Synthesis and characterization of concrete mortars reinforced with thermostable polymer from industrial waste

Síntesis y caracterización de morteros de concreto reforzados con polímeros termoestables de desecho industrial

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Manuscript Code: 1086
Date of Acceptance/Reception: 03.12.2018/15.03.2018
DOI: 10.7764/RDLC.17.3.465

Abstract
The present research is focused on synthesizing and physically characterization different mixtures of concrete mortar reinforced with thermostable polymers from industrial waste. The mortars were made from the homogeneous mixture of cement, gravel, and water with additions of polyepoxide in different percentages. This polymer carried a milling process to obtain particle sizes of 1, 2 and 3mm. The mixtures were emptied in cubic bronze molds (5cm side) without vibrating compaction and allowed to stand for 24 hours before being removed. Ten mortars were prepared by mixture and they were cured in water for 28 days at room temperature before being characterized. Subsequently, the weight, compression strength and thermal conductivity of the samples were measured. The best results were for the mortars with additions of 100% polyepoxide (without gravel) and 3mm particle size, with a compression strength of 76.6kgcm^{-2} (higher than that required in mortars, 70kgcm^{-2}), a thermal conductivity of 0.68Wm^{-1}K^{-1} (59.93% less than conventional mortar, 1.70Wm^{-1}K^{-1}) and a weight of 141g (33.80% lower than the traditional mortar, 213g). According to the results obtained, a reliable alternative is presented to reuse waste material in the construction industry, replacing gravel by polyepoxide polymer particles in the process of manufacturing masonry elements providing the final product with the characteristics of lightness, thermal insulation, and acceptable compression strength, through simple, economical and sustainable processes.
Keywords: mortar, thermostable polymer, industrial waste, thermal conductivity, compression strength.

Resumen

La presente investigación se centra en la síntesis y caracterización física de diferentes mezclas de mortero de hormigón reforzado con polímeros termoestables de residuos industriales. Los morteros se hicieron a partir de la mezcla homogénea de cemento, grava y agua con adiciones de poliepóxido en diferentes porcentajes. Este polímero llevó un proceso de molienda para obtener tamaños de partículas de 1, 2 y 3mm. Las mezclas se vaciaron en moldes cúbicos de bronce (5cm de lado) sin compactación vibrante y se dejaron reposar durante 24 horas antes de ser retiradas. Se prepararon 10 morteros por mezcla y se curaron en agua durante 28 días a temperatura ambiente antes de ser caracterizados. Posteriormente, se midió el peso, la resistencia a la compresión y la conductividad térmica de las muestras. Los mejores resultados fueron para los morteros con adiciones de 100% de poliepóxido (sin grava) y 3mm de tamaño de partícula, con una resistencia a la compresión de 76.6kgcm^{-2} (mayor que la requerida en morteros, 70kgcm^{-2}), una conductividad térmica de 0.68Wm^{-1}K^{-1} (59.93% menos que el mortero convencional, 1.70Wm^{-1}K^{-1}) y un peso de 141g (33.80% menos que el mortero tradicional, 213g). De acuerdo con los resultados obtenidos, se presenta una alternativa sólida para reutilizar material de desecho en la industria de la construcción, reemplazando la grava por partículas de polímero poliepóxido en el proceso de fabricación de elementos de mampostería proporcionando al producto final las características de ligereza, aislamiento térmico y resistencia a la compresión aceptable, a través de procesos simples, económicos y sostenibles.

Palabras clave: mortero, polímero termoestable, residuo industrial, conductividad térmica, resistencia a la compresión.

Introduction

The block is one of the elements of masonry most used in the construction industry; it has had great commercial success in almost all regions of the world and is mainly due to the ease of production, good mechanical properties, durability and affordable price to the public. However, these elements have some limitations such as weight and poor thermal insulating properties compared with others masonry materials, such as bricks. This results on possibility of constructing buildings that facilitate the collapse in seismic events and living conditions intramural outside the comfort zone in extreme climates due to the high heat transfer (Al-Hadhrami & Ahmad, 2009; Munive, Leal-Cruz, Pech-Canul, Rodríguez-García, & Rocha-Rangel, 2013; Pérez, Cabanillas, Hinojosa, & Borbón, 2011; Vergara Gonzalez, Vergara Gonzalez, Nájera Hernáez, & Otaño Jimenez, 2014). That is why today, there is a significant trend in the use of lightweight and thermal materials within the construction industry (Pérez et al., 2011; Vergara Gonzalez et al., 2014). As an example, recent studies in the University of Sonora (Mexico), showed the development of thermal mortars with zeolite aggregate, microporous mineral located in many parts of the world, including the state of Sonora in Mexico. This type of elements showed a compression strength of 74kgcm^{-2} (greater than the minimum necessary in construction, 70kgcm^{-2}) and a thermal conductivity of 0.37Wm^{-1}K^{-1} (77% lower compared to the traditional mortars, 1.70Wm^{-1}K^{-1}) (Munive et al., 2013). In Argentina, the possibility of using recycled plastic as aggregates to replace coarse gravel has been analyzed. The samples registered values of thermal conductivity of 1.4Wm^{-1}K^{-1} (less than that of a traditional mortar: 1.63Wm^{-1}K^{-1}) and a resistance to compression above the minimum required in lightweight blocks (Sánchez Soloaga, Oshiro, & Positieri, 2014). Other studies consisted of the manufacture of blocks with aggregates of plagioclase, highly porous igneous rocks that are abundant in the central area of Mexico (Jiménez-Alvarez & Téllez-Jurado, 2010). This block turned out to be lighter than the traditional, facilitating handling and transport, decreased the weight of the buildings constructed. Furthermore, through the use of plasticizing additives, the compression strength increased to 90kgcm^{-2}. Moreover, the reuse of waste materials, natural or artificial, is a pressing need. In this context, there have been studies of physical characterization of hydraulic cement with aggregates of rice husk. The results showed a decreasing in the thermal conductivity of the concrete of up to 14% compared to traditional cement, with a small reduction in compressive strength (Chabannes, Bénézet, Clerc, & Garcia-Diaz, 2014). In Cuba, they analyzed the possibility of using mortars with fine aggregates from ground concrete, this as an alternative for the reuse of demolition material. The samples were analyzed by mechanical tests and the results were compared with traditional mortars (without aggregates). The results showed that the mechanical properties between the mortars are similar, which means that the use of demolition material in the manufacture of masonry elements is a feasible possibility (Martínez, Etxeberria, Pavón, & Díaz, 2016). Researchers from Mexico had similar results, where they reported the use of crushed concrete as an aggregate in the manufacture of mortars (with 30% aggregates). The physical tests showed the similarity in the mechanical behavior of the samples with and without recycled aggregates (Gutiérrez Moreno, Mungaray Moctezuma, & Hallack Alegría, 2015). In Argentina, taking advantage of a large number of agro-industrial waste, mortars concrete with peanut shell as aggregates were developed. Despite not getting the expected results within compression strength, the authors propose a sustainable way to use this waste material in the manufacture of lightweight blocks for partition walls that will not be exposed to excessive loads (Gatani, Argüello, & Sesín, 2010). Italian researchers reached similar conclusions, combining hydraulic cement with mineralized wood decreased the weight and the thermal conductivity of the final product (Becchio, Corgnati, Kindinis, & Pagliolico, 2009). However, the compression strength is also affected, recording a maximum value of 57.10kgcm^{-2}. The Spanish country is one of the main producers of olives worldwide. With this, they also generate tonnage of olives bones and an alternative is to use as aggregates in the manufacture of blocks. The results showed that mortars with this type of aggregate were 30% lighter and with 20% higher compressive strength compared to traditional mortars (Del Río Merino, Guijarro Rodríguez, Fernández Martínez, & Santa Cruz Astorqui, 2017). In Brazil, blocks with polymer aggregates type EVA (Ethylene, Vinyl, and Acetate) generated in regions with high production of footwear had been developed. Despite the developed blocks did not perform good compression strength, the researchers demonstrated the technical feasibility for these polymer waste recycling, making blocks that can be used in the construction of nonstructural walls (De Melo & Silva, 2013). As can be seen, there has been a huge amount of research related to the use of waste as aggregates in the construction industry. That is why Spanish researchers have developed a database with the main characteristics of the manufactured elements, taking references from more than 150 scientific articles. (González-Taboada, González-Fonteboa, Martínez-Abella, & Carro-López, 2016).

Considering the above information, the primary objective of this research was to analyze the contribution generated in the physical properties of concrete mortars by the addition of recycled polyepoxide particles. The purpose is presenting an alternative for using this type of industrial waste in the production of masonry elements with characteristics of lightweight, with thermal insulation and adequate compression strength. The above is attributed to the physical properties of this type of thermosetting polymer (Askeland, Fulay, & Wright, 2011). As additional information, in Mexico, there are two important companies producing electrical capacitors, each generating more than 100ton of epoxide waste per year which, being a thermostable polymer, cannot be recycled by thermal means. In addition to presenting an environmental impact, this waste also generates a significant economic impact on companies in their transportation, processing, and storage.

Material and methods

Preparation of mixtures and manufacture of mortars

The starting materials were: Portland cement composed of fast resistance (CPC-30R) with a density of 3.12gcm^{-3}, specific surface of 4156cm^{2}g^{-1} and fineness of 96.5% (M-325); gravel with a density of 2.66gcm^{-3}, a fineness modulus of 3.5 and absorption of 0.8%; polyepoxide as aggregates with a density of 1.77gcm^{-3} and particle size of 1, 2 and 3mm; and water. The polyepoxide (industrial waste) previously was chemically analyzed determining its feasibility for use in this project, because it lacks reactivity, flammability, and toxicity. Subsequently, a grinding process was carried out in a cutting mill IKA model MFLOBS1 to 4000rpm in order to standardize the particle size in accordance with ASTM C33. For comparative purposes, it was included in the experimental design particles of expanded polystyrene, with the same preparation process and the same particle size: referring to results obtained in the literature (Ferrándiz-Mas & García-Alcocel, 2012). On the other hand, the gravel was sieved by employing meshes from 4 to 200 (4.76mm to 74µm); a fineness modulus of 3.5 was determined. To remove residual humidity, the sieved gravel was placed inside an electric furnace at 60°C for 24 hours. Groups of 10 types of mixtures were prepared, the mixture composition of each group is presented in Table 1.

Table 1. Compositions of the mixtures used in the design of mortars. The amount of water and cement were constant. Source: Self-elaboration, 2018.

Mixture	Gravel, %	Expanded polystyrene, %	Polyepoxide, %		
			1mm	2mm	3mm
M1	100	–	–	–	–
M2	50	50	–	–	–
M3	25	75	–	–	–
M4	75	25	–	–	–
M5	50	–	50	–	–
M6	50	–	–	50	–
M7	50	–	–	–	50
M8	–	–	100	–	–
M9	–	–	–	100	–
M10	–	–	–	–	100

The mixture 1 was used for the manufacture of control samples without the polymer aggregates, in order to have reference values. The remaining mixtures exhibit different compositions. In all cases, the amount of cement and water was the same. The mixtures were introduced into cylindrical containers which were placed on rotating rollers in order to be homogenized as specified in ASTM C192. Subsequently, the homogenized mixtures were introduced in cubic bronze molds (5cm side) without vibrating compaction and were allowed to stand for 24 hours before being removed.

Ten mortars were made for each mixture and were cured in water for 28 days at room temperature; later the physical properties were characterized.

Characterization of mortars

After curing, measurements of the weight and density of the mortars were made using a digital balance. Subsequently, the evaluation of the compression strength was carried out in a hydraulic press type Universal (LT 900/920, Forney, Zelienople, PA, USA), according to the standard test method for compression strength ASTM C109. A capping was applied to samples before compression test for obtaining flat and parallel faces when the load was applied. The compression strength was determined using Equation 1 (Fitzgerald, 2000).

$$F'c = PA^{-1} \qquad (1)$$

where: $F'c$ is the compression strength of solid materials, in $kgcm^{-2}$, P is the load applied to the study sample in kg and A is the cross-sectional study in cm^{-2}.

Finally, the thermal conductivity (K) of the mortars was determined, according to a standard test method for steady-state heat flux measurements and thermal transmission properties by mean of the guarded-hot-plate apparatus ASTM C177 and referring to Fourier's law presented in Equation 2 (Askeland et al., 2011).

$$QA^{-1} = K\,(\Delta T/\Delta x) \qquad (2)$$

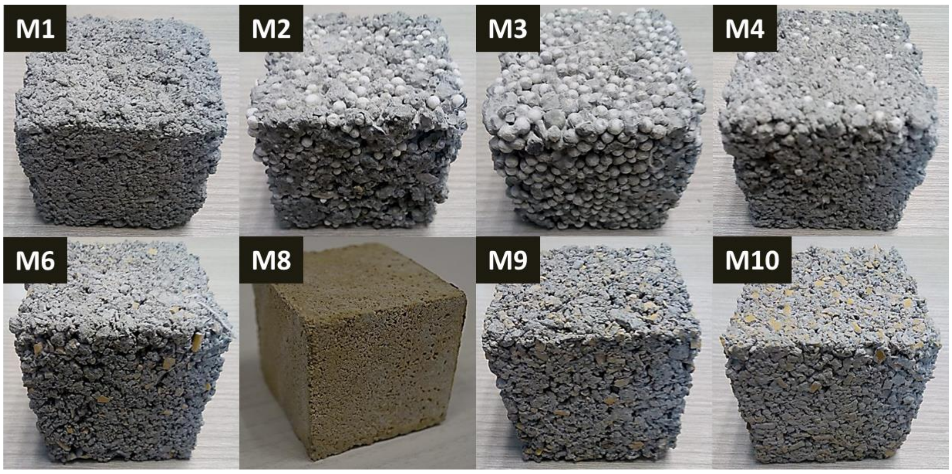
where: QA^{-1} is the heat flow per unit area, in Wcm^{-2}, K is the coefficient of thermal conductivity of a material, in $Wm^{-1}K^{-1}$ and $\Delta T/\Delta x$ is the temperature gradient over the thickness of the sample, in Kcm^{-1}.

Results

Physical appearance of mortars

Figure 1 present 8 of the 10 types of mortars used in this study. The samples M1, M6, M8, M9, and M10 presented an acceptable physical appearance, with solidity, rigidity and without loss of material. This is mainly due to the physical characteristics of the solid elements that constitute them (gravel and polyepoxide) since they are very hard, rigid and dense materials. Furthermore, this type of thermoset polymer exhibits excellent interaction with other elements of the mixture, as the cement and water. On the other hand, the samples with expanded polystyrene aggregates, M2, M3, and M4, presented zones of high porosity, generating samples with dimensional defects. This is attributable to the physical characteristics of expanded polystyrene (low values of hardness, strength, and rigidity) and a poor interaction with the cement and water.

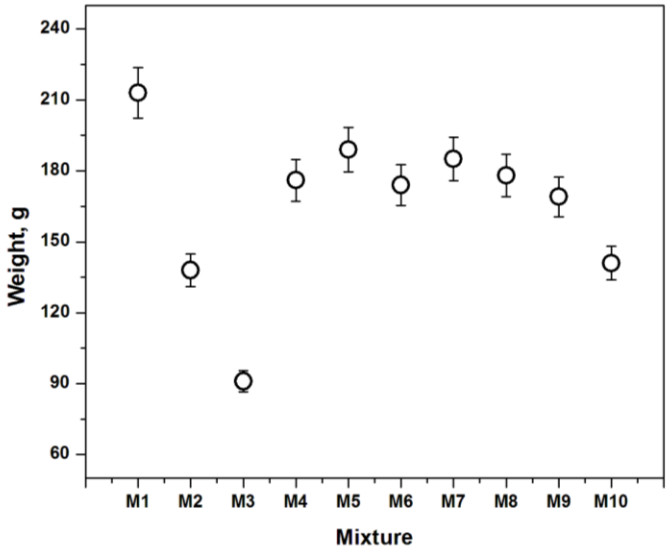
Figure 1. Photographs showing the physical appearance of 8 of the 10 types mortars used in this study. Source: Self-elaboration, 2018.



Evaluation of the weight of mortars

Figure 2 shows the measurements of the weight of the mortars under study. It can be clearly seen that the weight of the mortars decreases when replacing the gravel by polymeric particles and is directly proportional to the amount of aggregate used. Also, the expanded polystyrene affects in greater the weight of the samples than the epoxide. For example, mortars with expanded polystyrene aggregates (M2 and M3) showed a higher reduction in weight with respect to control samples, with 35.22% and 57.27%, respectively. On the other hand, mortars with epoxide aggregates reported low reduction in weight with respect to control samples. For example, the specimen that was prepared with the mixture 7 attained an average in weigh 189g, representing a reduction of 13.14%. It is necessary to mention, that the observed result is directly proportional to the amount of aggregate, as can be observed in the specimens of the mixtures M3 and M4 reflecting a weight reduction difference of 39.9%. Moreover, another aspect that influences the weight reduction is the particle size used in the aggregates. This phenomenon is observed in the samples M8, M9, and M10, where the weight is reduced according to the particle size is increased (16.34, 20.65, and 33.80%, respectively).

Figure 2. Measurement of the weight of the mortars used in this research. Source: Self-elaboration, 2018.



Evaluation of compression strength

Compression tests were performed on the mortars representative of the 10 mixtures. To verify that the mortars mechanical behavior is the same as the final element (block), static analysis simulations were performed on a virtual platform known as SolidWorks (see Figure 3). First, virtual tests of compression were performed at mortars cubic (5cm side). Besides the gravel, the polymeric material (polyepoxide) with an elastic limit 150kgcm^{-2} was chosen, a charge 1925kg on the upper area of the cube (Figure 3A), and a safety factor of 1 was used. Von Mises stress 152kgcm^{-2} were obtained and applying Equation 1, values of compression strength 77kgcm^{-2} are obtained (Gómez González, 2010). Similarly, virtual compression tests in blocks (15/20/40cm size) were performed and besides the gravel, the polymeric material (polyepoxide) with an elastic limit 150kgcm^{-2} was chosen. A maximum load of 23100kg was used and Von Mises stress of 151kgcm^{-2} was obtained, (see Figure 3B). Applying Equation 1, values of compression strength 77kgcm^{-2} are obtained. These results support the use of mortars (Figure 1) in mechanical tests in the specialized laboratory, ensuring reproducibility in the final blocks.

Figure 4 shows the results of the compressive strength *F´c* of the mortars corresponding to each mixture. According to the results, control samples exhibited the highest compressive strength with a value of 85.20kgcm^{-2}, followed by mortars of mixtures 5 and 6 with values average of 82.97kgcm^{-2} and 80.75kgcm^{-2}, respectively. The effect of replacing gravel with polymers in the mortars is clear, as it decreases compressive strength of the samples. However, in the case of samples with polyepoxide aggregates (M5, M6, M8 – M10), it does not significantly affect the compression strength. On the other hand, mortars made with expanded polystyrene registered the lowest compression strength values (M2, M3, and M4).

Figure 3. A) Simulation of cubic mortar (5cm side); B) Block (15/20/40cm size) in SolidWorks, using uniformly distributed loads up to the failure. Source: Self-elaboration, 2018.

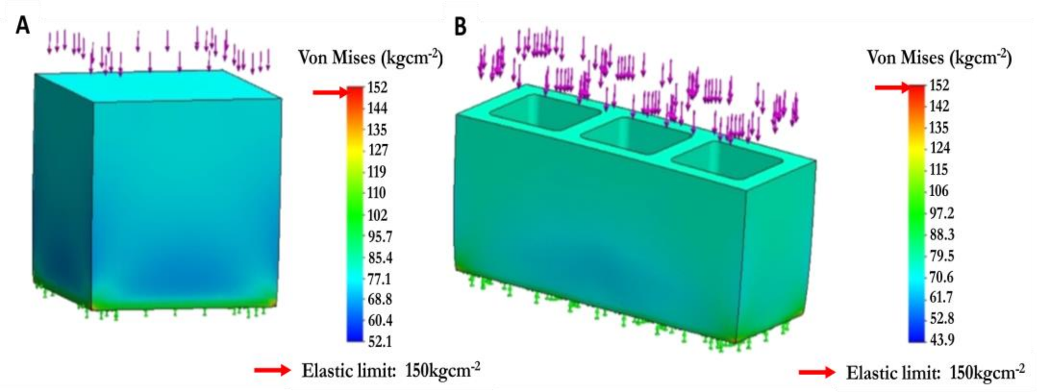
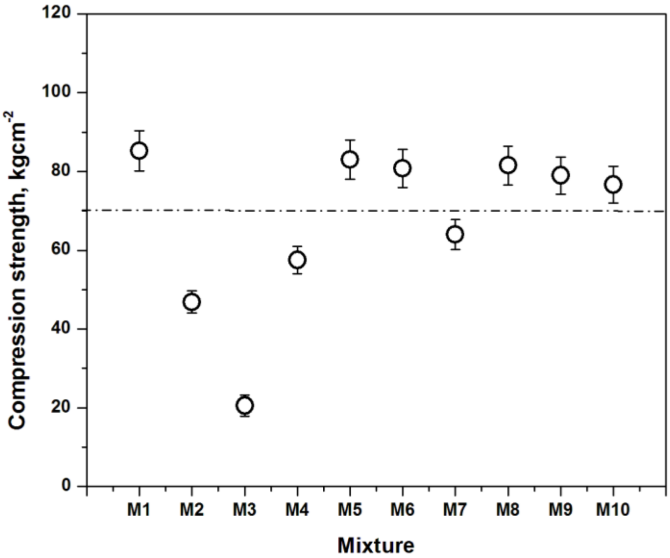


Figure 4. Compression strength of the mortars after 28 days curing. Source: Self-elaboration, 2018.



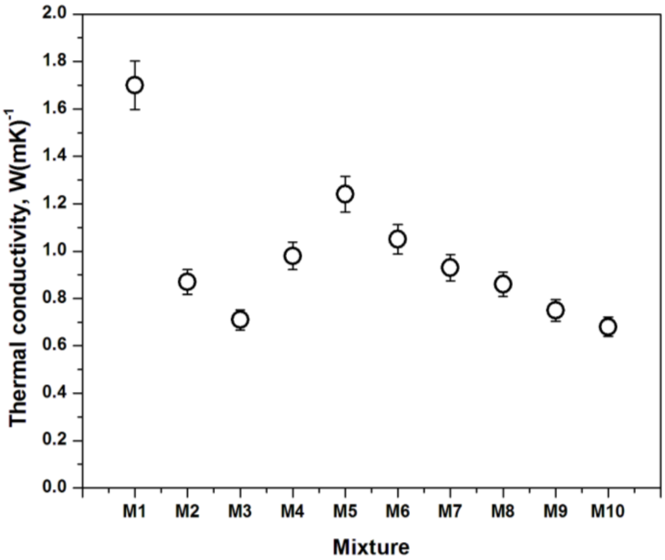
The mortars that showed the lowest values of resistance to compression were those that were manufactured with the largest amount of expanded polystyrene (M3). It is a fact that the expanded polystyrene, by their physical characteristics (low values of hardness, rigidity and elastic modulus), reduces the weight of the samples, as discussed in Figure 2 having weight reductions of up to 57.27%; however, the value of the compressive strength of the samples is also lowered. For comparison, by referring to the specimens with polyepoxide aggregates, the effect of reducing the compressive strength is less critical. This result can be attributed to the physical characteristics of this type of polymer, especially its hardness and rigidity. It is important to mention that for the six types of evaluated mortars its maximal resistance in compression is upper to the limit value, 70kgcm^{-2} (dash line), established by the Mexican standard (Mexican norm NMX-C-404-ONNCCE-2012).

Thermal conductivity

The results of the evaluation of the thermal conductivity (*K*) in the mortars are shown in Figure 5. According to the results, all mortars presented a reduction in thermal conductivity in different percentages, with respect to the value of 1.70Wm^{-1}K^{-1} registered in mortars made of mixture 1 (control sample).

Mortars that recorded the lower thermal conductivity were the manufactured with the mixture 10 (M10) with values 0.68Wm^{-1}K^{-}, representing 59.93% reduction in this physical property. With very close values have mortars made with the mixture 3 and 9 (M3 and M9), with values of thermal conductivity of 0.71Wm^{-1}K^{-1} and 0.70Wm^{-1}K^{-1} thermal conductivity, respectively. Clearly, it reflects the effect of polymeric aggregates in mortars and this can be attributed to the physical characteristics of this type of polymer. However, as has been discussed, due to its low density and stiffness, the compression strength of the samples is disfavored. In the case of mortars made with polyepoxide aggregates, besides presenting a good percentage reduction in thermal conductivity, the compression strength is above the standards established (70kgcm^{-2}). Finally, by completing the analysis, the particle size of the aggregates considerably affects the thermal conductivity of the mortars. In the case of polyepoxide, when the particle size is reduced to 1mm (M8) the thermal conductivity increases in comparison with sample 10 (3mm particle size).

Figure 5. Thermal conductivity of the mortars. Source: Self-elaboration, 2018.



Conclusions

According to the results obtained, it is possible to build blocks with polyepoxide particles from industrial waste. Because the mortars manufactured with this material presented a reduction in weight and thermal conductivity, as well as a resistance to compression within the standards. Another detail is the physical appearance since firmness is observed between the particles, good finish throughout the volume of the solid element and without porous or rough zones. The best results were for mortars of mixture 10 with a weight of 169g (33.80% less than that reported by the control samples), a thermal conductivity 0.68$Wm^{-1}K^{-1}$ (59.93% less than reported by the control samples) and a compression strength of 76.67$kgcm^{-2}$ (above the established standards, 70$kgcm^{-2}$). In the case of samples 8 and 9, the effect of the reduction of the particle size of the polyepoxide (1 and 3mm, respectively) in the physical properties of the mortars was observed, since there was an increase in thermal conductivity and resistance to the compression.

On the other hand, it was observed that the aggregates of expanded polystyrene allow the manufacture of light mortars and with excellent thermal insulation. However, it significantly affects the compression strength of the samples. In addition, samples with a poor finish are observed, without firmness between their particles, with porous and roughened zones.

Finally, a solid alternative is presented to reuse waste material in the construction industry, replacing gravel with polyepoxide particles in the process of manufacturing masonry elements (blocks, bricks, slabs, among others), providing the final product the characteristics of lightness, thermal insulation and an acceptable compression strength, through simple, economic and sustainable processes.

Acknowledgments

Authors would like to thank National Council of Science and Technology of Mexico (CONACyT) for financial support for the development of this work (number of support: 395196) as well as the laboratory of physical testing of building materials LACONTE by technological support used in the development of this research.

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