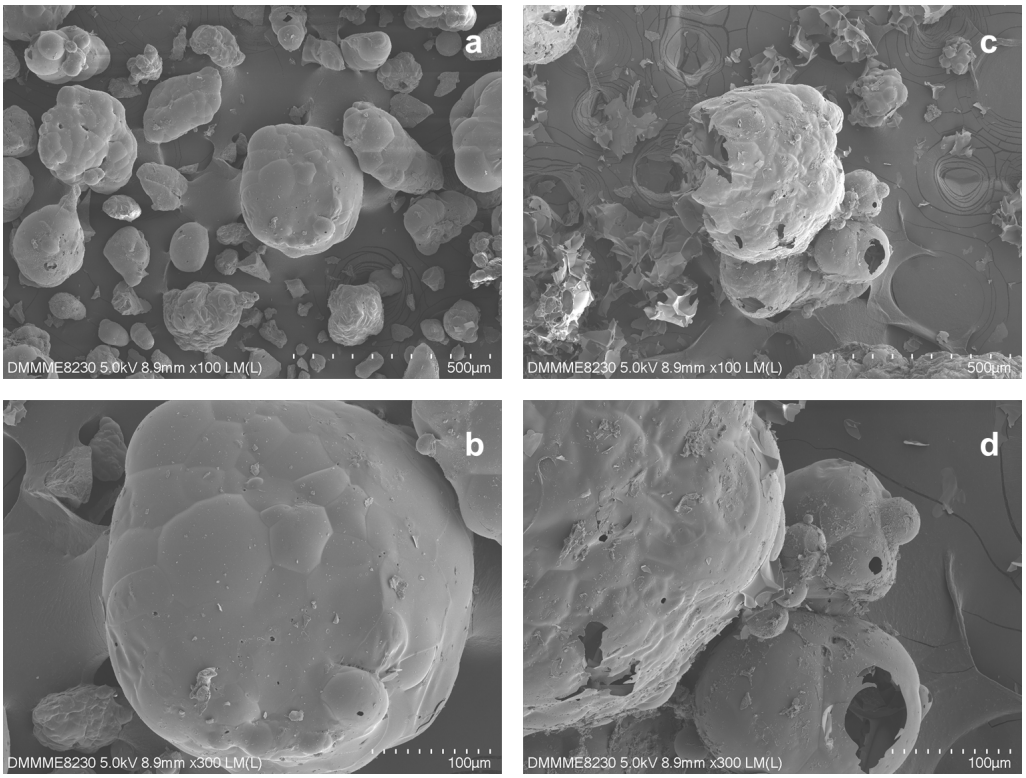


Figure 10 SEM images of EPA A (a and b) and EPA Coarse (c and d)

Figure 10 presents the SEM images of EPA A and EPA Coarse. EPA B was not viewed under the microscope since statistical analysis previously established that there is no significant difference between the strength results of EPA A and EPA B. Examination of the SEM images demonstrates a ruptured internal microstructure of EPA Coarse particles (Figure 10c and Figure 10d). In Figure 10c, it can be observed that some of the EPA coarse samples have completely burst open as compared to the intact EPA A samples in Figure 10a. Increased interstitial void spaces of the EPA Coarse sample generate a decrease in the load-bearing capacity of the EPA particle, and when more EPA particles possess this similar highly porous characteristic, it translates to a decrease in compressive strength of the resulting mortar as well. As the thermal expansion of EPA Coarse particles is more evident in comparison with EPA A particles, EPA Coarse samples tend to be very brittle and permeable. This explains the apparent decrease in the compressive strength of EPA Coarse-mortars as shown in Figure 9.

The presence of multiple burst EPA Coarse samples was also supported by the water absorption value. Perlite holds water in one of three ways: in between individual grains (outer surface area of EPA), in channels leading to the cores of the grains (individual bubble structure within the EPA), and on the highly irregular surfaces of each particle [24]. Upon explosion, EPA Coarse produces an open EPA structure with highly irregular surfaces, and hence, the absorption capacity of EPA Coarse is 263.9% in comparison with 29.8% for EPA A.

The difference between the microstructures of the EPA A and EPA Coarse is primarily due to the expansion process as it should be noted that EPA Coarse was expanded from raw perlite particles at a much higher temperature than EPA A and EPA B. The thermal shock induced by the rapid heating at higher temperatures expands the internal microstructure even more, causing the pores to explode. Findings in this study are consistent with the results from Angelopoulos et al. [23] wherein it was reported that the expansion of perlite grains treated in conventional furnaces occur violently and that rather than

"expanding", the rapid expansion due to uncontrolled temperature control causes the perlite particles to actually "pop" or "explode".

4.0 CONCLUSIONS AND RECOMMENDATIONS

The experimental study was conducted to investigate the resulting compressive strengths and densities of Type M EPA-mortars. It was found that increasing the percentage replacement of EPA causes a decrease in the resulting mortar density due to the low specific gravity and porous property of EPA. The density of Type M EPA mortars can go as low as 1422 kg/m^3, a 30.8% reduction in comparison to the control mortar density of 2055 kg/m^3. Since the resulting EPA-mortar is lighter than the conventional sand-mortar, the use of EPA in mortar opens the possibility of a reduction in the overall amount of materials needed to support building weight that could lead to a reduction in construction costs as well. Analysis of the compressive strengths results showed that EPA-mortars using EPA A and EPA B exceeded the Type M compressive strength requirement of 17.2 MPa. The mean compressive strengths of EPA A-mortar and EPA B-mortar are 27.01 MPa and 26.15 MPa respectively. For mortars that utilized EPA Coarse, only 20% and 40% replacements passed the compressive strength requirement for Type M mortar. The compressive strengths at 20% and 40% replacements are 27.54 MPa and 21.35 MPa, respectively.

The effect of EPA morphology on the resulting mechanical properties was also investigated. Rapid, uncontrolled heating induces thermal shock on the EPA particle and causes the internal microstructure to expand even more and eventually burst. The presence of a large number of voids in the EPA particle increases its permeability and lessens its load-bearing capacity. When similar void-rich EPA particles are used to fabricate mortar, it contributes to a reduction in the mortar compressive strength.

It is recommended that future studies investigate other mechanical properties of mortars prepared with EPA and look into the possibility of using perlite for concrete or other construction-related products. Analysis of the possible interaction between the internal structure of the EPA with the compressive strength of the resulting EPA-mortars using microscopy and other necessary tests is also recommended.

Acknowledgement

The authors would like to gratefully acknowledge the funding provided by the Philippine Department of Science and Technology – Philippine Council for Industry, Energy and Emerging Technology Research and Development and the equipment and perlite samples provided by Orophil Stonecraft Inc.

References

[1] Burkhardt, M., Zuleeg, S., Vonbank, R., Schmid, P., Hean, S., Lamani, X., Bester, K., & Boller, M. 2011. Leaching of additives from construction materials to urban storm water runoff. *Water Science and Technology*. 63(9): 1974-1982. DOI: 10.2166/wst.2011.128

[2] Ametepey, S. O., & Ansah, S. K. 2014. Impacts of construction activities on the environment: the case of Ghana. *Journal of Construction Project Management and Innovation.* 4(sup-1): 934-948.

[3] Bandow, N., Gartiser, S., Ilvonen, O., & Schoknecht, U. 2018. Evaluation of the impact of construction products on the environment by leaching of possibly hazardous substances. Environmental Sciences Europe. 30(14): 1-12. DOI: 10.1186/s12302-018-0144-2

[4] Murray, S. 2019. The critical role of infrastructure for the sustainable development goals. *The Economist Intelligence Unit*.

[5] Rafieizonooz, M., Mirza, J., Salim, M. R., Hussin, M. W., & Khankhaje, E. 2016. Investigation of coal bottom ash and fly ash in concrete as a replacement for sand and cement. *Construction and Building Materials*. 116: 15-24. DOI: 10.1016/j.conbuildmat.2016.04.080

[6] Jani, Y., & Hogland, W. 2014. Waste glass in the production of cement and concrete–A review. *Journal of environmental chemical engineering*. 2(3): 1767-1775. DOI: 10.1016/j.jece.2014.03.016

[7] Tamanna, N., Sutan, N. M., Lee, D. T. C., & Yakub, I. 2013. Utilization of waste glass in concrete. In *Proceedings of the 6th International Engineering Conference, Energy and Environment (ENCON 2013), Kuching, Sarawak, Malaysia*. 2-4.

[8] Almeshal, I., Al-Tayeb, M. M., Qaidi, S. M., Bakar, B. A., & Tayeh, B. A. 2022. Mechanical properties of eco-friendly cements-based glass powder in aggressive medium. *Materials Today: Proceedings*. (58): 1582-1587. DOI: 10.1016/j.matpr.2022.03.613

[9] Najaf, E., & Abbasi, H. 2022. Using recycled concrete powder, waste glass powder, and plastic powder to improve the mechanical properties of compacted concrete: cement elimination approach. Advances in Civil Engineering. (2022)9481466: 1-12. DOI: 10.1155/2022/9481466

[10] Celik, A. G., Kilic, A. M., & Cakal, G. O. 2013. Expanded perlite aggregate characterization for use as a lightweight construction raw material. *Physicochemical Problems of Mineral Processing*. *49*.

[11] Perlite Institute. 2009. Applications of Perlite [Fact sheet]. https://www.perlite.org/wp-content/uploads/2018/03/perlite-wheel.pdf

[12] Humanitarian Shelter Working Group. 2014. Key messages for commonly used shelter materials: Concrete Hollow Blocks.

[13] American Society for Testing and Materials. 2019. Standard Specification for Mortar for Unit Masonry (ASTM C270-19AE1). DOI: 10.1520/C0270-19AE01

[14] Jedidi, M., Benjeddou, O., & Soussi, C. 2015. Effect of expanded perlite aggregate dosage on properties of lightweight concrete. Jordan Journal of Civil Engineering. 9(3): 278-291. DOI: 10.14525/jjce.9.3.3071

[15] Wadie, R. N. 2013. Properties of High Strength Structural Lightweight Mortar Using Perlite as Partial Replacement of Fine Aggregate. *Engineering and Technology Journal.* 31(2): 266-276.

[16] Zulkifeli, M. F. H. B. M., & Saman@ Hj Mohamed, H. B. M. 2017. Compressive and flexural strength of expanded perlite aggregate mortar subjected to high temperatures. In *AIP Conference Proceedings 1875(1): 030006*. DOI: 10.1063/1.4998377

[17] American Society for Testing and Materials. 2017. Standard Specification for Lightweight Aggregates for Structural Concrete (ASTM C330/C330M-17A). DOI: 10.1520/C0330_C0330M-17A

[18] American Society for Testing and Materials. 2019. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates (ASTM C136/C136M-19). DOI: 10.1520/C0136_C0136M-19

[19] American Society for Testing and Materials. 2020. Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency (ASTM C305-20). DOI: 10.1520/C0305-20

[20] American Society for Testing and Materials. 2021. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens) (ASTM C109/C109M-21). DOI: 10.1520/C0109_C0109M-21

[21] Tie, T. S., Mo, K. H., Alengaram, U. J., Kaliyavaradhan, S. K., & Ling, T. C. 2022. Study on the use of lightweight expanded perlite and vermiculite aggregates in blended cement mortars. *European Journal of Environmental and Civil Engineering*. 26(8): 3612-3631.

[22] Sharma, B., Sharma, R., & Bansal, P. P. 2022. Effect of fine aggregate replacement with expanded perlite and pumice on the development of lightweight concrete. *Australian Journal of Civil Engineering*. 20(1): 115-129.

[23] Angelopoulos, P. M., Maliachova, C., Papakonstantinou, K., Taxiarchou, M., & Diplas, S. 2016. Structural and physical

characteristics of fine perlite expanded with a novel method in a vertical electric furnace. *Mineral Processing and Extractive Metallurgy*. 125(2): 71-80. DOI: 10.1080/03719553.2016.1156244

Perlite Institute. 2019. The Water-Holding Capacity of Perlite [Fact sheet]. https://www.perlite.org/wp-content/uploads/2019/06/Perlite-Water-Holding-Capacity.pdf