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Study on the use of lightweight expanded perlite and vermiculite aggregates in blended cement mortars

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ABSTRACT

This paper presents an experimental investigation on lightweight aggregate mortars containing high volume cement replacement materials. For this purpose, expanded perlite (EP) and expanded vermiculite (EV) are used as the lightweight aggregate (at sand replacements of 50% and 100%), while ground granulated blast furnace slag (GGBS) (35% and 70% replacement level) and fly ash (25% and 50% replacement level) are adopted as the supplementary cementitious materials (SCMs). The results showed that EP is beneficial for improving the flow of fresh mortar, and soft mortar (flow diameter $>$ 200 mm) can be produced by using EP in SCM-cement blends. Both EP and EV can be utilised to produce lightweight mortar in the density range of 1400–1700 kg/m^3 and 900–1100 kg/m^3 at 50% and 100% sand replacements, respectively. Although the lightweight aggregates resulted in compressive strength decrease, the developed lightweight mortar using 50% EP (with or without SCMs) can be classified as type N mortar (compressive strength exceeding 5.17 MPa) while those prepared with 100% EP as well as 50% EV can be categorised as type O mortar. Response surface methodology carried out in this study also demonstrated that the mathematical equations can suitably estimate the studied performances of the lightweight mortars.

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Lightweight aggregate; lightweight mortar; expanded perlite; expanded vermiculite; supplementary cementitious materials; response surface methodology

1. Introduction

Mortars for masonry construction can be classified into two major categories, namely, rendering mortars and masonry (bedding) mortars (Mortar Industry Association (MIA), 2015). Usually, the former is applied in external or internal renderings on wall, ceiling, and partitions, whereas bedding mortar is used to lay and bind construction units such as bricks or blocks. In the construction process, mortar rendering on structural elements is one of the final stages before the application of architectural finishes. Typically, the compressive strength requirement of cement mortar for such purpose can be fulfilled with ease, and this gradually opens up the opportunity to introduce alternative materials without significantly compromising its strength performance.

Among the type of alternative materials popularly experimented is waste materials or industrial by-products as cement replacement in the mortars. This is done mainly to promote sustainable construction materials, which encourages the reuse of waste materials and, at the same time reducing the environmental impact commonly associated with cement. For this purpose, common SCM originating from

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industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS) have been explored in mortars for masonry. Chindaprasirt et al. (2005) and Christy and Tensing (2010) suggested that fly ash can be incorporated between 20 and 40% as cement replacement to produce rendering and masonry mortars with adequate strength. Binici (2011) found adequate strength in adhesive mortars made of GGBS, while Cerulli et al. (2003) also recommended the use of GGBS in rendering mortar, especially in terms of the ecological consideration. Based on past studies done in using these materials, fly ash and GGBS were found to have the potential to be used as high volume cement replacement in cement mortar or concrete. The maximum fly ash content that can be used was reported to be 50% (Siddique, 2004), while the optimum replacement GGBS content could be as high as 50–70% cement replacement (Oner & Akyuz, 2007; Onn et al., 2019; Rao et al., 2016). Other benefits of fly ash and GGBS include improvement in the chemical resistance (Osborne, 1999; Saha & Sarker, 2019, 2020; Siddique & Bennacer, 2012) and mitigation of alkali-silica reaction (Saha & Sarker, 2019) in concrete.

Lightweight aggregate appears to be the latest alternative material studied for use in mortar. Although lightweight aggregates commonly caused a reduction in mechanical properties, the optimised amount can lead to improved thermal performance of mortars without significantly compromising the mechanical strength. This is especially useful for application as rendering mortar for buildings as there is potential for improved thermal comfort and energy efficiency. For instance, lightweight aggregates such as aerogel (Júlio et al., 2016), expanded clay (Barnat-Hunek et al., 2017), and cork granules (Borges et al., 2018) were investigated and the resulting cement mortars were found to exhibit lower thermal conductivity. Cement-based renders made using these aggregates can be classified as thermal mortars (Borges et al., 2018; Júlio et al., 2016). There are also other more commercially available lightweight aggregates which include expanded vermiculite (EV), expanded perlite (EP), crumb rubber and more.

EV is a natural mica-like mineral which is formed from vermiculite under a high temperature of 650–950˚C through the exfoliation process. EV exhibits prospective properties such as low thermal conductivity, low bulk density, endurance, and chemical inertness compare to conventional aggregates (Koksal et al., 2015; Rashad, 2016a; Schackow et al., 2014). Silva et al. (2010) and Rashad (2016a) concluded that the workability of cement-based products increased when the content of EV was increased. The high content of vermiculite could also decrease the thermal conductivity, which was attributed to its high porosity or sponge-like structure which hinders the transmission of heat energy. However, the major drawback of utilizing high volume EV in cement-based products is the reduction in mechanical properties because of its high porosity content (Koksal et al., 2015; Rashad, 2016a; Schackow et al., 2014; Silva et al., 2010). For example, Schackow et al. (2014) found that a maximum of 55% of EV can be used as fine aggregate replacement, while the strength decreased significantly when the replacement level was increased to 65%. EP also possesses the unique properties of high porosity, chemical inertness, as well as exhibiting excellent thermal and acoustic insulating properties (Allameh-Haery et al., 2017; Rashad, 2016b; Rozycka & Pichor, 2016; Sengul et al., 2011). Similar as EV, utilisation of EP as lightweight aggregate (up to 50%) is accompanied with a decrease in mechanical properties of cement-based materials (Isikdag, 2015; Lu et al., 2018; Rashad, 2016b; Rozycka & Pichor, 2016) because of its high porosity, though the thermal conductivity can be reduced (Gandage et al., 2013; Lu et al., 2018).

Considering that both EV and EP have similar lightweight nature which could be beneficial for cement mortar application, this study aims to compare the performance between the two materials when used as lightweight aggregate. As high mechanical strength is not the prime consideration for mortar applications, utilisation of a high amount of these lightweight aggregates is explored (50% and 100% as fine aggregate replacement) in this investigation to produce lightweight cement mortars. Furthermore, in view of sustainability of cement mortar, the incorporation of high volume SCM of fly ash (25% and 50%) and GGBS (35% and 70%) as cement replacement is studied. This preliminary research to produce sustainable lightweight cement mortar is focused on the materials development whereby the influence of the said materials in terms of the mortar strength will be assessed.

2. Materials and methods

2.1. Raw materials

White Portland cement was used for all mixes in this study. GGBS and fly ash were used as partial cement replacement. The chemical compositions of GGBS and fly ash were evaluated by X-ray

Table 1. Chemical composition of GGBS and fly ash.

Chemical composition (%)	GGBS	Fly ash
Al_2O_3	11.80	16.07
SiO_2	33.33	35.14
CaO	40.71	15.28
Na_2O	0.27	3.06
MgO	6.10	8.08
P_2O_5	0.02	0.25
SO_3	5.92	2.43
K_2O	0.32	1.10
TiO_2	0.65	0.69
MnO	0.28	0.19
Fe_2O_3	0.35	17.32

Table 2. Physical properties of GGBS, fly ash, EV and EP.

Materials	GGBS	Fly ash	EV	EP	Sand
Specific gravity	2.9	2.5	1.01	0.70	2.85
Water absorption (%)	–	–	101.88	141.55	4.71
Particle size	$d_{50} = 14.90\ \mu m$	$d_{50} = 7.45\ \mu m$	$0 - 2.36$ mm	$0 - 2.36$ mm	$0 - 2.36$ mm

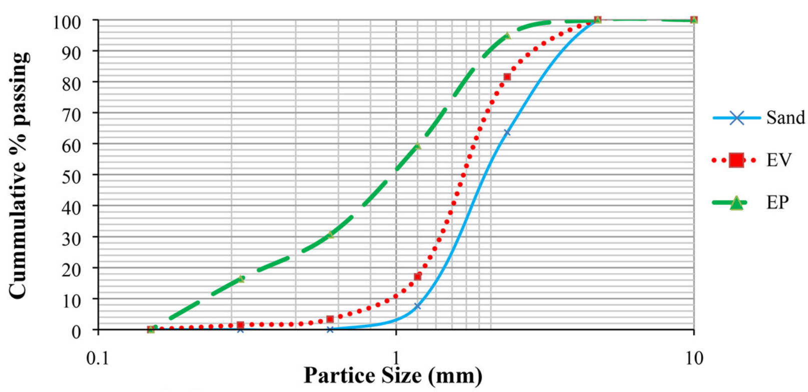


Figure 1. Size distribution of sand, EP, and EV.

fluorescence (XRF) spectrometry analysis and presented in Table 1. Mining sand was used as fine aggregates while two different types of lightweight aggregates (EV and EP) were incorporated as the sand replacement. The physical properties of GGBS, fly ash, EV, EP and sand are summarised in Table 2. The particle sizes of GGBS and fly ash were determined by particle size distribution (PSD) analysis whereas the particle sizes of sand, EV and EP were obtained by sieve analysis based on BS EN 933-1: 2002 and presented in Figure 1. The specific gravity and water absorption of sand, EV and EP were determined through pycnometer test based on BS EN 1097-6: 2013 and given in Table 2. The mixing water used was from pipe water in the laboratory.

2.2. Mix proportion

In this research, the mixes composed of binder: sand: water in the ratio 1: 3: 0.5. The cement replacement levels by GGBS were 35% and 70% (by mass), respectively, whereas 25% and 50% (by mass) of fly ash were adopted as cement replacement. EV and EP aggregates were used as a sand replacement at 50% and 100% replacement levels (by volume). A total of 25 mixtures were prepared as shown in Table 3. The nomenclature of mixes represents the type and amount of cement and fine aggregate replacement. For example, G35-EV50 denotes 35% cement replacement with GGBS and 50% sand replacement with EV, while F50-EP100 denotes 50% of cement replaced by fly ash with full replacement of sand by EP.

Table 3. Mix proportion of materials used.

	Replacement content (%)			
Mix	GGBS (by mass)	Fly ash (by mass)	EP (by volume)	EV (by volume)
G0-0	–	–	–	–
G0–EV50	–	–	–	50
G0-EP50	–	–	50	–
G0-EV100	–	–	–	100
G0-EP100	–	–	100	–
G35-0	35	–	–	–
G35-EV50	35	–	–	50
G35-EP50	35	–	50	–
G35-EV100	35	–	–	100
G35-EP100	35	–	100	–
G70-0	70	–	–	–
G70-EV50	70	–	–	50
G70-EP50	70	–	50	–
G70-EV100	70	–	–	100
G70-EP100	70	–	100	–
F25-0	–	25	–	–
F25-EV50	–	25	–	50
F25-EP50	–	25	50	–
F25-EV100	–	25	–	100
F25-EP100	–	25	100	–
F50-0	–	50	–	–
F50-EV50	–	50	–	50
F50-EP50	–	50	50	–
F50-EV100	–	50	–	100
F50-EP100	–	50	100	–

2.3. Testing procedure

In order to account for the water absorption of EV and EP during mixing, both EV and EP were soaked in water for 30 minutes to avoid reducing the effective water/binder ratio (Lu et al., 2018; Sengul et al., 2011; Silva et al., 2010). The mixing process began with dry-mixing of fine aggregates and binder materials (cement and SCM). After that, water was added gradually to the dry mixture and mixed at high speed. In order to assess the workability of the fresh mortar mix, the consistency of the mortar was determined by a flow table test (Figure 2) according to BS EN 1015-3: 1999. After that, the fresh mortar was cast into 50 mm cube moulds. The mortar specimens were de-moulded after 24 hours and cured in laboratory conditions until the age of testing. At the age of 28 days, the mortar specimens were subjected to a compressive strength test in accordance with BS EN 12390-3: 2002 using a 2000 kN ELE compression testing machine.

2.4. Response surface methodology

Response surface methodology (RSM) is a statistical technique used for modelling, optimizing and analyzing problems in which a response is influenced by several variables (Kumar & Baskar, 2014; Rooholamini et al., 2018). In this study, RSM was adopted to predict the properties of mortar, namely flow, density, and compressive strength as the responses based on the materials that were used. Face-centered central composite design with $\alpha = 1$ was used in this study (Kumar & Baskar, 2014). The content of SCM (GGBS or fly ash) was coded as A and amount of sand replacement by EP or EV was coded as B; both were selected as the factors and studied based on the 3 different types of properties for mortar as its response variables. The factors and factor levels are shown in Table 4. The experiment runs were summarised as shown in Table 5. Equation (1) shows the full quadratic model in terms of coded factors:

$$y = \beta_0 + \beta_1 A + \beta_2 B + \beta_{12} AB + \beta_{11} A^2 + \beta_{22} B^2 + \varepsilon. \tag{1}$$

where, y = predicted response, β_0 = intercept, β_1, β_2 = linear effect coefficients, β_{11}, β_{22} = quadratic effect coefficients, β_{12} = interaction effect coefficient, A and B = independent variables, ε = residual.

Figure 2. Flow diameter measurement.

Table 4. Factors and factor levels adopted for RSM.

Mixture types	Factor	Code	Factor level (%)		
			−1 (Low)	0 (Intermediate)	1 (High)
GGBS mortar with EP	GGBS	A	0	35	70
	EP	B	0	50	100
GGBS mortar with EV	GGBS	A	0	35	70
	EV	B	0	50	100
Fly ash mortar with EP	Fly ash	A	0	25	50
	EP	B	0	50	100
Fly ash mortar with EV	Fly ash	A	0	25	50
	EV	B	0	50	100

Table 5. Factor combinations as per face-centred composite response surface design.

Run	Code factor		Actual factors replacement (%)	
	A	B	GGBS/fly ash	EP/EV
1	0	0	35/25	50/50
2	0	1	35/25	100/100
3	−1	−1	0/0	0/0
4	1	0	70/50	50/50
5	0	−1	35/25	0/0
6	−1	0	0/0	50/50
7	1	−1	70/50	0/0
8	1	1	70/50	100/100
9	−1	1	0/0	100/100
10	0	0	35/25	50/50
11	0	0	35/25	50/50
12	0	0	35/25	50/50
13	0	0	35/25	50/50

3. Results and discussion

3.1. Flow diameter

Figure 3 gives the flow diameter of mortars containing EV and EP as sand replacement with GGBS as the cement replacement, whereas Figure 4 gives the corresponding flow diameter of mortars with fly ash as cement replacement.

As sand replacement, it appears that EP had more positive influence on the flow diameter of mortar compared to the use of EV. Regardless of the type of binder (cement/cement + GGBS/cement + fly ash), the mixtures containing EP consistently gave higher flow diameter range (215–243 mm) than the

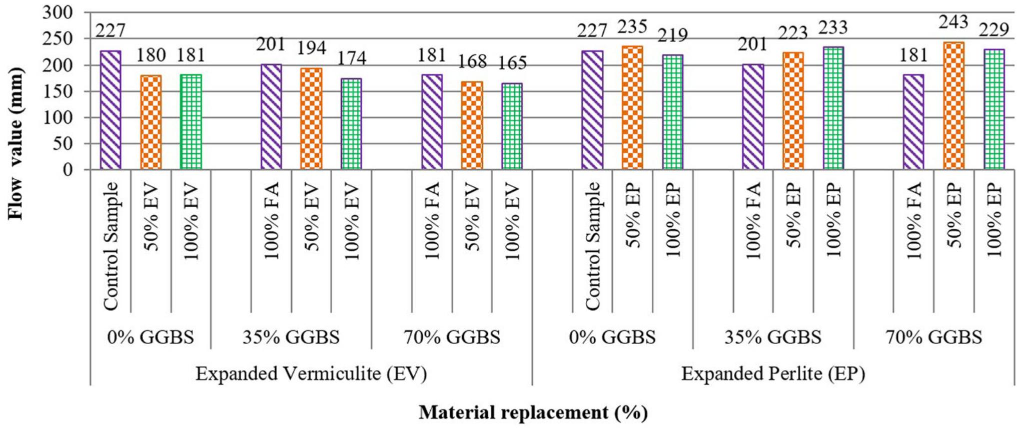


Figure 3. Flow value of GGBS-blended mortar containing EV and EP as sand replacement.

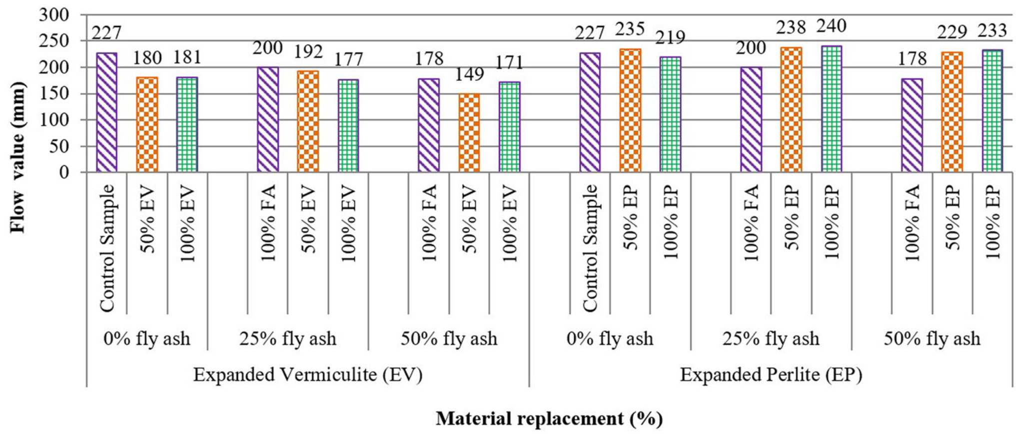


Figure 4. Flow value of fly ash-blended mortar containing EV and EP as sand replacement.

corresponding EV mixtures (149–195 mm). In particular, at 50% EP sand replacement level, the improvement in the flow diameter was most obvious, as observed in Figures 3 and 4. The inclusion of saturated EP in mixtures could increase workability of mortar due to the increased air content within the mixture (Isikdag, 2015; Rashad, 2016b) as well as smoother surface of the EP particle compared to normal sand. Also, reduced viscosity of the fresh mortar could be achieved with the use of EP, thereby improving the flow of the mortar (Wan et al., 2018). However, generally the flow diameter was reduced when EP content was increased from 50% to 100%, which could be attributed to the small particle size of EP which had larger surface area than sand. This increased the water demand as well as amount of cement paste to coat the EP particles within mix. Thus, the flow was reduced when EP was adopted as complete sand substitute.

On the other hand, the flow diameter of mortar generally decreased in the presence of EV as sand replacement. Insufficient water added (based on water absorption of EV) could be one of the main reasons for causing the low workability of mortar containing EV. Schackow et al. (2014) and Koksal et al. (2015) have suggested to soak EV in water for longer period, i.e. at least 1 hour or 24 hours prior to mixing. This is to ensure that EV is fully saturated for mixing. This also explains the difference in observation whereby improved workability in EV mortar was reported in Mo et al. (2018).

In general, in mortar mixes without the lightweight aggregates, inclusion of high volume GGBS and fly ash as partial cement replacement resulted in lower flow values. Despite this, it could be clearly seen from Figures 3 and 4 that when GGBS and fly ash were used along with EP, there was some synergistic effect observed. When EP was incorporated, its positive influence on workability was able to offset the reducing effect of the GGBS and fly ash at high replacement levels. As a result, most mortar mixes (with

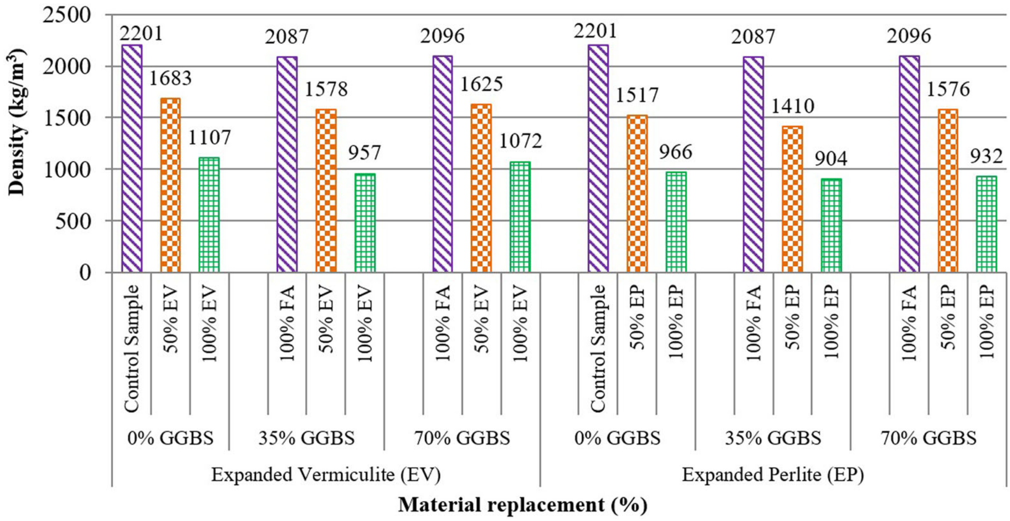


Figure 5. 28-day density of GGBS-blended mortar.

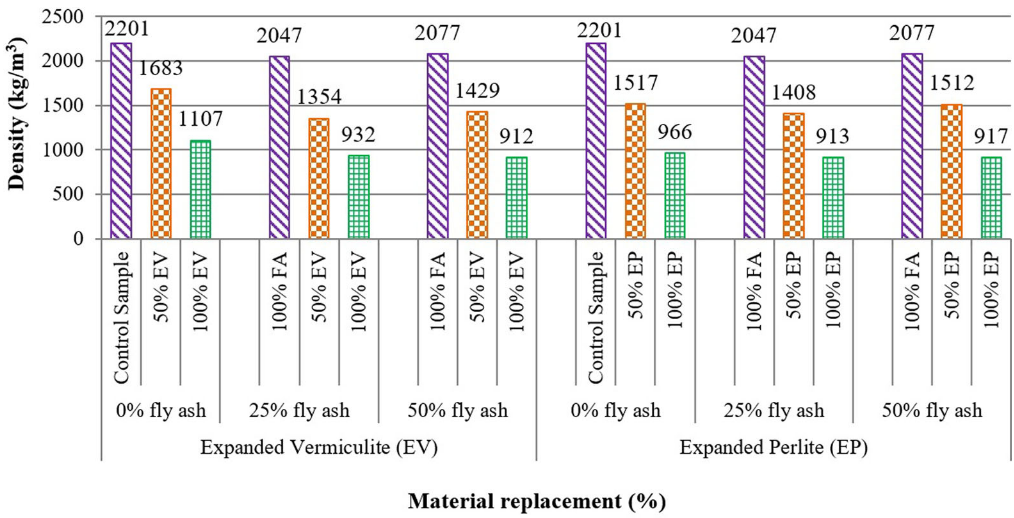


Figure 6. 28-day density of fly ash-blended mortar.

GGBS or fly ash) containing EP had similar if not higher flow diameter compared to the control mortar. Besides that, the reduction in workability due to the use of EV could be decreased in the presence of GGBS and fly ash. For instance, among the studied replacement level, when GGBS and fly ash were used at 35% and 25% respectively, the flow diameter obtained for the mortars with 50% EV was close to the corresponding ones without EV.

In overall conclusion, combination of either GGBS or fly ash with EP as sand replacement can be categorised as soft mortar (flow value $>$ 200 mm), while the combination of either GGBS or fly ash with EV as sand substitute can be classified as plastic mortar (flow value within range 140 mm to 200 mm) in accordance with BS EN 1015-3.

3.2. Density

The density of all mortars blended with GGBS and fly ash is given in Figures 5 and 6, respectively. The density of the control mortar (G0-0) without any replacement materials was about 2200 kg/m^3 and a

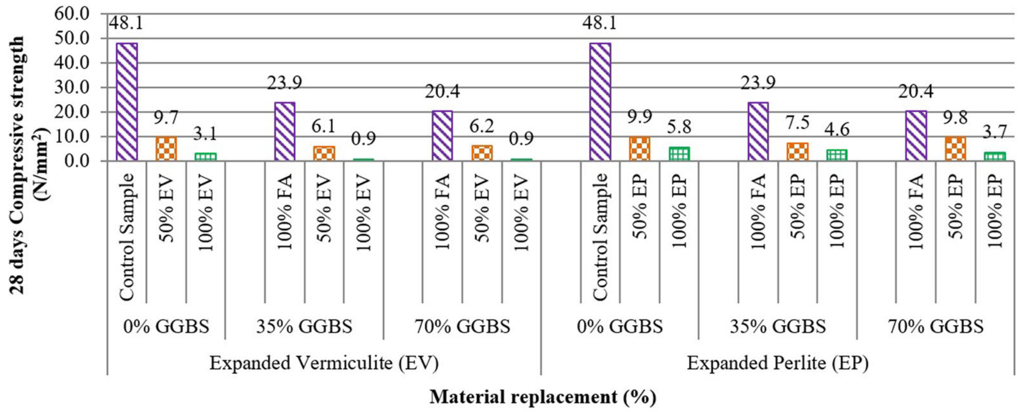


Figure 7. 28-day strength of GGBS-blended mortar.

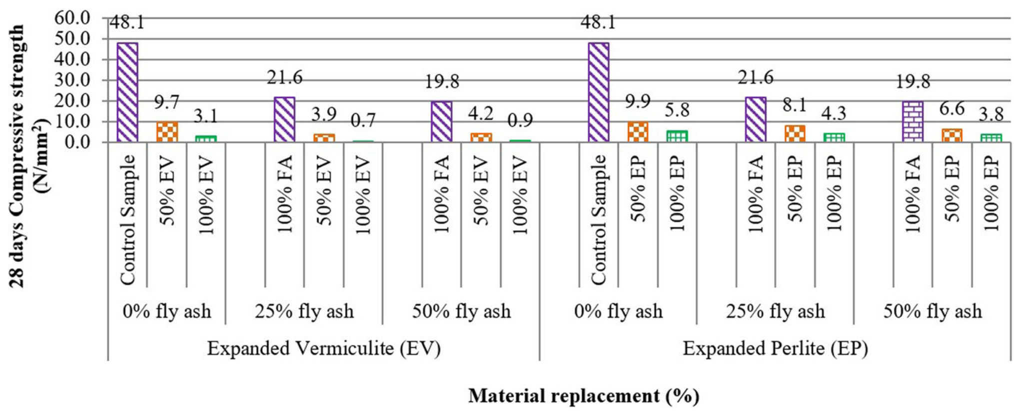


Figure 8. 28-day strength of fly ash-blended mortar.

reduction in density of up to 6% was obtained in the presence of either 70% GGBS (G70-0) or 50% fly ash (F50-0) as high volume cement replacement. This reduction is associated with the lower specific gravity of GGBS and fly ash compared to cement.

When mining sand was substituted by 50% and 100% of EV, about 24% and 50% reduction in density could be observed for the plain cement mortar. Similar trend in the density reduction could also be observed for the case of mortars containing EP, albeit to a slightly higher extent. The density of mortars containing 50% and 100% EP could be reduced up to 31% and 56%, respectively. Similarly, Sengul et al. (2011), Schackow et al. (2014) and Rozycka and Pichor (2016) reported that when the replacement level of sand by either EV or EP was increased, the unit weight of the cement-based products decreased significantly. The lightweight nature of the materials with low specific gravity and high porosity was the main contributing factor in reducing the density of the mortars (Koksal et al., 2015; Rozycka & Pichor, 2016; Sengul et al., 2011; Turkmen & Kantarci, 2007). In short, a significant reduction in mortar density could be achieved with full replacement of mining sand with either EV or EP. When the lightweight aggregates were used in mortars blended with the SCMs, similar observation was generally found, indicating minimal influence of the SCM on the density of lightweight aggregate mortars.

Mortar density as low as in the range of $900-1100\,kg/m^3$ could be achieved when the lightweight aggregates were used as complete sand substitute, whereas density in the range of $1400–1700\,kg/m^3$ was attained with 50% sand replacement. This is in line with previous reports whereby density below $1300\,kg/m^3$ was found when the sand replacement was higher than 60% (Ramakrishnan et al., 2017; Rozycka & Pichor, 2016; Schackow et al., 2014). Hence, the mortars containing EV and EP produced in this study can be considered as lightweight mortars.

Table 6. Actual and predicted values for GGBS mortar with EP as sand replacement.

	Code factor		Flow (mm)		Density (kg/m^3)		Strength (MPa)	
Run	A	B	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	0	0	223	226	1410	1421	7.5	7.9
2	0	1	233	224	904	869	4.6	3.9
3	−1	−1	227	224	2201	2191	48.1	33.8
4	1	0	243	230	1576	1505	9.8	6.5
5	0	−1	201	199	2087	2064	23.9	23.3
6	−1	0	235	237	1517	1531	9.9	9.6
7	1	−1	181	189	2096	2131	20.4	17.1
8	1	1	229	241	932	970	3.7	3.4
9	−1	1	219	220	966	962	5.8	5.0
10	0	0	223	226	1410	1421	7.5	7.9
11	0	0	223	226	1410	1421	7.5	7.9
12	0	0	223	226	1410	1421	7.5	7.9
13	0	0	223	226	1410	1421	7.5	7.9
Residual standard deviation			7.071		30.664		4.56	
Coefficient of variation (%)			3.90		2.59		8.29	
R^2			0.822		0.995		0.937	

3.3. Compressive strength

Figures 7 and 8 show the effect of sand replacement with the lightweight aggregates in GGBS and fly ash blended mortars, respectively. Generally, the compressive strength of mortar was reduced by up to 58% when the cement replacement by GGBS was increased from 0% to 70%. These results correspond well to those reported by Oner and Akyuz (2007) and Bilim and Atiş (2012). This is known to be attributed to the slower hydraulic activity of GGBS compared to cement. The fly ash-blended mortar demonstrated similar trend when the cement content was reduced from 100% to 50%, as reflected with the 59% reduction in the 28-day compressive strength. This is likely due to the dilution effect and slower pozzolanic reaction of the fly ash. Nevertheless, it should be noted that the use of GGBS was more beneficial compared to that for fly ash, as higher compressive strength could still be obtained even at higher replacement levels. This encourages the use of lesser amount of cement towards producing a more sustainable cement mortar.

In terms of the use of lightweight aggregates, when lightweight aggregates were used at 50% and 100% sand replacement, the compressive strength was decreased significantly by up to 80–88% and 80–94%, respectively. This could be attributed to the low inherent strength of the EV and EP which contained high porosity, resulting in reduction of its mechanical properties (Rashad, 2016b). In addition, the lightweight aggregates had greater fineness and therefore surface area, thus requiring higher amount of cement paste to coat the aggregates compared to mining sand. Nevertheless, the results clearly highlighted that the mortar containing 50% of EP had higher compressive strength than the corresponding EV mixtures. This could be due to the difference in particles size between EP and EV whereby the fineness is greater for EP. Hence, the fine particles of EP in the mixtures could exhibit pozzolanic reactivity and this could enhance the strength properties (Turkmen & Kantarci, 2007).

From Figures 7 and 8, it is apparent that low compressive strength (<3.5 MPa) was found for the mortars containing 100% EV, which represents a significant strength reduction of close to 95% compared to the mortars without EV. The compressive strength was even lower (<1.0 MPa) for 100% EV in SCM-blended mortars. In contrast, in the SCM-blended mortars containing EP, the compressive strength obtained was in the range of 3.7–4.6 MPa. The corresponding compressive strength reduction was lower at about 80% compared to the SCM-blended mortars without EP. This demonstrates that the use of SCM is more beneficial in reducing the strength decrease in EP mortars. A possible reason for this occurrence is the improved lightweight aggregate-matrix bonding due to the use of SCM such as GGBS and fly ash (Mo et al., 2017). This helps to reduce the compressive strength decrease associated with high EP contents. Hence, in order to obtain the adequate compressive strength of lightweight aggregate mortar, EP is a more suitable choice as the lightweight fine aggregate compared to EV.

In general, mortars prepared with maximum amount of 50% EP can be classified as type N as all mortars (cement or SCM-blended) attained the minimum requirement of 5.17 MPa according to ASTM C270. For the use of 50% EV, only the cement and GGBS-blended mortars could be classified as type N. Fly

Table 7. Actual and predicted values for GGBS mortar with EV as sand replacement.

	Code factor		Flow (mm)		Density (kg/m^3)		Strength (MPa)	
Run	A	B	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	0	0	194	188	1578	1576	6.1	5.2
2	0	1	174	173	957	991	0.9	0.7
3	−1	−1	227	215	2201	2207	48.1	44.5
4	1	0	168	176	1625	1628	6.2	4.7
5	0	−1	201	203	2087	2070	23.9	23.3
6	−1	0	180	201	1683	1695	9.7	11.8
7	1	−1	181	191	2096	2105	20.4	25.4
8	1	1	165	161	1072	1060	0.9	0.5
9	−1	1	181	186	1107	1093	3.1	1.89
10	0	0	194	188	1578	1576	6.1	5.2
11	0	0	194	188	1578	1576	6.1	5.2
12	0	0	194	188	1578	1576	6.1	5.2
13	0	0	194	188	1578	1576	6.1	5.2
Residual standard deviation			9.414		13.73		2.14	
Coefficient of variation (%)			5.11		1.07		8.86	
R^2			0.707		0.998		0.987	

Table 8. Actual and predicted values for fly ash mortar with EP as sand replacement.

	Code factor		Flow (mm)		Density (kg/m^3)		Strength (MPa)	
Run	A	B	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	0	0	238	239	1408	1415	8.1	8.7
2	0	1	240	237	913	877	4.3	5.0
3	−1	−1	227	222	2201	2185	48.1	41.7
4	1	0	229	228	1512	1470	6.6	7.2
5	0	−1	200	206	2047	2052	21.6	22.4
6	−1	0	235	239	1517	1529	9.9	12.27
7	1	−1	178	178	2077	2089	19.8	17.7
8	1	1	233	242	917	951	3.8	4.2
9	−1	1	219	221	966	972	5.8	6.5
10	0	0	238	239	1408	1415	8.1	8.7
11	0	0	238	239	1408	1415	8.1	8.7
12	0	0	238	239	1408	1415	8.1	8.7
13	0	0	238	239	1408	1415	8.1	8.7
Residual standard deviation			4.011		21.460		2.234	
Coefficient of variation (%)			1.93		1.82		4.23	
R^2			0.966		0.997		0.996	

Table 9. Actual and predicted values for fly ash mortar with EV as sand replacement.

	Code factor		Flow (mm)		Density (kg/m^3)		Strength (MPa)	
Run	A	B	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	0	0	192	186	1354	1367	3.9	3.6
2	0	1	177	174	932	891	0.7	0.7
3	−1	−1	227	214	2201	2239	48.1	47.0
4	1	0	149	171	1429	1428	4.2	3.2
5	0	−1	200	199	2047	2008	21.6	19.6
6	−1	0	180	201	1683	1607	9.7	11.1
7	1	−1	178	184	2077	2077	19.8	22.2
8	1	1	171	159	950	943	0.6	0.5
9	−1	1	181	189	1107	1140	3.1	2.7
10	0	0	192	186	1354	1367	3.9	3.6
11	0	0	192	186	1354	1367	3.9	3.6
12	0	0	192	186	1354	1367	3.9	3.6
13	0	0	192	186	1354	1367	3.9	3.6
Residual standard deviation			11.78		33.583		1.149	
Coefficient of variation (%)			6.66		2.84		7.25	
R^2			0.600		0.994		0.995	

Table 10. Analysis of variance (ANOVA) for flow, density and strength for GGBS mortar with EP by RSM model.

	Flow (mm)					Density (kg/m^3)					Strength (MPa)				
Sources	$\sum$X	D_f	$\bar{X}$	F value	p value	$\sum$X	D_f	$\bar{X}$	F value	p value	$\sum$X	D_f	$\bar{X}$	F value	p value
Model	2418.01	5	483.60	6.48	0.0147	2188000	5	437600	295.28	<0.0001	0.1208	2	0.0604	75.43	<0.0001
A-GGBS	130.67	1	130.67	1.75	0.2273	1066.67	1	1066.67	0.7197	0.4243	0.0056	1	0.0056	7.01	0.0244
B-EP	864.00	1	864.00	11.58	0.0114	2138000	1	2138000	1442.88	<0.0001	0.1152	1	0.1152	143.84	<0.0001
AB	784.00	1	784.00	10.51	0.0142	1260.25	1	1260.25	0.8503	0.3871	–	–	–	–	–
A^2	128.75	1	128.75	1.73	0.2304	25618.55	1	25618.55	17.29	0.0043	–	–	–	–	–
B^2	635.80	1	635.80	8.52	0.0224	5670.27	1	5670.27	3.83	0.0914	–	–	–	–	–
Residual	522.30	7	74.61	–	–	10374.53	7	1482.08	–	–	0.0080	10	0.008	–	–
Lack of fit	522.30	3	174.10	–	–	10374.53	3	3458.18	–	–	0.0080	6	0.0013	–	–
Pure error	0.0000	4	0.0000	–	–	0.0000	4	0.0000	–	–	0.0000	4	0.0000	–	–
Total	2940.31	12				2,198,000	12				0.1288	12			

$\sum$X = Sum of square; D_f = Degrees of freedom; $\bar{X}$= Mean squares.

Table 11. Analysis of variance (ANOVA) for flow, density and strength for GGBS mortar with EV by RSM model.

	Flow (mm)					Density (kg/m^3)					Strength (MPa)				
Sources	$\sum$X	D_f	$\bar{X}$	F value	p value	$\sum$X	D_f	$\bar{X}$	F value	p value	$\sum$X	D_f	$\bar{X}$	F value	p value
Model	2232.83	2	1116.42	12.09	0.0021	1787000	5	357400	1230.95	<0.0001	15.37	5	3.07	113.81	<0.0001
A-GGBS	912.67	1	912.67	9.88	0.0104	6534.00	1	6534.00	22.50	0.0021	1.08	1	1.08	39.89	0.0004
B-EV	1320.17	1	1320.17	14.30	0.0036	1,758,000	1	1,758,000	6055.56	<0.0001	13.93	1	13.93	515.85	<0.0001
AB	–	–	–	–	–	1225.00	1	1225.00	4.22	0.0791	0.0359	1	0.0359	1.33	0.2867
A^2	–	–	–	–	–	20492.62	1	20492.62	70.58	<0.0001	0.3169	1	0.3169	11.74	0.0110
B^2	–	–	–	–	–	5809.20	1	5809.20	20.01	0.0029	0.0849	1	0.0849	3.14	0.1194
Residual	923.47	10	92.35	–	–	2032.47	7	290.35	–	–	0.1890	7	0.0270	–	–
Lack of fit	923.47	6	153.91	–	–	2032.7	3	677.49	–	–	0.1890	3	0.0630	–	–
Pure Error	0.0000	4	0.0000	–	–	0.0000	4	0.0000	–	–	0.0000	4	0.0000	–	–
Total	3156.31	12				1,789,000	12				15.56	12			

$\sum$X = Sum of square; D_f = Degrees of freedom; $\tilde{X}$= Mean squares.

ash-blended mortar containing 50% EV can only be categorised as type O, as do all mortars containing 100% EP and cement mortar (no SCM) with 100% EV. SCM-blended mortars with 100% EV studied in this research is generally not recommended for use due to the low compressive strength.

3.4. RSM analysis

The flow, density and compressive strength of mortar were analyzed through RSM and the design matrix of the variables are summarised in the code units as shown in Tables 6–9 along with the actual (experimental values) and estimated value of all responses. Based on the RSM, a full quadratic model was employed for each factor and the coefficients of all parameters were given by the regression equation. Analyses of the variance (ANOVA) of the response surface models for all variables are presented in Tables 10–13. P value approached in this study was employed for hypothesis testing, where 'Prob > F' less than 0.05 denotes that the RSM model is statistically significant (Awolusi et al., 2019; Kumar & Baskar, 2014).

3.4.1. GGBS mortar with EP as sand substitute

For GGBS mortar containing EP as sand substitute, the ANOVA of flow diameter, density and strength are shown in Table 10. The flow results showed that the GGBS level effect ($p = 0.2273$) and the quadratic GGBS level effect ($p = 0.2304$) are statistically not significant at the stipulated level of 5%, which means that the significant factors of confidence level for both of these effects are lesser than 95% ($P < 0.05$) in terms of probability value. Hence, null hypothesis should be considered in this case. The effect of EP content ($p = 0.0114$), quadratic EP content effect ($p = 0.0224$) and the effect of interaction of GGBS level and EP content ($p = 0.0142$) are statistically significant. Similarly, for density, only the quadratic of GGBS effect ($p = 0.0043$) are significant and other effects are insignificant. For the analysis of variance for strength in

Table 12. Analysis of variance (ANOVA) for flow, density and strength for fly ash mortar with EP by RSM model.

	Flow (mm)					Density (kg/m^3)					Strength (MPa)				
Sources	$\sum X$	D_f	$\bar{X}$	F value	p value	$\sum X$	D_f	$\bar{X}$	F value	p value	$\sum X$	D_f	$\bar{X}$	F value	p value
Model	3937.12	5	787.42	40.87	<0.0001	2123000	5	424,700	590.63	<0.0001	0.0565	5	0.0113	389.38	<0.0001
A-flyash	280.17	1	280.17	14.54	0.0066	5280.67	1	5280.67	7.34	0.0302	0.0049	1	0.0049	167.79	<0.0001
B-EP	1261.50	1	1261.50	65.47	<0.0001	2,076,000	1	2,076,000	2886.62	<0.0001	0.0505	1	0.0505	1739.94	<0.0001
AB	992.25	1	992.25	51.50	0.0002	1406.25	1	1406.25	1.96	0.2047	0.0009	1	0.0009	32.07	0.0008
A^2	95.47	1	95.47	4.95	0.0613	19,568.08	1	19,568.08	27.21	0.0012	0.0001	1	0.0001	2.09	0.1917
B^2	882.90	1	882.90	45.82	0.0003	6814.58	1	6814.58	9.48	0.0179	0.0002	1	0.0002	6.84	0.0346
Residual	134.88	7	19.27	–	–	5033.38	7	719.05	–	–	0.0002	7	0.0000	–	–
Lack of fit	134.88	3	44.96	–	–	5033.38	3	1677.79	–	–	0.0002	3	0.0001	–	–
Pure Error	0.0000	4	0.0000	–	–	0.0000	4	0.0000	–	–	0.0000	4	0.0000	–	–
Total	4072.00	12				2,129,000	12				0.0567	12			

$\sum X$ = Sum of square; D_f = Degrees of freedom; $\bar{X}$= Mean squares.

Table 13. Analysis of variance (ANOVA) for flow, density and strength for fly ash mortar with EV by RSM model.

	Flow (mm)					Density (kg/m^3)					Strength (MPa)				
Sources	$\sum X$	D_f	$\bar{X}$	F value	p value	$\sum X$	D_f	$\bar{X}$	F value	p value	$\sum X$	D_f	$\bar{X}$	F value	p value
Model	2312.67	2	156.33	7.50	0.0103	2,029,000	5	405,800	230.78	<0.0001	18.43	5	3.69	276.42	<0.0001
A-flyash	1350.00	1	1350.00	8.75	0.0143	47,704.17	1	47,704.17	27.13	0.0012	1.89	1	1.89	141.67	<0.0001
B-EV	962.67	1	962.67	6.24	0.0315	1855000	1	1,855,000	1054.92	<0.0001	15.58	1	15.58	1168.11	<0.0001
AB	–	–	–	–	–	272.25	1	272.25	0.1548	0.7057	0.1424	1	0.1424	10.68	0.0137
A^2	–	–	–	–	–	62,128.57	1	62,128.57	35.34	0.0006	0.6958	1	0.6958	52.18	0.0002
B^2	–	–	–	–	–	19,248.74	1	19,248.74	10.95	0.0130	0.0001	1	0.0001	0.0083	0.9300
Residual	1542.41	10	154.24	–	–	12,307.77	7	1758.25	–	–	0.0933	7	0.0133	–	–
Lack of fit	152.41	6	257.07	–	–	12,307.77	3	4102.59	–	–	0.0933	3	0.0311	–	–
Pure Error	0.0000	4	0.0000	–	–	0.0000	4	0.0000	–	–	0.0000	4	0.0000	–	–
Total	3855.08	12				2,041,000	12				18.52	12			

$\sum X$ = Sum of square; D_f = Degrees of freedom; $\bar{X}$= Mean square.

this mixture, effects of GGBS level ($p = 0.0244$) and EP content ($p < 0.0001$) are significant. Equations (2)–(4) gives the final mathematical models in terms of actual factors. Since the maximum to minimum ratio for strength response is high, inverse square root transformation was adopted to achieve adjusted R^2 of 0.925. Figure 9 illustrates the effect of contour plot and response from RSM model for the variables of flow, density and strength in this mixture.

$$\text{Flow} = 223.943 - 0.923\text{A} + 0.567\text{B} + 0.008\text{AB} + 0.006A^2 - 0.006B^2 \tag{2}$$

$$\text{Density} = 2191.187 - 6.392\text{A} - 14.107\text{B} + 0.010\text{AB} + 0.079A^2 + 0.018B^2. \tag{3}$$

$$\text{Strength} = \left[\frac{1}{0.172 + 0.001A + 0.003B}\right]^2. \tag{4}$$

3.4.2. GGBS mortar with EV as sand substitute

Table 11 shows the ANOVA for GGBS mortar with EV as sand substitute. In this mixture, the effects of GGBS level ($p = 0.0104$) and EV content ($p = 0.0036$) are statistically significant to the stipulated level for flow value. For the case of density, the effect of GGBS level ($p = 0.0021$), effect of EV content ($p < 0.0001$), quadratic effect of the GGBS level ($p < 0.001$) and EV content ($p = 0.0029$) are significant yet the effect of interaction between GGBS level with EV content ($p = 0.0791$) is not statistically significant at the stipulated level. Hence, null hypothesis is considered for the combination effect of GGBS with EV. The analysis of variance output for strength showed similar trend as that for the density as shown in Table 11. However, only the effect of interaction between GGBS level with EV content ($p = 0.2867$) and quadratic effect of EV content ($p = 0.1194$) are found not statistically significant for the strength of mortar. The final mathematical models in term of actual factors for estimation of the flow (mm), density (kg/m^3) and strength (MPa) of the mortar are given through Equations (5), (6) and (7). Figure 10 shows the contour

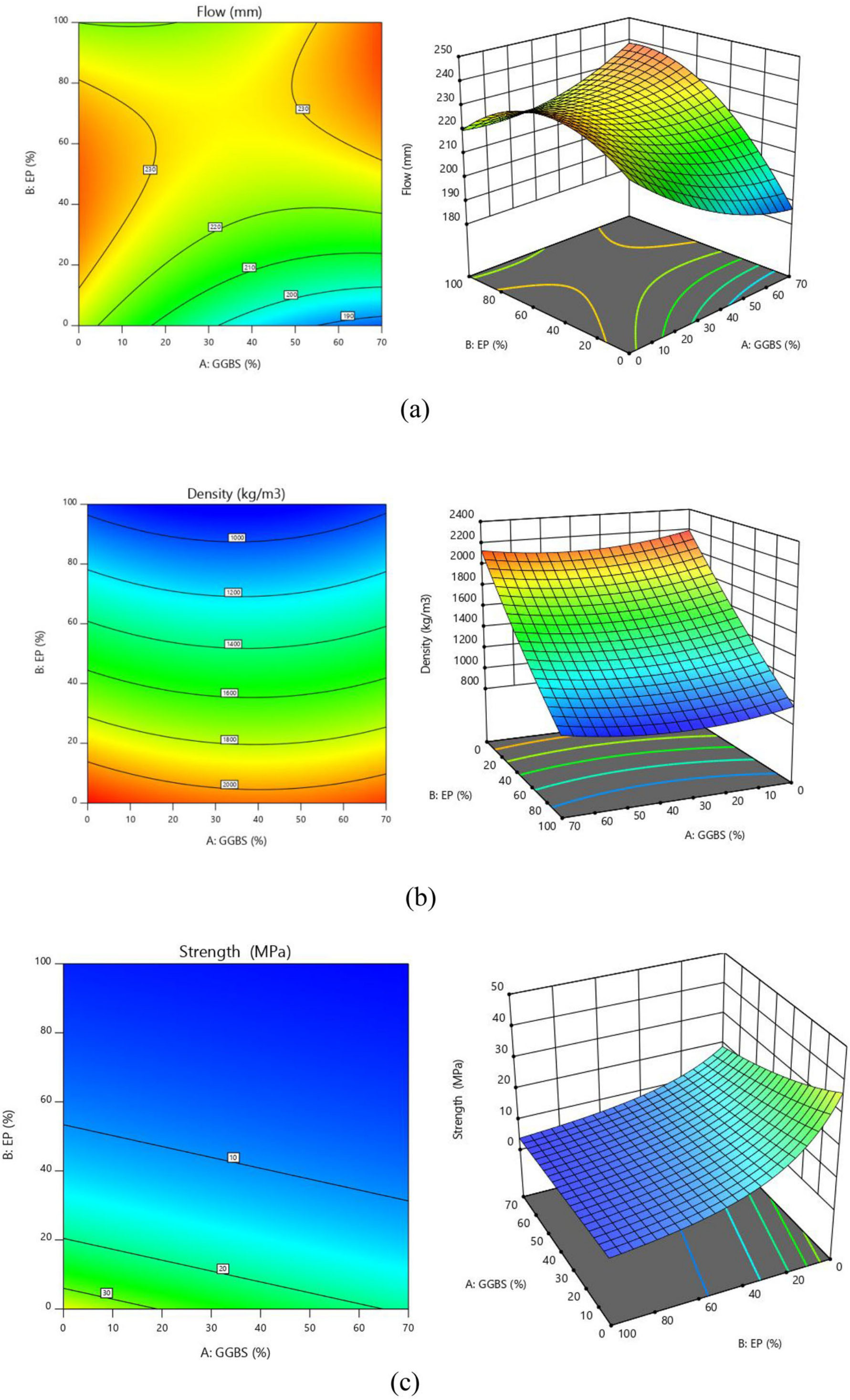
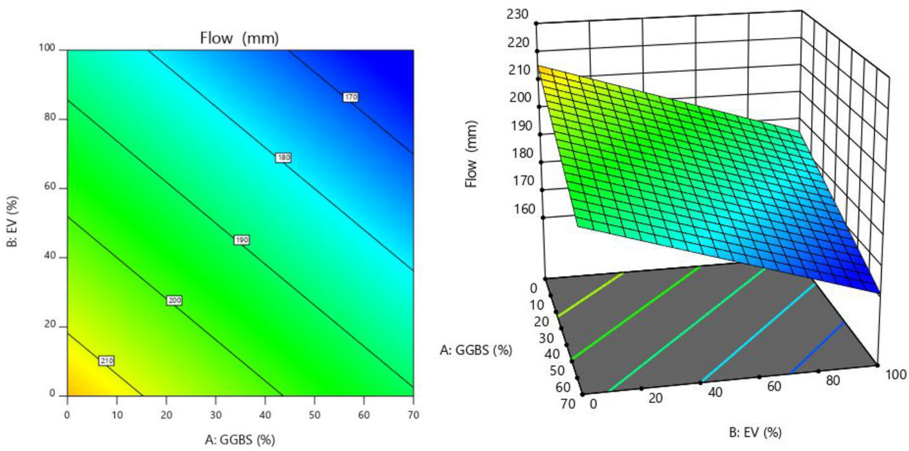
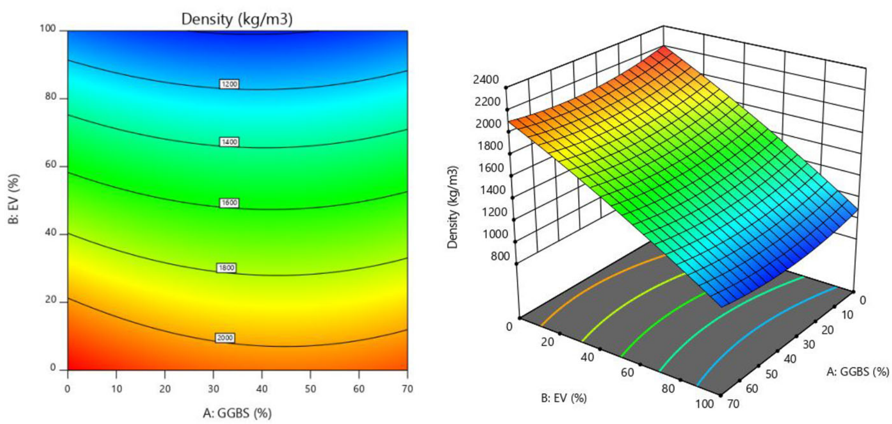


Figure 9. Contour plot and response surface of flow, density and strength for GGBS mortar with EP.

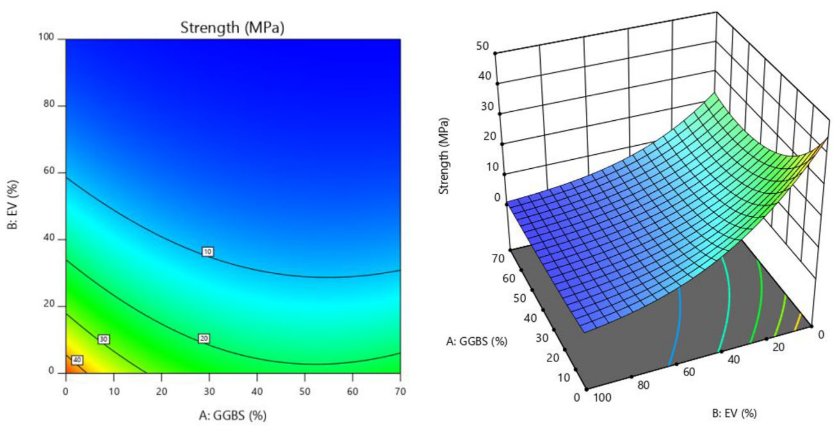
plot and response for the variable of flow, density and strength of this mixture from the RSM model. It can be observed that the GGBS level and EV content, individually, had more significant effect on the flow, density and strength of the mortars.



(a)



(b)



(c)

Figure 10. Contour plot and response surface of flow, density and strength for GGBS mortar with EV.

$$\text{Flow} = 215.397 - 0.352\text{A} - 0.297\text{B}. \quad (5)$$

$$\text{Density} = 2207.213 - 6.365\text{A} - 9.342\text{B} + 0.010\text{AB} + 0.070A^2 - 0.018B^2. \quad (6)$$

$$\text{Strength} = e^{3.796-0.029A-0.0216B-0.0001AB+0.0003A^2-0.0001B^2}. \quad (7)$$

3.4.3. Fly ash mortar with EP as sand substitute

Table 12 summarises the analysis output of flow, density and strength for fly ash mortar containing EP based on the RSM analysis. For flow diameter, the effects of fly ash level ($p = 0.0066$), EP content ($p < 0.0001$), quadratic effect of EP content ($p = 0.0003$) and the interaction of fly ash level with EP content ($p = 0.0002$) are statistically significant within the stipulated level of 5%, while only the quadratic effect of fly ash ($p = 0.0613$) is not statistically significant, which denotes that the significant factor of confidence level for this effect is lesser than 95%. When considering the effect on density, the analysis output shows that only the effect of interaction between fly ash with EP ($p = 0.2047$) is not statistically significant while the effect of fly ash level, EP content, quadratic effect of fly ash level and quadratic effect of EP content are all significant as shown in Table 12. Only the quadratic effect of fly ash content ($p = 0.1917$) is not significant for the case of the strength of mortar, while other effects are all statistically significant to the stipulated level of 5%. Equations (8)–(10) presents the final mathematical models in term of actual factors for estimating the flow, density and strength of the mortar mix. Figure 11 shows the contour plot and response for the variables of flow, density and strength of the mix based on the RSM model. Similar as the trend observed in the corresponding GGBS mixes containing EP, high volume replacement of fly ash and EP content reduced the overall density and compressive strength. It should be noted that there is also an optimum combination of fly ash and EP to produce mortar with enhanced flow.

$$\text{Flow} = 222.290 - 0.433\text{A} + 0.690\text{B} + 0.013\text{AB} - 0.009A^2 - 0.007B^2. \quad (8)$$

$$\text{Density} = 2184.807 - 8.670\text{A} - 14.125\text{B} + 0.015\text{AB} + 0.135A^2 + 0.020B^2. \quad (9)$$

$$\text{Strength} = \frac{1}{0.024 + 0.001A + 0.001B + 0.00001AB - 0.000007A^2 + 0.000003B^2} \quad (10)$$

3.4.4. Fly ash mortar with EV as sand substitute

Table 13 summarises the ANOVA for all 3 responses in the mixture containing fly ash with EV as sand replacement. From the RSM analysis, it was found that the effect of fly ash level ($p = 0.0143$) and EV content ($p = 0.0315$) on the flow of the mortar are statistically significant. Similar trend was found for the density, whereby the effect of fly ash level ($p = 0.0012$), effect of EV content ($p < 0.0001$), quadratic effect of fly ash level ($p = 0.0006$) and quadratic effect of EV content ($p = 0.0130$) are statistically significant at the stipulated level of 5%. However, the interaction between fly ash level and EV content ($p = 0.7057$) is not statistically significant on the density of mortar. Therefore, null hypothesis is required for this effect due to larger probability value. In terms of the mortar strength, only the quadratic effect of EV content ($p = 0.9300$) is found to be not statistically significant, while the other effects, namely fly ash level ($p < 0.0001$), EV content ($p < 0.0001$), interaction of fly ash level with EV content ($p = 0.0137$) and quadratic effect of fly ash level ($p = 0.0002$) are statistically significant. From RSM analysis, Equations (11), (12) and (13) were obtained in terms of actual factors to predict the flow, density and strength of the mix. The contour plot and response of each variable in this mixture are shown in Figure 12. Similar as the observation in GGBS mortar containing EV, the fly ash level and EV content were found to have more significant effect individually on the properties of this mortar.

$$\text{Flow} = 214.051 - 0.600\text{A} - 0.253\text{B} . \quad (11)$$

$$\text{Density} = 2239.244 - 15.235\text{A} - 14.294\text{A} - 0.007\text{AB} + 0.240A^2 + 0.033B^2 \quad (12)$$

$$\text{Strength} = e^{3.850-0.055A-0.029B-0.0002AB+0.0008A^2+0.000003B^2} \quad (13)$$

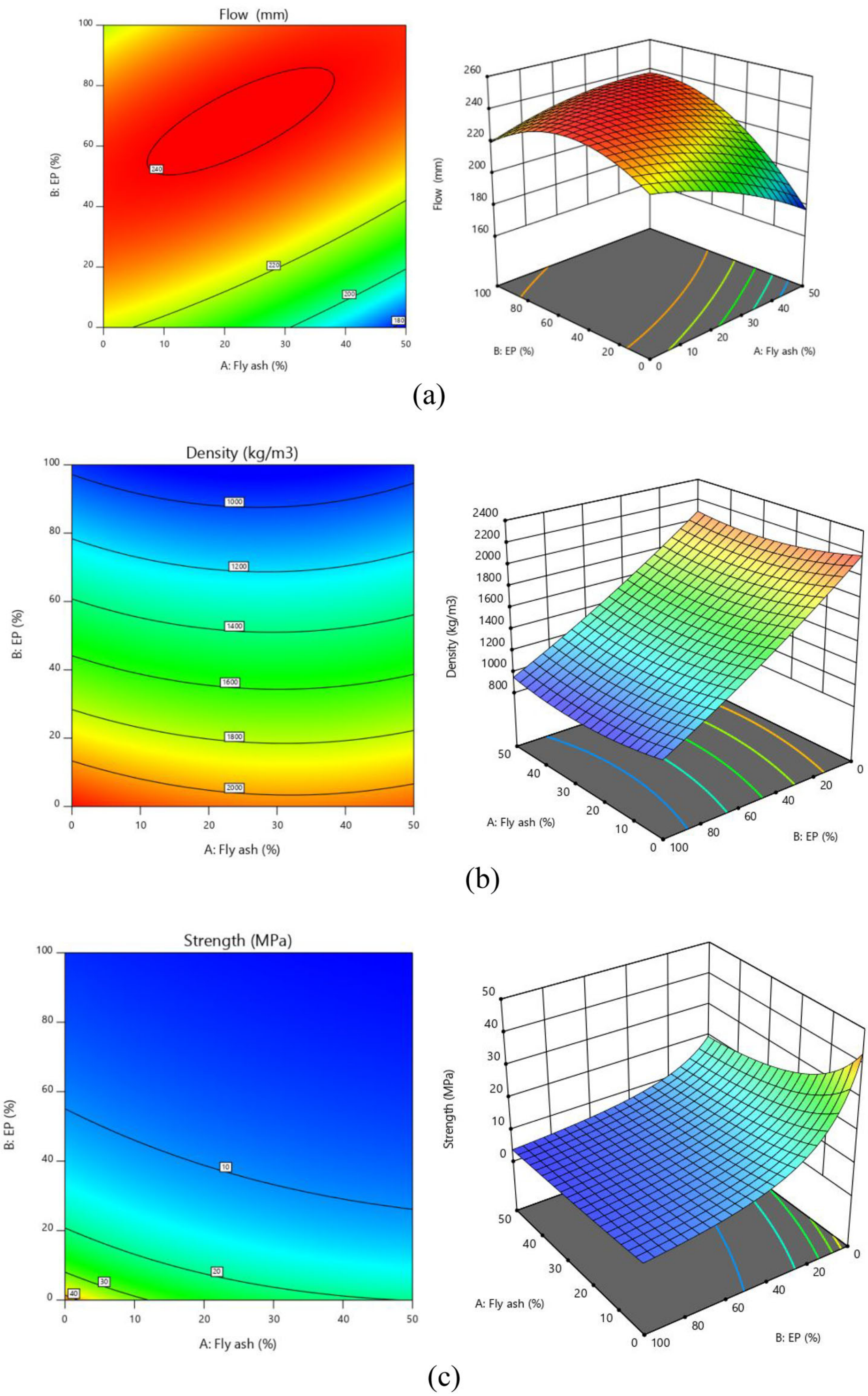


Figure 11. Contour plot and response surface of flow, density and strength for fly ash mortar with EP.

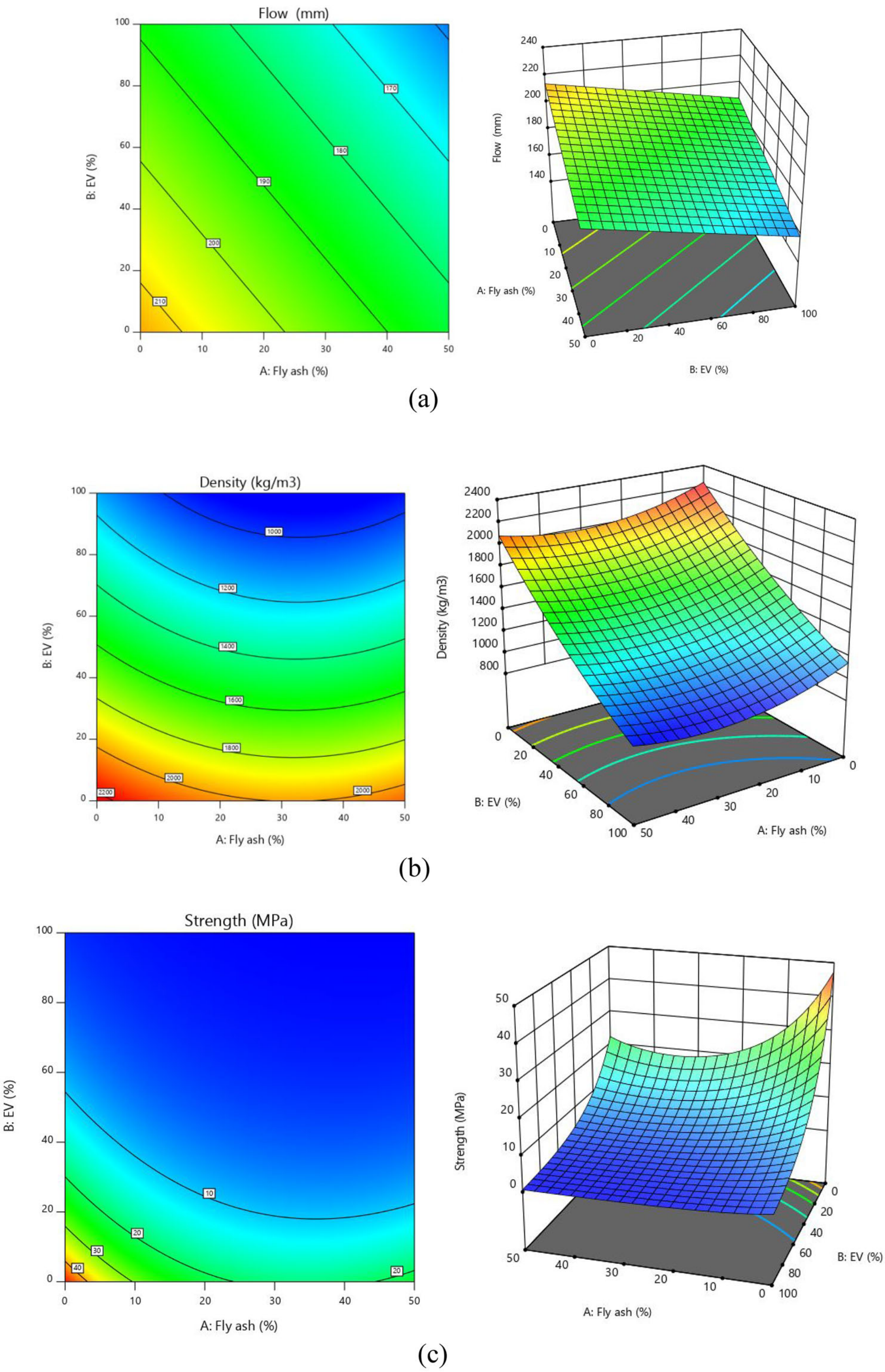


Figure 12. Contour plot and response surface of flow, density and strength for fly ash mortar with EV.

Table 14. Validation of the responses surface model for different mixes.

	Properties								
	Flow (mm)			Density (kg/m^3)			Strength (MPa)		
Mix types	A	B	Diff.	A	B	Diff.	A	B	Diff.
GGBS with EP mix	223	226	−1.35	1410	1421	−0.78	7.5	7.9	−5.3
GGBS with EV mix	194	188	3.09	1578	1576	0.13	6.1	5.2	14.8
Fly ash with EP mix	238	239	−0.42	1408	1415	−0.50	8.1	8.7	−7.4
Fly ash with EV mix	192	186	3.13	1354	1367	−0.96	3.9	3.6	7.7

A = Experiment Results.
B = Predicted Results.
Diff. = Differences (%).

3.5. Validation of experiments

The overall models of all mixtures are statistically significant for chosen significant level of 5% (Kumar & Baskar, 2014). The experimental values of flow, density and strength of the mortars were used to validate the calculated statistical models. For validation of mortar mixtures contain GGBS with either EP or EV as sand replacement, the constituent of 35% GGBS with 50% of EP or EV content were taken, whereas 25% fly ash with 50% of EP or EV content were adopted for the validation analysis in the fly ash mortar mixes. It can be seen from Table 14 that the experimental values agreed well with the predicted values, and this validates the calculated response surface models (Kumar & Baskar, 2014).

4. Conclusion

An experimental study was conducted to assess the properties of lightweight mortars prepared with EP and EV fine aggregates, as well as containing high volume SCMs (GGBS and fly ash) as cement replacement materials. The following conclusions can be drawn based on this investigation:

a. Inclusion of EP as sand replacement improved the flow of fresh mortar while the effect of EV was opposite. There is positive synergistic effect between use of SCM and EP on the flow of fresh mortar. The SCM-blended fresh mortars containing EP can be classified as soft mortar (flow diameter > 200 mm).
b. Lightweight mortars with density in the range of 1400–1700 kg/m^3 can be produced with 50% sand replacement by EP or EV, while density as low as 900–1100 kg/m^3 can be achieved with 100% sand replacement.
c. Inclusion of the lightweight aggregates caused significant compressive strength reduction of mortar, though the use of SCMs could limit the strength decrease in the EP mortars. Mortars containing 50% EP can be classified as type N mortar (compressive strength > 5.17 MPa) while the mortars containing 100% EP may be categorised as type O mortar (compressive strength > 2.4 MPa).
d. RSM demonstrated that full quadratic model can be employed to predict the studied properties (flow, density and compressive strength) of mortars containing the lightweight fine aggregates (EP and EV) and SCMs (GGBS and fly ash).

Disclosure statement

No potential conflict of interest was reported by the authors.

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