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Experimental and numerical analysis of new bricks made up of polymer modified-cement using expanded vermiculite

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Abstract. In this paper, the properties of the cement mortar modified with styrene acrylic ester copolymer were investigated. Expanded vermiculite as lightweight aggregate was used for making the polymer modified mortar test specimens. To study the effect of polymer–cement ratio and vermiculite-cement ratio on various properties, specimens were prepared by varying the polymer–cement and vermiculite-cement ratios. Tests of physical properties such as density, water absorption, thermal conductivity, three-point flexure and compressive tests were made on the specimens. Furthermore, a coupled thermal-structural finite element model of an entire corner wall was modelled in order to study the best material configuration. The wall is composed by a total of 132 bricks of 120 × 242 × 54 size, joined by means of a contact-bonded model. The use of advanced numerical methods allows us to obtain the optimum material properties. Finally, comparisons of polymer–cement and vermiculite-cement ratios on physical properties are given and the most important conclusions are exposed.

Keywords: polymer; lightweight mortar; expanded vermiculite; thermal conductivity; FEM and DOE analysis

1. Introduction

The polymers are dispersed in water or redispersible powders, and added to hydraulic cement, with or without aggregate or admixtures. Polymers have good binding properties and good adhesion with aggregates, and also have long-chain structure, which helps in developing long-range network structure of bonding (Islam *et al.* 2011). Polymer-modified mortars (PMM) are known as a composite made by using polymer along with cement and aggregates. Polymers incorporated in a cement–aggregate mix can greatly improve the properties of mortars such as

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strength, adhesion, resilience, impermeability and durability (ACI 548.3R-95 1995, Mirza *et al.* 2002, Aggarwal *et al.* 2007).

The use of polymers also provides good resistance to physical damage (abrasion, erosion, impact) and chemical attack (Islam *et al.* 2011). PMM has a wide-range of application areas such as; pavements and overlays, industrial floors, structural and non-structural precast products, repairing and retrofitting of reinforced concrete structures, anticorrosive and decorative finishes (Ohama 1987, Mehta and Monteiro 1993, Mirza *et al.* 2002). Many thermoplastic or thermosetting polymers are used in modifying mortars in various forms such as liquid resins, latexes, redispersible powders and water-soluble homopolymers or copolymers (Ohama 1998). Polymer type to be used in modification of mortar is chosen depending on the intended use and requirement of performances like strength, durability and chemical resistance. Latexes of a single or combinations of polymers like polyvinyl acetate, copolymers of vinyl acetate–ethylene, styrene–butadiene, styrene–acrylic, and acrylic and styrene butadiene rubber emulsions are generally used in water based polymer systems for improvement in the properties of plain cement mortar.

Vermiculite is a naturally-occurring mineral formed by weathering or hydrothermal alteration of biotite or phlogopite and it is composed of shiny flakes and resembling mica (Hombostel 1991). Vermiculite expands with the application of heat as much as 8-30 times their original size. In its expanded form, vermiculite has a very low density and thermal conductivity. Therefore it becomes attractive for use as a lightweight construction aggregate and thermal insulation filler. Expanded vermiculite has been used for various industrial and agricultural applications such as potting soils, soil conditioners, carrier for fertilizers, insecticides and herbicides, various livestock applications, seed germination and ammonia filtering in aquaculture, and also in production of high-temperature insulation and refractory materials, acoustic panels, fireproofing of structural steel and pipes, roof and floor screeds and insulating concretes (Köksal *et al.* 2012, Schulze 2002, Suvorov and Skurikhin 2003). Expanded vermiculite is classified as natural type of lightweight aggregate like pumice, diatomite, volcanic cinders, etc.

In consequence, the economic benefits derived from the use of both materials, polymer modified-cement lightweight and expanded vermiculite, for making bricks are clear: improve the strength and thermal properties without increase the manufacturing cost.

Furthermore, the study of actual structural failures has become a useful tool for both structural engineers and students, as shown by the ever-growing number of books and articles published and the conferences dedicated to the subject. Much can be learned from failures that can later be applied to improvements in the field of structural design in the form of new theories, concepts, structural details, etc. (Adam and Pallarés 2010, Delatte 2010). In this sense, an important number of books and research articles have been published in recent years, dealing with building and masonry failures (Betti and Vignoli 2008, Betti *et al.* 2011, Calderon *et al.* 2009, Del Coz Diaz *et al.* 2010, Ivorra *et al.* 2009, Lourenco *et al.* 2007). However, most of the studies related to failures in masonry structures have concentrated on historical buildings and very few of the recent publications have given their attention to new buildings in which masonry plays an important structural role (Del Coz Diaz *et al.* 2011a).

Outside wall failures can be due to diverse reasons, one of these being thermal or structural actions on bricks, as in the specific case analyzed in this paper: a typical corner wall. This common failure is studied by Del Coz Diaz in different actual cases and the material properties play an important role in the structural integrity of the external walls (Del Coz Diaz *et al.* 2011a, 2012).

In this sense, the most important innovation of this paper is the use of the FEM modeling joined with the laboratory tests in order to obtain the best material properties from the thermal and structural points of view. With the basis on a sophisticated coupled thermal-structural numerical model, a search for optimal value based on the designs of experiments (DOE) (Del Coz Diaz *et al.* 2010, 2011b) and goal optimization analysis is done to propose the best block mixture.

Other objective of this study is to investigate the combined effect of styrene acrylic ester copolymer as a cement modifier and expanded vermiculite as lightweight aggregate in properties of cementitious lightweight mortar. The properties of polymer modified mortars are compared with those of unmodified cement mortars.

Table 1 Properties of expanded vermiculite

Chemical properties	
Compositions	%
SiO_2	34.1
Al_2O_3	17.2
K_2O	4.52
CaO	6.4
MgO	16.3
Fe_2O_3	14.7
pH (in water)	6.1
Others	0.68
Physical properties	
Colour	Silver
Shape	Accordion-shaped granule
Water holding capacity	240% by weight)
Cation exchange capacity	90 meg / 100 g
Thermal conductivity value	0.063 watt/m/^{o}C
Sintering temperature	1170^{o}C
Combustibility	Non-combustible
Specific heat	0.22 Kcal / Kg^{o}C
Bulk density	140 kg/m^3

Table 2 Mix proportions of mortars

SAE/cement (by weight) (%)	Vermiculite/ Cement (by volume)	Cement (kg/m^3)	Water (kg/m^3)	Vermiculite (kg/m^3)	SAE Latex Polymer (kg/m^3)	Water reducer admixture (kg/m^3)
0	3	864	438	155	0	9.5
	6	565	457	203	0	6.2
	9	434	496	235	0	4.8
10	3	712	402	142	79	7.8
	6	471	423	188	52	5.2
	9	356	452	214	40	3.9
20	3	625	286	141	156	6.9
	6	423	318	190	106	4.7
	9	278	292	188	70	3.1
30	3	530	245	136	227	5.8
	6	318	242	163	136	3.5
	9	253	267	195	109	2.8

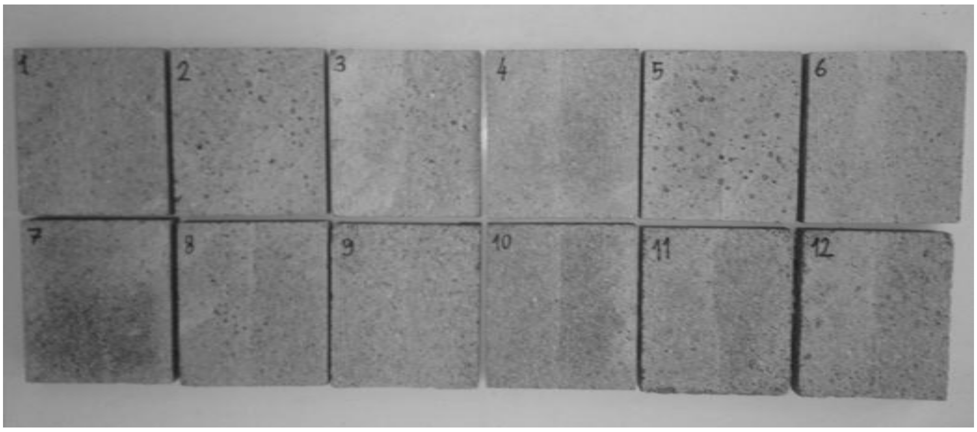


Fig. 1 Plate specimens prepared for thermal conductivity test

Fig. 2 Test setup of thermal conductivity test

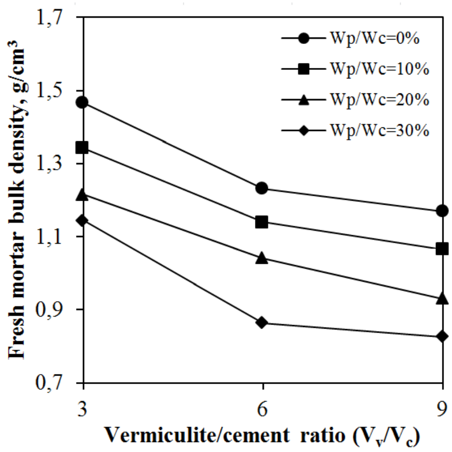
2. Materials and experimentation

CEM I 42.5R Portland Cement, which complies with the requirement of European Standards (EN 197-1/A1 2005), was used as a hydraulic binder. Expanded vermiculite, with a particle size of 0-4 mm, obtained by exfoliation of raw vermiculite at about 600℃ for 10 seconds was used as a lightweight aggregate. The chemical and physical properties of expanded vermiculite are given in Table 1.

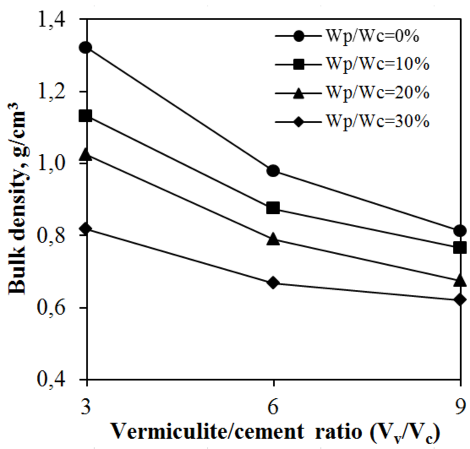
Styrene-acrylic ester copolymer (SAE) latex (solid content: 50%; viscosity: 5000-25000 cPs; pH: 7.5-9.0; Tg: + 6.5℃; minimal film formation temperature: 13.5℃; average particle size: 0.1 μm) was used in the experiment. A high-range water reducer chemical admixture was also used for settling of fresh mortar to molds easily.

Table 3 Physical properties and strength test results of mortars

SAE/ cement (by weight) (%)	Vermiculite/ Cement (by volume)	Fresh Bulk Density (g/cm^3)	Dry Bulk Density (g/cm^3)	Water Absorption (by weight) (%)	Porosity (%)	Thermal Cond. (W/mK)	Flexural strength (MPa)	Compressive strength (MPa)	
w_p/w_c	V_c/V_c					TC	f_f	f_c	f_c/f_f
0	3	1.467	1.320	7.9	10.4	0.836	2.93	10.84	3.70
	6	1.231	0.979	26.1	22.5	0.533	1.95	5.00	2.56
	9	1.169	0.813	46.7	31.6	0.368	1.38	2.73	1.97
10	3	1.343	1.132	11.6	11.9	0.536	2.39	6.83	2.86
	6	1.140	0.874	32.0	25.5	0.514	1.39	3.40	2.44
	9	1.066	0.766	49.0	33.5	0.377	1.09	2.01	1.84
20	3	1.215	1.023	16.5	13.5	0.580	3.68	6.40	1.74
	6	1.041	0.788	41.0	27.3	0.515	2.03	3.20	1.58
	9	0.931	0.673	54.0	37.9	0.422	1.41	1.81	1.28
30	3	1.145	0.817	19.0	21.5	0.472	2.43	4.10	1.69
	6	0.864	0.667	43.4	33.6	0.407	1.55	2.40	1.55
	9	0.826	0.620	64.6	43.0	0.399	1.02	1.21	1.19



(a) Fresh mortar



(b) Hardened mortar

Fig. 3 Bulk densities of the SAE latex-modified mortars

The mortar specimens were prepared with varying SAE latex/cement ratio (W_p/W_c) of 0%, 10%, 20% and 30%, constant flow of 180 ± 10 mm, and expanded vermiculite/cement ratio (V_v/V_c) of 3, 6 and 9, by volume. The mix proportions of mortars are given in Table 2. Prismatic specimens with the dimension of 40 mm × 40 mm × 160 mm, for flexural tensile (f_f) and compressive strength (f_c) tests, were prepared according to EN1015-11 standard rule (EN 1015-11

1999). 150 mm ×150 mm × 30 mm plate specimens were also prepared for thermal conductivity (*TC*) tests. The specimens were demolded after 24 hours and then cured in water at 23 ± 2℃ for 27 days. Test of fresh bulk density during production of mortars, and dry bulk density and water absorption (*WA*) tests on the specimens at the end of 28 days were performed. Flexural strength tests were made on three prismatic specimens and compressive strength tests were made on six broken pieces obtained from the flexural test. Average values of strengths of specimens were taken as the test results. The thermal conductivity of plate specimens was determined by the 'hot wire method' according to ASTM C1113 standard test (ASTM C1113-99 2004). In this method, the temperature variation with time at certain locations is measured instead of measuring heat flow. *TC* of mortars was determined in 3 different points on plate specimen surface and average value of 3 points readings was taken as *TC* of mortars. Specimens prepared and test setup for thermal conductivity test was given in Figs. 1 and 2, respectively.

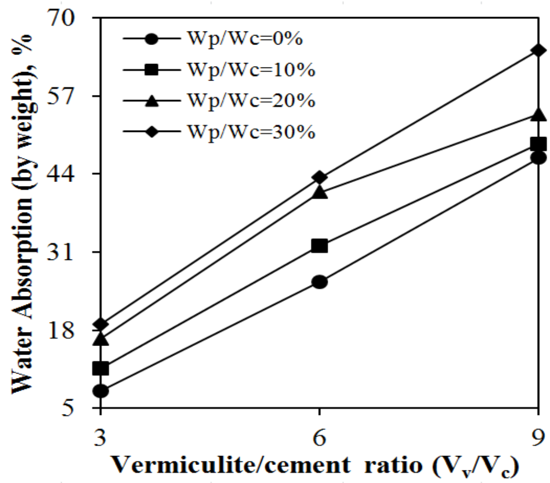


Fig. 4 Water absorption of mortars

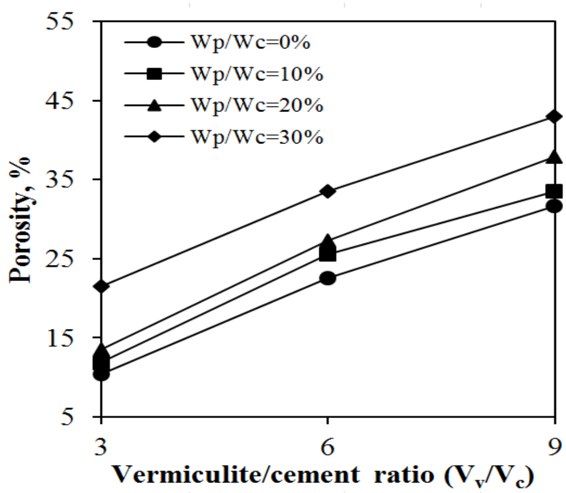


Fig. 5 Porosity of mortars

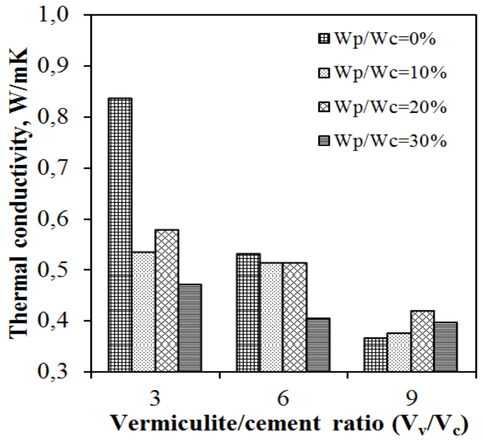


Fig. 6 Thermal conductivity of mortars

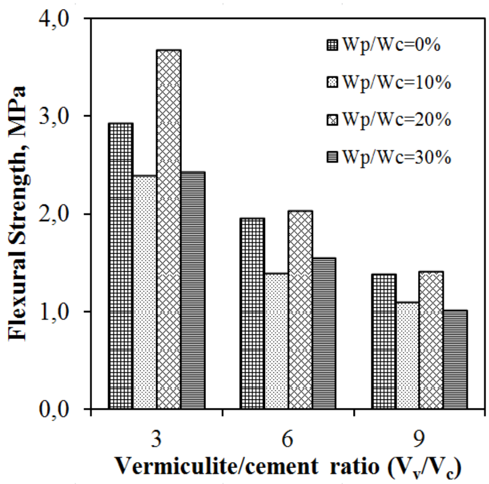


Fig. 7 Flexural strength of mortars

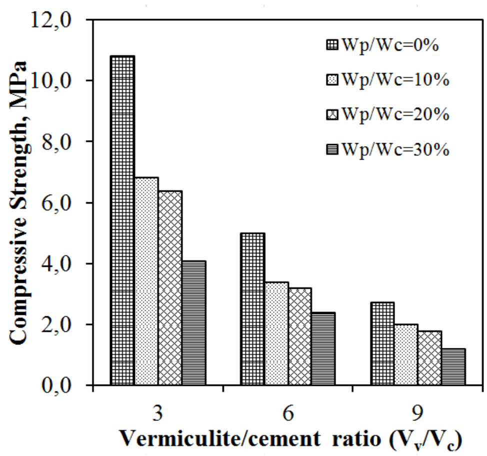


Fig. 8 Compressive strength of mortars

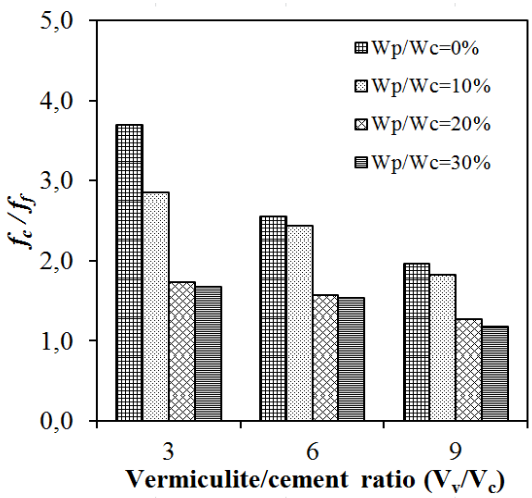


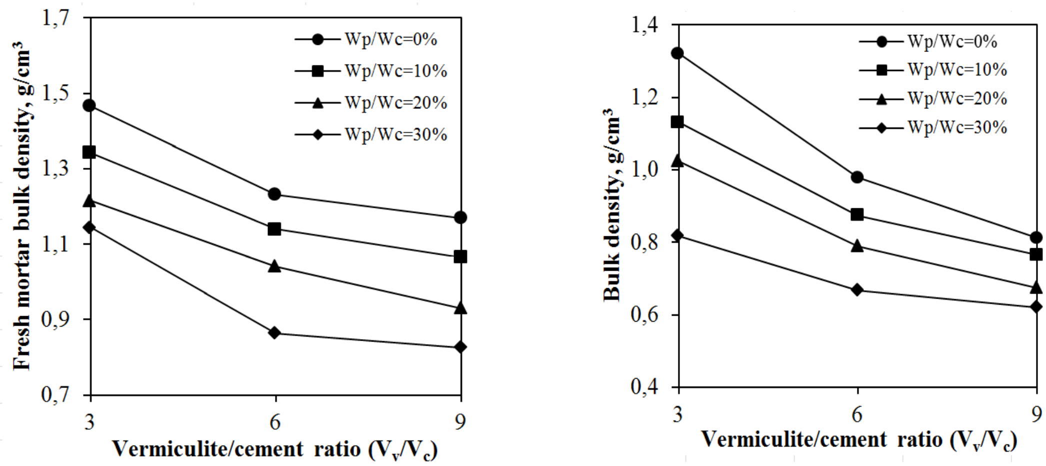
Fig. 9 Ratio of the compressive strength to the flexural strength of mortars

2.1 Tests results and discussion

Physical properties and strength test results of mortars were given in Table 3. Water absorption of mortars decreased with the increases of both SAE/cement and vermiculite/cement ratios while fresh and dry bulk densities were decreasing. SAE latex has air entrainment effect and augments the porosity of the fresh mortar (Wang and Wang 2010). On the other hand, expanded vermiculite has high pore structure and very low bulk density. Therefore, those are expected experimental results for bulk densities, water absorption capacity and porosity of mortars. The lowest fresh and dry bulk densities were obtained at vermiculite/cement ratio of 9 and SAE/cement ratio of 30% as 0.826 gr/cm^3 and 0.620 gr/cm^3, respectively. At the same vermiculite/cement and SAE/cement ratios, maximum water absorption and porosity were obtained as 64.6% and 43%, respectively. The relations between V_v/V_c and W_p/W_c with the bulk densities, water absorption and porosity of mortars were given in Figs. 3-5, respectively.

In generally, SAE has a decreasing effect on *TC* for vermiculite/cement ratios of 3 and 6 when compared to mortar with no SAE. However, it has a negative effect on *TC* for vermiculite/cement ratios of 9. On the other hand, TC significantly decreased by increasing vermiculite/cement ratio at each SAE/cement ratio. The highest values of *TC* of concrete is obtained for mortars produced with vermiculite/cement ratio of 3, in which cement content is high, for all SAE contents. The lowest *TC* was 0.368 W/mK, which was obtained at vermiculite/cement ratios of 9 when the mortar has no SAE content. The relationship between V_v/V_c and W_p/W_c with thermal conductivity of mortars were given in Fig. 6.

The flexural strengths of mortars (see Fig. 7) decreased when increasing the vermiculite/cement ratio from 3 to 9. However, flexural strengths of mortars with SAE/cement ratio of 20% increased when compared to mortars with no SAE polymer for each vermiculite/cement. 25.6% increase, which is the maximum increase in flexural strength, was obtained at vermiculite/cement ratio of 3 and SAE/cement ratio of 20%. Compressive strengths of mortars (see Fig. 8) decreased with the increasing of both vermiculite/cement and SAE/cement ratios. The relative loss of compressive strengths was lower at SAE/cement ratio of 20% for all vermiculite/cement ratios. However, ratio



(a) Compressive strength (b) Thermal conductivity

Fig. 10 Surface fitting results as a function of the vermiculite/cement and SAE/cement ratios

of the compressive strength to the flexural strength of mortar decreased with increasing of both SAE/cement vermiculite/cement ratios. The ratio of the compressive strength to the flexural strength is an important factor since lower ratio of the compressive strength to the flexural strength indicates better toughness. Therefore, it can be concluded that the SAE latex improves the toughness of the PMM with lightweight aggregate. Graphical representations of strengths are provided, as seen in Figs. 7 and 8. The ratio of the compressive strength to the flexural strength of the SAE latex modified mortars, depending on V_v/V_c and, W_p/W_c was displayed in Fig. 9.

Strength results showed that an optimization can be required to use of SAE latex polymers as modifier of cement for PMM mixtures incorporating lightweight aggregate such as expanded vermiculite, pumice, diatomite, perlite, etc.

3. Numerical models: fem and doe analyses

3.1 Material properties

In order to use the laboratory results obtained in the previous section, a curve fitting analysis with an evolutionary scheme has been applied for the strength and thermal conductivity results, taking into account the following equations (see Fig. 10)

$$f_c = c_1 + c_2 \times \frac{W_p}{W_c} + c_3 \times \frac{V_v}{V_c} \tag{1}$$

$$\lambda_c = d_1 + d_2 \times \frac{W_p}{W_c} + d_3 \times \frac{V_v}{V_c} \tag{2}$$

From the numerical curve fitting analysis, the following values of the function's parameters has been obtained:

$c_1 = 9.74879635247553; c_2 = -0.0901408580191444; c_3 = -0.765869634953704$

$d_1 = 0.689399979043739; d_2 = -0.00186749915166652; d_3 = -0.0260989019828188$

To do this, the goodness of the fitted curves compared to the observed values was performed using the coefficient of determination as a significant statistic (Fox 2008)

$$r^2 = \frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2} \tag{3}$$

where

Y_i are the observed values obtained in the actual tests.

$\hat{Y}_i$ are the modeled values obtained from the fitted curve or 'predicted values'.

$\bar{Y}$ is the mean of the observed data.

n is the number of the observed values obtained in the actual tests or 'sample size'.

Therefore, in this research work the fitted surfaces have been carried out according to the following steps:

- Transformations for data linearization for linear theoretical models. Once the curve has been chosen, a suitable transformation of the variables must be found so that a linear relation is obtained.
- Finding the best fitted surface in each direction with least squares fitting technique using the MATLAB software (Chapman 2008).
- Refinement of the previous best-fit parameters using a quasi-Newton method.

With this evolutionary procedure, the best fitting surface is obtained as a function of the vermiculite/cement and SAE/cement ratios for the compressive strength and thermal conductivity material properties (see Fig. 10).

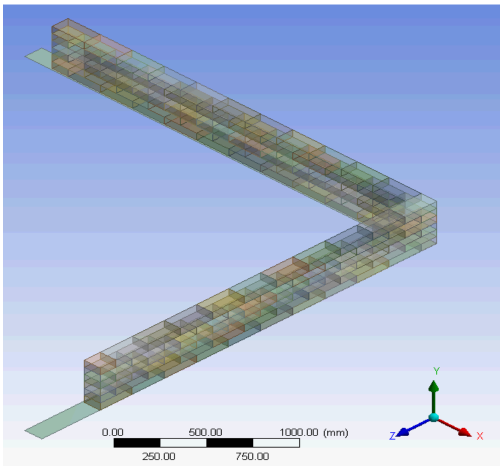
3.2 Thermal –structural analysis

In order to verify the stresses and displacements in a typical corner wall, a coupled thermal-structural analysis was carried out by the finite element method (FEM) with the ANSYS program (Moaveni 2007, Madenci and Guven 2007) in the Workbench environment. A corner section of half foot brick wall was built with a total of 132 bricks ($241.5 \times 120 \times 51.5$) to a height of 0.324 m and a length of 2.56 m, simply supported on a rigid soil (see Fig. 11).

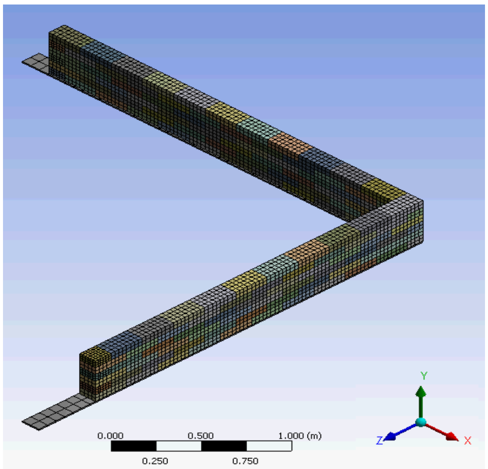
The geometric model was meshed by Solid95 (with reduced integration option for brick shape) and Solid90 finite elements for the structural and thermal analysis, respectively. The FE model had a total of 61,419 nodes and 8,888 elements. A total of 859 contact surfaces were generated with the following characteristics

- Friction type contact between the wall and the rigid soil, with a coefficient of friction of 0.5 (Del Coz Díaz *et al.* 2011a).
- Rough contact between brick surfaces, simulating the mortar behaviour.
- Contact algorithm: Augmented Lagrange.

The FE model was solved considering the following characteristics (Del Coz Diaz *et al.* 2011b,

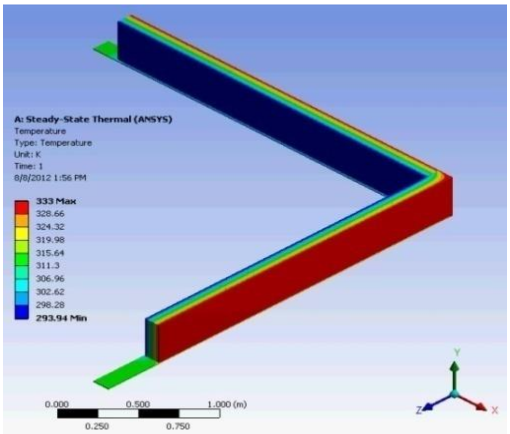


(a) Geometrical model

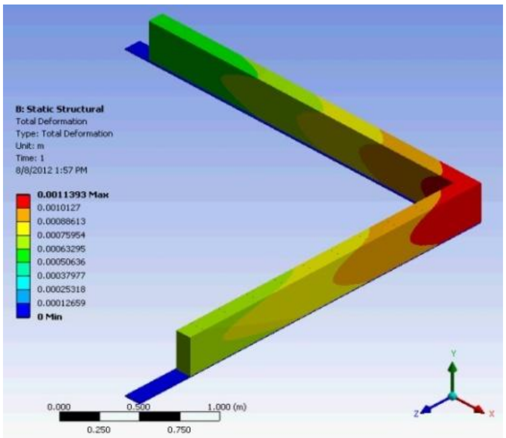


(b) Finite element mesh

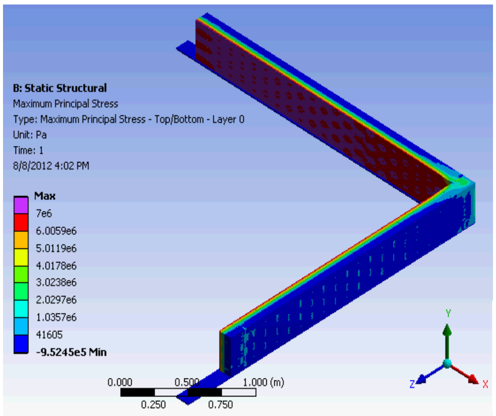
Fig. 11 Wall overall view



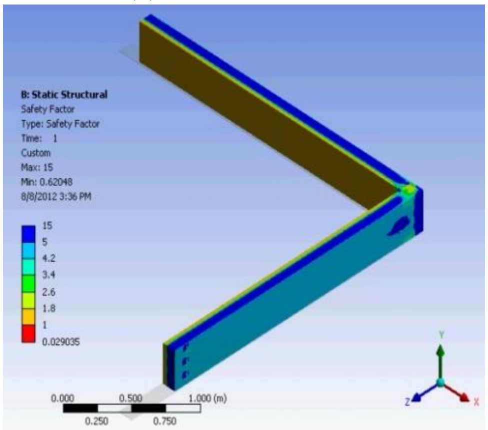
(a) Temperature distribution



(b) Total deformation

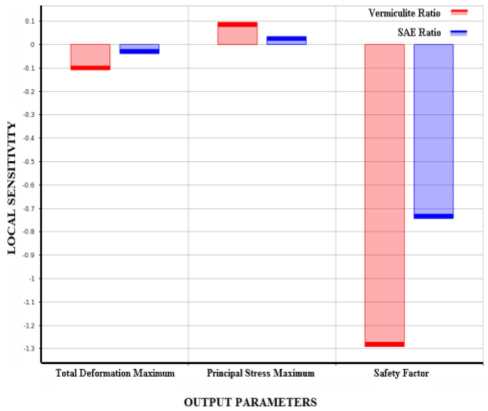


(c) Principal stress

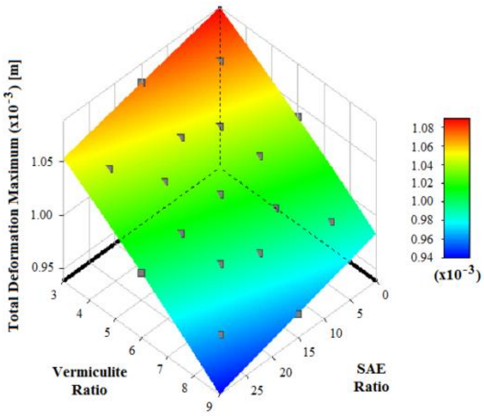


(d) Wall safety factor

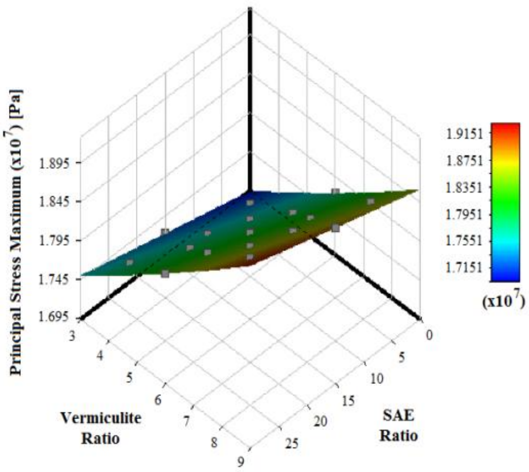
Fig. 12 FEM results



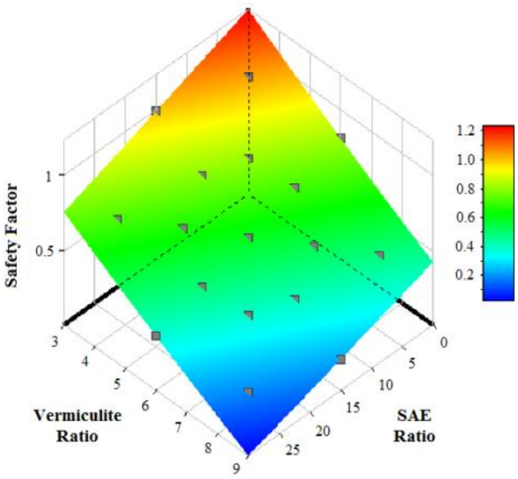
(a) Sensitivity analysis



(b) Total deformation



(c) Principal stress



(d) Wall safety factor

Fig. 13 Results of sensitivity analysis and surface responses from the DOE analysis: SAE/cement versus vermiculite/cement ratios

Table 4 Optimization based on DOE analysis

	V_v/V_c (%)	W_p/W_c (%)	f_c (Pa)	f_t (Pa)	λ (W/mK)	Δ_{max} (m)	Safety factor (%)
Candidate Point 1	3.39	11.40	6.12×10^6	8.56×10^5	0.58	1.07×10^{-3}	0.99
Candidate Point 2	4.23	4.84	6.06×10^6	8.49×10^5	0.57	1.06×10^{-3}	0.98
Candidate Point 3	3.09	15.15	6.01×10^6	8.41×10^5	0.58	1.07×10^{-3}	0.98

Del Coz Diaz *et al.* 2012)

a) Thermal case:

- Ambient temperature 273 K.
- Uniform temperature of 333 K on external wall surfaces.
- Natural convection coefficient of 7.7 W/m^{2}K inside the building.

- The remaining surfaces were considered to be adiabatic.

b) Structural case

- Thermal temperature distribution as calculated in the preceding step.
- Gravitational actions.
- Longitudinal displacement was prevented at the ends of the wall.
- A load of 20,000 Pa was applied to the upper part of the wall, corresponding to the weight of bricks up to a height of 2 m.

The Drucker Prager constitutive model (Adam and Pallarés 2010, Lourenco and Pina 2006) was adopted for bricks, with the following values characteristics (Del Coz Diaz *et al.* 2011b):

- Compressive strength, f_c, obtained from the laboratory tests (see Table 3) and numerical curve fitting, according to Eq. (1).
- Tensile strength, obtained from the above compressive strength: $f_t = 0.21\sqrt[3]{f_c^2}$
- Cohesion value: $c = \dfrac{f_t \cdot (1 - \sin\Phi)}{2\cos\Phi}$
- Angle of internal friction (Φ): 25°
- Dilatance angle: 5°
- Elastic modulus as a function of the compressive strength, obtained from the following equation: $E = \dfrac{f_c}{0.63} \times 10^3\,\mathrm{MPa}$
- Poisson coefficient: $\nu = 0.09$
- Coefficient of thermal expansion: $\alpha = 5 \times 10^{-6}$
- Isotropic thermal conductivity, λ_c, obtained in laboratory tests (see Table 3) and numerical curve fitting, according to Eq. (2).

Owing to the large number of contact elements and the value adopted for the coefficient of friction, the coupled thermal-structural problem was solved by the full Newton-Raphson option for all degrees of freedom with unsymmetric solver including the adaptative descent option. The Newton-Raphson analysis options for a time step of 1 second, discarding the inertial effects, were as follows

- Initial time step: 0.05 s.
- Minimum time step: 0.001 s.
- Maximum time step: 0.1 s.

The problem was solved on a workstation with double 8-core 2.53 GHz Intel Xeon E5630 processor, 64 GB of RAM and 8 TB of SATA-II hard drive. Total CPU time for each case was 6088 seconds, and 25 interactions were needed to achieve the convergence of the solution.

From the structural results, the wall safety factor was calculated based on the Mohr-Coulomb stress failure theory for brittle materials (Calderini *et al.* 2010, Del Coz Diaz *et al.* 2011b). This stress failure theory states that failure occurs when the combination of the maximum, middle, and minimum principal equal or exceed their respective stress limits.

In view of the results shown in Fig. 12, we can draw the following observations

- The temperature distribution in the wall is as expected from the conductivity of bricks, with a total temperature gradient in the wall of 39.06 K.
- Maximum displacements in the corner wall caused by thermal expansion reach values of 1.14×10^{-3} m, which are lower than those obtained without considering material flexibility

or thermal gradient, which would be of the order of 2.5 mm, as obtained from the following expression: $\Delta_t = \alpha \times L \times \Delta T = 1.4 \times 10^{-5} \times 3 \times 60 = 2.52 \times 10^{-3}$ m

- The principal maximum stresses are of the order of 7 MPa in some specific points, lower than the permitted maximum of the bricks.
- The integrity of the wall is adequate and in no case exceeds the material's permitted maximum.

3.3 DOE based on the coupled thermal-structural FEM models

In order to study the influence of both SAE/cement vermiculite/cement ratios in the structural behaviour of the corner wall, a design optimization based on design of experiments (DOE) is carried out (Antony 2003, Sanchez *et al.* 2010). In a design optimization based on DOE (used in the deterministic method), each change of the value of any input variable requires a new finite element analysis. The response surface generated is an explicit approximation function of the finite element results expressed as a function of all the selected input variables. This method can be applied in coupled thermal-structural problems for both linear and non-linear analysis (Del Coz Diaz *et al.* 2011b).

As output parameters we have taking into account the maximum wall displacement, the maximum principal stress and the safety factor as response parameters.

A strong computational effort was necessary to perform the DOE analysis. To fix ideas, a total of eighteen different coupled nonlinear thermal-structural FEM models has been implemented and calculated in this work, and the total elapsed CPU time was about 30 hours.

With the results of the DOE analysis, it is possible to prove the following findings

• Firstly, Fig. 13(a) shows the sensitivity analysis of the coupled thermal-structural problem analyzed here. It is possible to observe the major influence of the variation in the vermiculite/cement ratio.

• Secondly, Fig. 13(b) shown the variation of the maximum deformation on the corner wall as a function of the SAE/cement vermiculite/cement ratios. Increasing the addition of vermiculite and SAE, maximum deformation decreases.

• Thirdly, Fig. 13(c) shown the variation of the maximum principal stress as a function of the SAE/cement vermiculite/cement ratios. In this case, the vermiculite addition increases more the maximum stress in the corner wall.

• Finally, Fig. 13(d) shown the variation of the safety factors as a function of the SAE/cement and vermiculite/cement ratios. The SAE ratio has less importance than the vermiculite ratio in the wall safety factor.

3.4 Optimization based on DOE analysis

From the above response surfaces (Fig. 13), it is possible to obtain the optimum values of the SAE/cement and vermiculite/cement ratios in order to obtain a safety factor equal to one for the corner wall studied here. In this way, a goal driven optimization (GDO) is carried out (Antony 2003), and the closest solution to the objective function is found. The numerical GDO procedure is a constrained, multi-objective optimization technique in which the "best" possible designs are obtained from a sample set given the objectives to look for. The optimum material properties obtained from the above DOE-GDO analysis are shown in Table 4.

In summary, the optimum and more economic values of the SAE/cement and vermiculite/cement ratios are the following (see Table 4 for the candidate point 2):

- Vermiculite/cement ratio by volume: 4%
- SAE/cement ratio by weight: 5%

4. Conclusions

On one hand, test results of polymer modified mortars, in which expanded vermiculite with a high porosity was used as lightweight aggregate, showed that bulk density and thermal conductivity of the specimens decrease, whereas the water absorption and porosity increase. On the other hand, flexural and compressive strengths decrease with increases in percentage of expanded vermiculite in the mortar mixture. Similarly, SAE latex used as cement modifier result in decreasing of strengths, except flexural strengths of mortars with SAE/cement ratio of 20% for each vermiculite/cement ratio. It can be said that SAE latex showed better performance in improvement of strength in flexure than compressive. Besides, SAE latex improves the toughness of mortars so that the ratio of the compressive strength to the flexural strength of mortar decreased with increasing of SAE/cement for all vermiculite/cement ratios. Finally, mortar mixture optimization, incorporating both properties of polymer and lightweight aggregate and those volume fractions, can be required for providing desired properties of polymer modified-cement lightweight mortars.

Regarding the numerical analysis, the following observations can be drawn:

• The thermal gradient in the corner wall is important and, in general, the stresses are no greater than the permissible limits in the specific thermal loads considered in this study.

• The use of a numerical model with contacts, as proposed here, has advantages when studying the actual behaviour of the corner wall model, since it can include both mortar flexibility, from the structural point of view, and its conductivity, from the thermal.

• A constitutive brick model such as the Drucker-Prager has been shown to be efficient and is able to reproduce the behaviour of the bricks with a high degree of accuracy, as shown in this and previous case studies (Calderini *et al.* 2010, Del Coz *et al.* 2011b).

• The thermal-structural FEM model proposed in the present study presents a new methodology clearly able to calculate the maximum stresses when thermal expansion occurs.

• The numerical results of the FEM based on the DOE analysis shown the major influence of the variation in the vermiculite/cement ratio with respect to the SAE/cement ratio. With the help of an optimization based on the DOE analysis, it is possible to obtain the best vermiculite and SAE ratios, as it is indicated in the subsection 4.4, specifically 4% for the vermiculite V_v/V_c ratio and 5% for the SAE W_p/W_c ratio.

All in all, this new experimental and numerical methodology can be applied to other similar cases or studies to obtain the best concrete addition ratio in case of complex coupled thermal-structural problems.

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