Revista ALCONPAT
www.revistaalconpat.org
eISSN 2007-6835
Revista de la Asociación Latinoamericana de Control de Calidad, Patología y Recuperación de la Construcción

Marble residues in construction materials: a review of the use of marble powder in mortars, concrete, and bricks

A. Moreno[1]*, C. Ponce[2], E. Múzquiz[1], F. Avalos[1]
*Contact author: nicolas.moreno@uadec.edu.mx
DOI: https://doi.org/10.21041/ra.v12i2.522

Reception: 17/11/2020 | Acceptance: 19/04/2022 | Publication: 01/05/2022

ABSTRACT
The objective of this work is to make a review of the results carried out using marble powder as a substitute for cement, sand, or fine aggregate in concrete, mortar, and bricks. Research carried out in various parts of the world with different experimental procedures was reviewed. It is concluded that marble powder can be used as a partial substitute for cement or fine aggregate (up to 15%, depending on the material to be replaced) without affecting the compressive strength of the samples or pieces regardless of their shape. Therefore, marble powder not only helps to reduce the pollution it generates but also to reduce its use as sand and powder, contributing to sustainable development.
Keywords: marble powder; brick; mortar; concrete; cement.

Cite as: Moreno, A., Ponce P., Múzquiz, E., Avalos, F., (2022), "*Marble residues in construction materials: a review of the use of marble powder in mortars, concrete, and bricks*", Revista ALCONPAT, 12 (2), pp. 162 – 183, DOI: https://doi.org/10.21041/ra.v12i2.522

[1] Facultad de Ciencias Químicas Unidad Saltillo, Universidad Autónoma de Coahuila, Blvd. V. Carranza y José Cárdenas Valdés, C.P. 25280, Saltillo, México.
[2] Escuela de Arquitectura Unidad Torreón, Universidad Autónoma de Coahuila, Carretera Torreón - Matamoros km. 7.5. Ejido El Águila. Ciudad Universitaria. C.P. 27087. Torreón, Coahuila

Contribution of each author
In this work, the author Moreno, A. contributed with the conceptualization of the activity, the research, the methodology, the data collection and the writing of the original draft by 50%. Author Ponce, C. contributed 40% to validation, writing, review, and editing. The author Múzquiz, E. contributed 5% to validation, writing, revision and editing. Author Avalos, F., contributed 5% to data collection, writing, review, and editing.

Discussions and subsequent corrections to the publication
Any dispute, including the replies of the authors, will be published in the first issue of 2023 provided that the information is received before the closing of the third issue of 2022

Residuos de mármol en materiales para la construcción: una revisión del uso del polvo de mármol en morteros, concretos y ladrillos

RESUMEN

Este artículo tiene como objetivo hacer una revisión de los trabajos realizados usando polvo de mármol como sustitución de cemento, arena o agregado fino en concreto, mortero y ladrillos. Se revisaron investigaciones realizadas en varias partes del mundo con procedimientos experimentales diferentes. Se concluye que el polvo de mármol se puede usar como sustituto parcial de cemento o agregado fino (hasta por un 15 %, dependiendo del material a sustituir), sin afectar la resistencia a compresión de las muestras o las piezas, y sin importar la forma. Por lo tanto, el polvo de mármol no sólo ayuda a aminorar la contaminación que genera, sino que también a la reducción de uso como arena y polvillo, aportando al desarrollo sustentable.

Palabras clave: polvo de mármol; ladrillo; mortero; concreto; cemento

Resíduos de mármore em materiais de construção: uma revisão do uso do pó de mármore em argamassas, concreto e tijolos

RESUMO

O objetivo deste trabalho é fazer uma revisão dos trabalhos realizados utilizando pó de mármore como substituto do cimento, areia ou agregado miúdo em concreto, argamassa e tijolos. Pesquisas realizadas em várias partes do mundo com diferentes procedimentos experimentais foram revisadas. Conclui-se que o pó de mármore pode ser utilizado como substituto parcial do cimento ou agregado miúdo (até 15%, dependendo do material a ser substituído), sem afetar a resistência à compressão das amostras ou peças independentemente de sua forma. Portanto, o pó de mármore não só ajuda a reduzir a poluição que gera, mas também reduz seu uso como areia e pó, contribuindo para o desenvolvimento sustentável.

Palavras-chave: pó de mármore; tijolo; argamassa; concreto; cimento.

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1. INTRODUCTION

The Marble is a metamorphic rock composed of carbonates. In commercial terms, the word marble does not have a petrological meaning sometimes, the term is applied to rocks such as tuff, serpentine, and granite, although it often refers to calcareous rocks such as recrystallized limestone, dolomite, marble, onyx, and travertine (Coordinación General de Minería, 2014).
According to data from the United States Geological Survey (USGS) in 2018, Mexico is one of the world's largest producers of various non-metallic minerals. In 2019, the Directorate General of Mines (DGM) reported an increase of 4,663 million pesos from 2017 to 2018 in the national production of non-metallic minerals, which represents an increase of 23.9% (Servicio Geológico Mexicano, 2019).
China, India, and other countries, including Mexico, are the leading producers of dimensional rock. Dimensional rock includes a wide variety of rocks, including granite, limestone, and marble.
The marble production process begins with the extraction of the rock by mechanical means (saws), breaking large blocks, which will later be divided into smaller sizes for sale. This process is known as lamination.
The lamination process consists of cutting the block of rock to obtain slabs of 2 to 3 cm thick and is performed using saws with diamond inlays; then, the obtained slab is subjected to polishing to roughen the rough parts of the rock and polishing by means of abrasives and water. Once the polishing is finished, the plates are subjected to cuts to be sized according to the client's needs. Similarly, to meet the client's requirements, the product is subjected to a process of beveling, drying, or waxing. Finally, the product is packaged and shipped for national or international commercialization. (Coordinación General de Minería, 2014).
One ton of marble stone processed by vertical and horizontal cutting for block production and lamination produces 35% to 45% spillage or slurry of unused materials (Singh, et al., 2017).
This waste slurry, especially after drying, causes environmental hazards such as dust contamination, which occupies agricultural land and other nearby areas, rendering them infertile. (Singh, et al., 2017). In 2017, the world production of marble was 2,352,614 tons. (Servicio Geológico Mexicano, 2019), so, 941,045 tons of waste were generated, considering 40% of the processed product.
Due to the great problem generated by marble powder (waste disposal, contamination by calcium oxide (CaO), which is absorbed by the soil, causing it to become infertile), scientific research has been carried out for its application in the construction sector, either as a substitute for cement in mortars or concrete or also as a block or brick manufacturing applicable to construction systems in various parts of the world.
This paper reviews the work done using marble powder as a substitute for cement, sand, or fine aggregate in concrete, mortar, and bricks, with the purpose of reporting the ways in which it can substitute cement or fine aggregate to manufacture non-structural bricks, among other contributions.

2. MARBLE POWDER AS AN INPUT IN THE CONSTRUCTION INDUSTRY

This section evaluates the use of marble powder as an input in construction. An exhaustive review of published articles is conducted, and the results of each study on the application of marble powder in cement, mortar, concrete, and bricks are presented in a concise and detailed manner.

2.1 Marble powder as a partial cement substitute.

Marble powder has a high content of Calcium Carbonate (CaCO3), which can be added to Portland cement-based mortars and concretes to increase the service life, functioning as a pore filler. (Singh, et al., 2017).

Other authors, on the contrary, think that the partial substitution of CaCO3 produces chemical modifications, which result in changes in the mechanical and physical properties of the cement. (Tobón & Kazes Gómez, 2008).

Additions of between 3 and 5% of marble powder have been made to Portland cement pastes, and no changes in their mechanical behavior have been observed.

El-Sayed, Farag, Kandeel, Younes, and Yousef (2016) replaced 3, 4, and 5 wt% of the cement with marble powder, observing that, due to the high presence of calcium carbonate, it did not affect the properties of the cement. With the hardened cement pastes, compression tests were performed at ages of 1, 3, 7, 7, 14, and 28 days; it was observed that the strengths increased proportionally to the age of curing from 1 to 28 days, as shown in Figure 1.

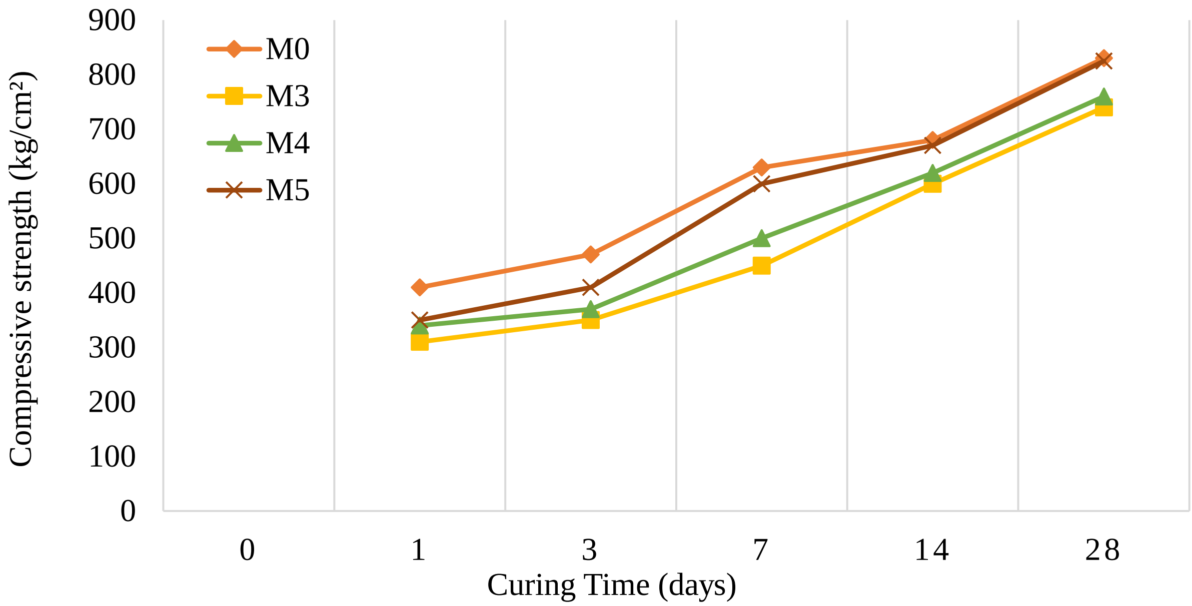

Figure 1. Compressive strength of hardened Portland cement pastes incorporating 3%(M3), 4% (M4), and 5%(M5) marble powder residues versus curing time. (El-Sayed, et al., 2016)

It was shown that the specimen with 5% (M5) of marble powder, at 28 days of curing, obtained the same compressive strength as the control specimen of ordinary Portland cement without additions. The other samples of 3 and 4 % cement substitution by marble powder have a lower compressive strength compared to M5 and M0.

With this, the use of marble powder in the cement industry becomes feasible due to the economic and ecological benefits that the use of a waste product represents.

Singh et al. (2017) mention that marble powder has a high content of Calcium Carbonate (CaCO3), and this helps to increase the service life of cement-based pastes and concretes, while Tobon & Kazes Gome (2008) mention the opposite. El-Sayed, Farag, Kandeel, Younes, and Yousef (2016), show that substituting marble powder for cement in small quantities does not affect the compressive strength.

These studies show that the compressive strength of the specimens is not affected when a maximum of 5% of marble powder is replaced by cement. It is observed in the test result graphs that the increase in strength is similar in the specimens with and without marble powder.

2.2 Marble powder and its application in mortars.

Portland cement-based mortars are among the most widely used composite materials in the construction industry, and cement is the construction material that generates the most CO2 pollution to the environment in its manufacturing process. For this reason, researchers have carried out experimental studies by partially replacing cement with marble powder to reduce its use. Corinaldesi, Moriconi, and Naik (2010) replaced 10% of the cement with marble powder from a reference sample and, in a second option, replaced 10% of the fine aggregate of the mortar (sand), as shown in Table 1. From each mixture, 3 bars of 40 x 40 x 160 mm were manufactured, from which cubes of 40 mm per side were *obtained* to perform compression tests at 3, 7, 28, and 56 days of curing.

Table 1. Mortar proportions (Corinaldesi, et al., 2010)

Mix	Ref	10% Cement	10% Sand
A/C	0.61	0.68	0.59
Water (kg/m³)	275	276	266
Cement (kg/m³)	450	405	450
Sand (kg/m³)	1350	1350	1215
Marble powder (kg/m³)	0	45	135

The results obtained are shown in Figure 2. It can be observed that the mixture with 10% cement replaced by marble powder showed a reduction in compressive strength. However, the marble powder used as a replacement for 10% sand obtained higher strength than the mixture with the replacement of marble powder by cement.

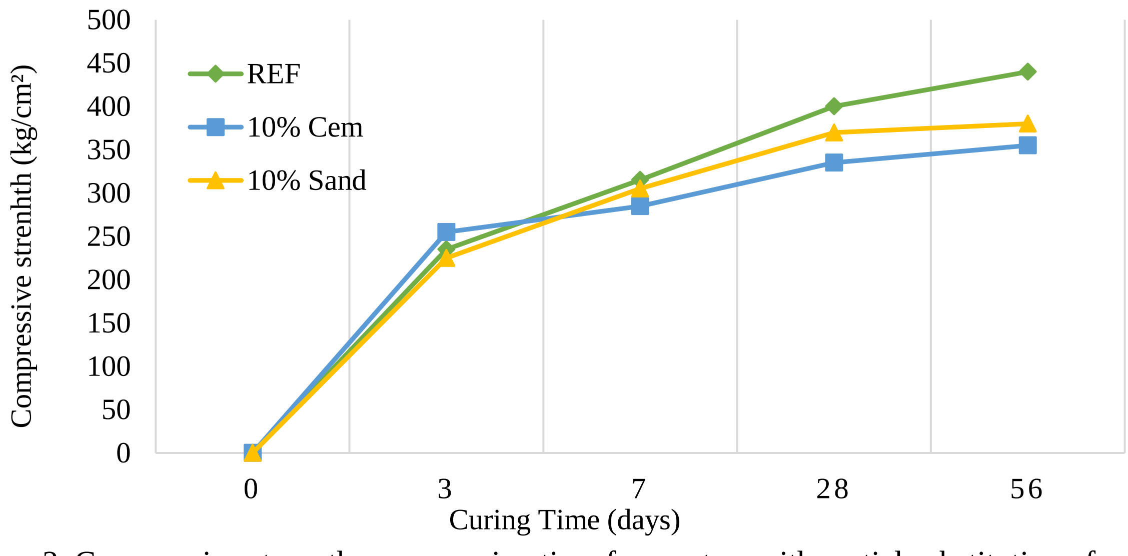

Figure 2. Compressive strength versus curing time for mortars with partial substitution of marble powder by cement and sand. (Corinaldesi, et al., 2010)

Li G. L. et al. (2019, propose the substitution with marble powder in two options for cement-based mortar. The first proposal is the partial substitution of cement in the mixture, without altering the water-cement ratio (w/c), and a second one in which a part of the cement and the water required for the manufacture of the mortar is replaced, changing the w/c ratio.

First, for each mortar mix, the volume of paste (volume of water, cement, expressed as a percentage of mortar volume) plus the volume of marble powder (expressed as a percentage of mortar volume) was set at 60%.

The marble powder was adjusted to 0, 5, 10, 10, 15, and 20 % and the respective paste volume was set to 60, 55, 50, 50, 45, and 40, to sum each of the mixes the 60 % set previously. The volume of fine aggregate was set at 40% of the total volume of the mortar (Figure 3). For the second proposal, the marble powder replaced 0, 5, 10, 10, 15, and 20% of the volume of cement, which was set at 100, 95, 90, 85, and 80%
It is important to emphasize that the volume of water in the mixture remains constant. (Figure 4). With each of the mixes, 3 cubes of 100 mm per side were made, and after 28 days of curing, compressive strength tests were carried out.

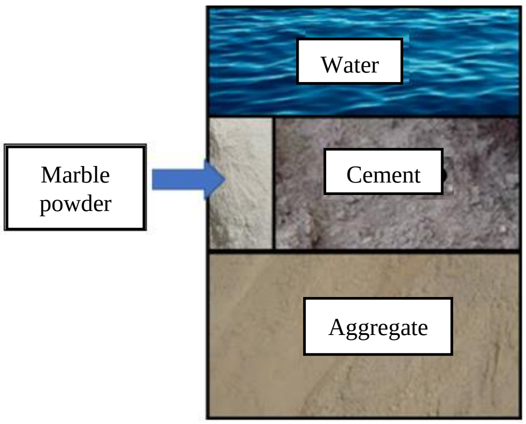

Figure 1. Cement replacement method (Li, et al., 2019)

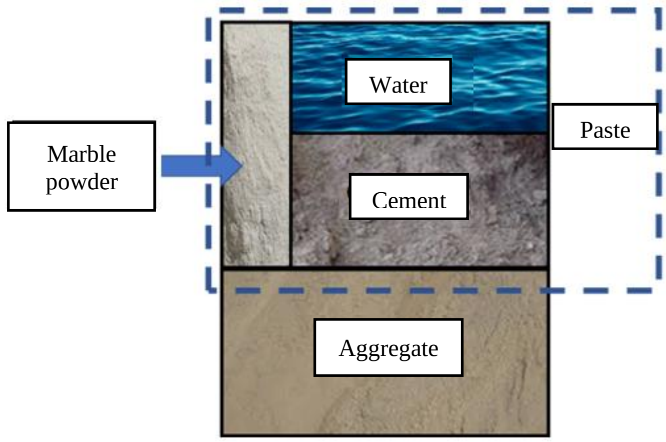

Figure 2. Paste replacement method (Li, et al., 2019)

The tests showed that in the mortar with paste replacement (cement and water) with a w/c ratio of 0.40 and increasing the volume of marble powder from 0% to 20% increased the cube strength from 607.75 to 730.12 kg/cm², in the w/c ratio of 0.55 increased the compressive strength from 402.79 to 543.51 kg/cm².
In mortar mixes where only the cement was partially replaced with marble powder from 0 to 5% and with a w/c ratio of 0.40, the cube strength increased from 607.75 to 610.81 kg/cm², and increasing the volume of marble powder from 0% to 20% showed a decrease in compressive strength from 607.5 to 488.44 kg/cm².
In the same case, but with a w/c ratio of 0.55, and replacing 0 to 10% of the cement with marble powder, the strength increased from 402.79 to 411.97 kg/cm², and with the replacement of 0% to 20% the cube strength decreased from 402.79 to 344.66 kg/cm². In the work done by Yamanel et al. (2019), they made mortars replacing 0, 5, 10, 10, 15, and 20 % of cement with marble powder and manufactured 40 x 40 x 160 mm prisms, cured for 28 days, before performing mechanical and durability tests on the samples (Table 2).

Table 1. Mortar Mix proportions. (Yamanel, et al., 2019)

Sample	**Cement g**	**Marble powder g**	**Sand g**	**Water g**
M-0	450.0	0.0	1350.00	225
M-5	427.5	22.5	1350.00	225
M-10	405.0	45.0	1350.00	225
M-15	382.5	67.5	1350.00	225
M-20	360.0	90.0	1350.00	225

At 28 days of curing, the compressive strength of the affected mixes at 5, 10, 15, and 20% is lower than that of the mix without cement substitution.
At 90 days of curing, the mix with a 5% replacement of marble powder to cement increased the compressive strength even more than the mix without marble powder (Figure 5).

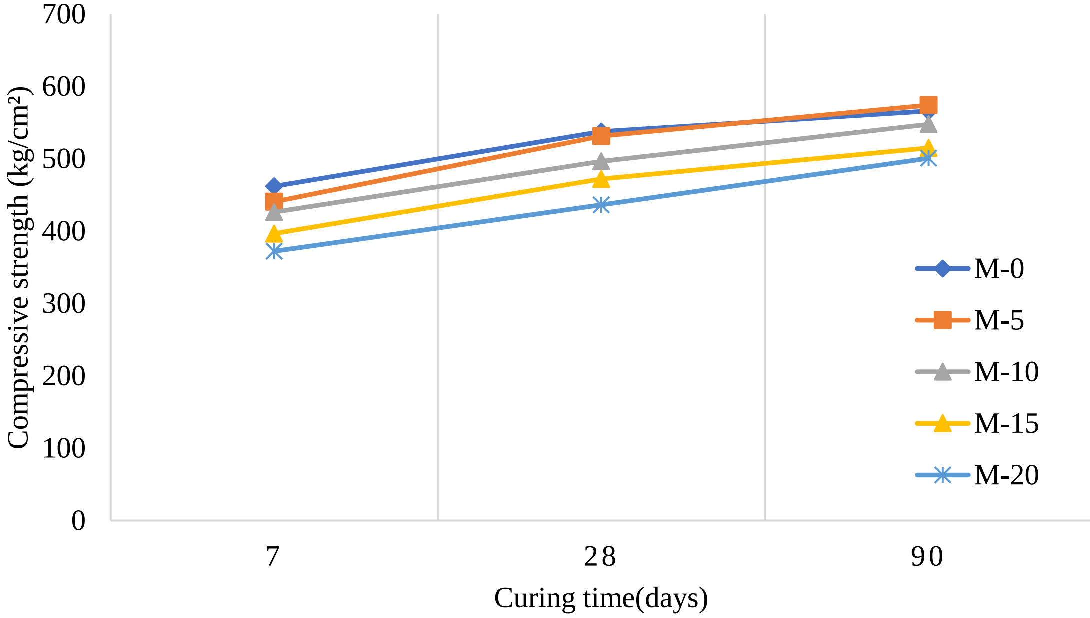

Figure 3. Compressive strength of mortars. (Yamanel, et al., 2019)

Figure 5. Compressive strength of mortars. (Yamanel, et al., 2019)

Toubal Seghir, N., et al. (2019) manufactured mortars with 3:1 sand-cement ratios and replaced at levels of 0%, 5%, 10%, and 15% of the weight of cement in the mortar with marble powder. A water/cement ratio of 0.5 (constant) was maintained. Compressive strength tests were performed with 50 mm cubes of the manufactured mortars, and were tested at 3, 7, 28, and 65 days. The samples were cured in open air, this study gave the following results: All samples up to 15% substitution obtained a lower compressive strength than the sample without marble powder; this decrease is attributed to the lack of curing, which caused voids and cracks within the samples, as well as a reduction in density of the samples.
Corinaldesi, Moriconi and Naik (2010) show that substituting marble powder for cement affects the compressive strength, and when marble powder is substituted for sand, it is not affected. Li G. L.et all (2010) show that increasing the substitution of marble powder for cement decreases the compressive strength and when the substitution is less, the strength is maintained or increased. Toubal Seghir, N et al. (2019) shows that to have good results in compressive strength, it is necessary to have a good curing of the specimens.
When marble powder is replaced by cement in mortars, in most cases, there is a decrease in compressive strength, especially at water/cement ratios lower than 0.5. When the water/cement ratio increases, the compressive strength of the samples also increases. Another important factor in the strength of the samples is curing; it is mentioned that when the samples are not cured, the strength at early ages is low.

2.3 Concrete with marble powder.

2.3.1 Marble powder as a partial substitute for fine aggregate in concrete.

The application of marble powder in concrete has also been sought, either as a partial substitute for cement or as a fine aggregate, without impairing compressive strength.
In 2010, Santos, Villegas, and Betancourt proposed the partial substitution of fine aggregate in concrete and the use of marble powder.
The proposal they made was the partial replacement of sand by marble powder in a 10 in 10 range, from 0-80 %, keeping fixed the w/c ratio, the weight of cement, and the weight of coarse aggregate, as shown in Table 3.

Table 2. Concrete dosages (Santos, et al., 2012)

Material		Control	M10	M20	M30	M40	M50	M60	M70	M80
Sand	kg/m³	793	714	634	555	476	397	317	238	159
Marble powder	kg/m³	0	79	159	238	317	397	476	555	634
Gravel	kg/m³	1044	1044	1044	1044	1044	1044	1044	1044	1044
Water	kg/m³	228	325	325	325	325	325	325	325	325
Cement	kg/m³	325	325	325	325	325	325	325	325	325
a/c	kg/m³	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7

From the compressive strength tests applied to the above dosages at 7 and 28 days of curing, the following results were obtained and are shown in Figure 6.

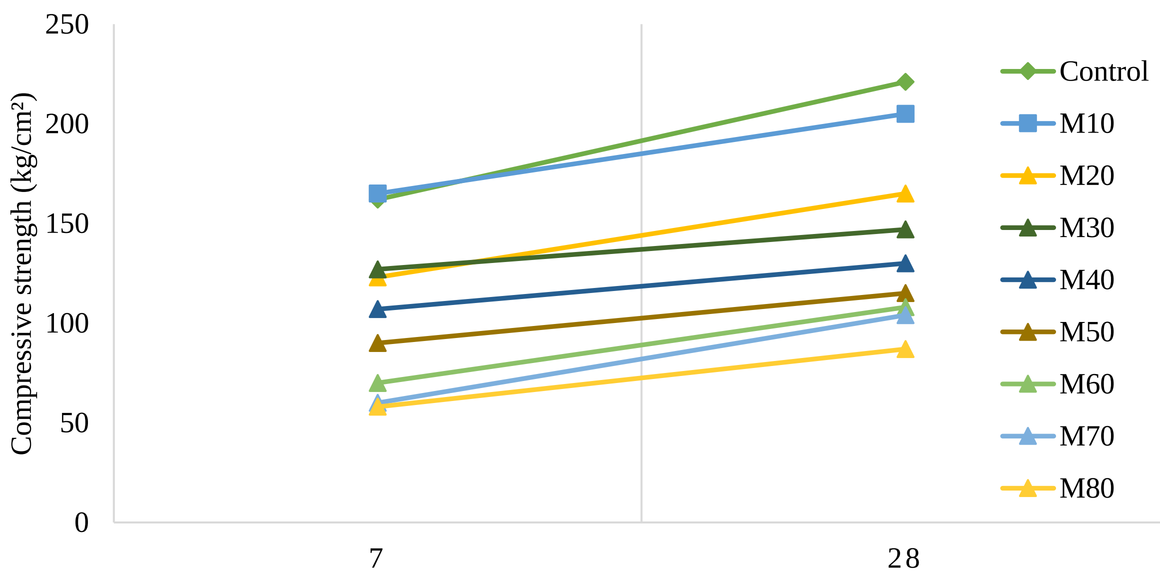

Figure 6. Compressive strength results from concretes with marble powder. (Santos, et al., 2012)

As the percentage of sand substitution by marble powder increases, the compressive strength decreases. Such loss of strength is like the percentage of marble powder, i.e., the M40 dosage has 40% less compressive strength compared to the control (Santos et al., 2012).
Hebnoub H. et al. (2011) partially substituted in proportions of 25%, 50%, 75%, and 100% marble powder for the fine aggregate; manufactured concrete cylinders and were cured and tested according to European Union (EU) standards. The samples were tested at 2, 14, 28, and 90 days of curing to determine their compressive strength. The results found by the authors reflected that the compressive strength at the 25, 5,0, and 75% substitution rates offered higher strength than the

control sample; the 100% substitution at ages 14 and 28 days presented lower strength than the sample without marble powder, but at the age of 90 days, the strength practically equaled the original sample.

Rahangdale, S. & Qureshi, S. (2018) conducted a study comparing the properties of a traditional concrete with one made with supplementary materials (fly ash for cement; stone and marble powder in partial replacement of fine aggregate).

Fourteen samples were manufactured, in the first three samples (1, 2, and 3), 35% of cement was replaced by fly ash, and 30% of the fine aggregate was replaced by stone and marble powder, in quantities of 20% - 10%, 15% - 15% and 10% - 20% respectively; the compressive strengths were lower than those recorded for the control concrete sample (35.58 N/mm²) varying at 28 days the strengths of 28.05, 28.87 and 30.35 N/mm².

In samples 4, 5, and 6, the amount of fly ash was maintained, but the amounts of stone and marble powder was increased to 40% as follows: 30-10%, 20-20%, 10-30%, obtaining the following strengths at 28 days: 27.25, 25.65 and 26.65 N/mm². From these results, it can be observed that the decrease shown in the compressive strength of series 1, 2 and 3 is maintained.

In samples 7, 8, and 9, the fly ash was reduced to 25%, and the substitution of fine aggregates in the same amount as in samples 1, 2, and 3 returned to 30%; the strengths recorded were 29.75, 32.04, and 35.45 N/mm², being higher than the previous ones but still below the original sample.

In the following three samples (10, 11 and 12) the fly ash is maintained, at 25% and the percentage of substitution of the fine aggregate changes to 40% as in samples, 4, 5 and 6, the results obtained were 30.29, 31.54 and 29.87 N/mm², and once again it is observed that the compressive strengths decrease.

In sample 13, the fly ash was considered in a percentage of 22.5%, and in the fine aggregate 30% (10% marble stone and 20% marble powder). At 28 days, the compressive strength recorded was 35.49 N/mm², which is the highest of the samples analyzed, practically equal to the compressive strength of the control sample.

In the last sample (14), the fly ash replaced 20% of the cement, and in the 30% fine aggregate (10% marble stone and 20% marble powder) at 28 days, the registered resistance was 38.87 N/mm, increasing the compressive strength by 0.75%, being practically the same resistance as the reference sample.

Thus, with the dosages of sample 14, the use of cement is minimized; therefore, the authors recommend the use of supplementary materials to solve environmental problems and advance the sustainability of the development of the construction industry.

Verma, M., Kaushal, N. & Sharma, A. (2019) substituted fine aggregate in the manufacture of concrete in proportions of 0%, 5%, 10%, 15%, 20%, 25% and 30% by marble powder, and performed compression tests at 7 and 28 days of age. The results obtained in the sample without modifications were 19.10 and 24.73 N/mm² at 7 and 28 days, respectively.

In the 5% sample, an increase of 20.36 and 27.40 N/mm² was observed in 7 and 28 days, respectively. Similarly, in the 10% sample, an increase in resistance of 20.51 and 29.92 N/mm² was observed in 7 and 28 days, respectively.

From the samples with 15% to 30%, the compressive strengths showed a decrease with respect to the original sample with decreases at 7 days from 15.85 to 12.14 N/mm² and at 28 days from 24.44 to 18.07 N/mm², so it is determined that a partial substitution of the fine aggregate by up to 10% of marble powder generates a higher compressive strength.

In Giza, Egypt, Mostafa Shaaban (2020) carried out a study where he substituted in shotcrete percentages of 5, 10, 15, 15, 20, 25 and up to 30% of sand partially with marble powder. At seven days of age the samples tested for compressive strength with the partial substitution of 5% obtained a lower value than the sample without marble powder.

Samples from 10% presented an increase in compressive strength at 28 days of age (from 5% to

30%), due to the fineness of the marble powder that performs a filling effect in the concrete. It was also determined that the adhesion of the shotcrete increases proportionally to the greater substitution of marble powder for sand.
Ince, C. et al. (2020) used marble powder in pozzolanic concrete; the concrete was prepared with 20% silica fume replacing cement, and marble powder in fine aggregate replacement proportions of 10% and 20%, 15 cm diameter cylinders with a height of 30 cm were manufactured. The study lasted 1 year, and all the samples were cured under water. The compressive strength results show that the substitution of 20% silica fume increased the long-term compressive strength, this increase in strength is attributed to the pozzolanic activity of silica fume. As for the substitution of marble powder in the fine aggregate, the 20% substitution presents a slight decrease in compressive strength than that shown by the 10% substitution compared to the control sample without substitution. Both the 10% and 20% samples show an increase in compressive strength.
Santos, Villegas, and Betancourt (2010) and Rahangdale, S. & Qureshi, S. (2018) found that the higher the amount of marble powder the lower the compressive strength. Hebnoub, H., et al. (2011) and Verma, M., Kaushal, N. & Sharma, A. (2019) show that more marble powder can be substituted without affecting the strength. Ince, C., et al. (2020) results show that the substitution of marble powder up to 20% in pozzolanic concrete can have an increase in compressive strength.
According to the authors of this section, it is mentioned that substituting marble powder for fine aggregate up to 10% does not affect the compressive strength since it does not increase or decrease when the substitution of marble powder for fine aggregate in concrete is increased. If the strength was to decrease considerably, it could be attributed to the fact that the marble powder up to 10% helps to cover pores that the fine aggregate can not do, and when it is greater than 10%, there is a lack of aggregate to help give strength to the concrete.

2.3.2 Marble powder as a partial substitute for cement in concrete.

High performance concretes have also been tested, in a study by Talah, Kharchi, and Chaid (2015). They developed two study mixes, the first as reference concrete (RC) and a second high performance concrete mix with marble powder (HPCMP) to which 15% of cement was replaced by marble powder. The dosages used are shown in Table 4.

Table 4. Mix proportions and properties of concrete. (Talah, et al., 2015)

Mix	Ratio a/c	Cement kg/m³	Marble powder kg/m³	Water kg/m³	Sand kg/m³	Gravel 3/8 kg/m³	Gravel 8/16 kg/m³
RC	0.5	400	0	200	788	163	886
HPCMP	0.5	340	60	200	788	163	886

The compressive strengths of each mix were evaluated on 160 x 320 mm cylinders at 7, 28, 90, 180, and 365 days of age. All samples were compacted using a vibrating table after demolding, the samples were divided into two equal groups and cured in the following conditions: in the first curing condition, the samples were immersed in water until the test age, while, in the second curing condition, they were immersed in aggressive water (5% CaCl2) until the test age.
Figure 7 shows the compressive strength results of the mixes, according to the curing condition and age of the concrete.

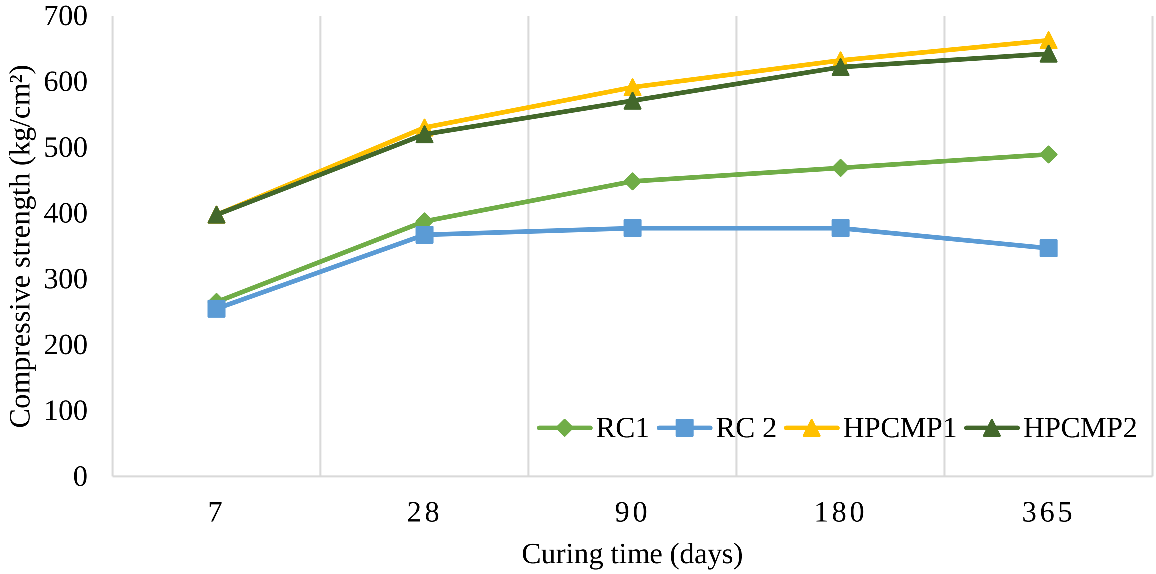

Figure 7. Evolution of compressive strength at different ages. (Talah, et al., 2015)

The result indicates that there was a systematic gain in compressive strength with marble powder content. It was observed that the ratio between the compressive strength of specimens subjected to water curing and those cured under aggressive conditions the reference concrete deviated up to 29%. However, this ratio for concretes containing marble powder is within a range of 3%, depending mainly on the marble powder content and test age. This implies that reference concretes are more sensitive to aggressive media than concrete with marble powder. (Talah et al., 2015).
In 2017 Singh, Srivastava, and Bhunia, performed tests on concretes by substituting 0, 10, 15, 15, 20, and 25% of the cement with marble powder, also experimenting with 3 w/c ratios 0.35, 0.4, and 0.45. The dosage of the concretes is shown in Table 5.
Ghorbani S. et al. (2018) proportionally replaced Portland cement type II with 0%, 5%, 10%, and 20% of marble powder, granite powder, or combination of both. The samples were subjected to curing and analyzed at 7 and 28 days of age. In the samples with marble powder and granite powder as a partial cement substitute, the compressive strength was not significantly affected, both at 7 days and 28 days. In the samples where only marble powder was substituted, the samples with 5 to 15% substitution showed an improvement in compressive strength, but not the 20% substitution, which showed a decrease in compressive strength of 0.94 and 0.96 times in both the marble powder and granite powder mixtures; in the samples where granite powder was substituted for cement, the 10% sample offered a higher strength between the ranges of 1.14 and 1.09 times of the sample without any substitution. The authors determined that the increase in compressive strength presented in this study is due to the improvement in the density of the samples due to the filling of their pores. Finally, as the age of curing increases, the loss of compressive strength decreases.
Mostafa Shaaban (2020) partially substituted cement for marble powder in the mix for the manufacture of shotcrete, in proportions of 5, 10, 15, 20, 25, up to 30%. The results obtained reported that the use of marble powder in any of the substitution proportions presented a decrease in compressive strength; in the samples with 5% substitution at early ages (7 days) presented a decrease in compressive strength of 5.4% in relation to the original sample, and at 28 days, a decrease that reached 23.4% in the samples with 30% marble powder substitution.
Babouri L. et al. (2020) used marble powder as a partial substitute for ordinary portland cement in the manufacture of concrete; the substitution percentages used were 5%, 10%, 15%, and 20%, and performed compressive strength tests at 2, 7, 14, and 28 days cured.

The samples with 5%, 10%, and 15% presented lower compressive strength results than the original sample without marble powder, but the sample with 5% marble powder, from day 2 to day 28 of the last test, showed an increase in strength, this increase in compressive strength is attributed to the fact that the marble powder reduces porosity, which is reflected in a sample with fewer voids, and, therefore, more resistant.

Table 5. Concrete mix proportions (Singh, Srivastava y Bhunia, 2017)

Ratio a/c	Mix	Cement kg/m³	Marble powder %	Marble powder kg/m³	Coarse aggregate kg/m³	Fine aggregate kg/m³	Water kg/m³
0.35	Control	422	0	0	1278	689	148
	M10	379.8	10	42.2	1278	689	148
	M15	358.7	15	63.3	1278	689	148
	M20	337.6	20	84.4	1278	689	148
	M25	316.5	25	105.5	1278	689	148
0.40	Control	394	0	0	1257.2	707.2	158
	M10	354.6	10	39.4	1257.2	707.2	158
	M15	334.9	15	59.1	1257.2	707.2	158
	M20	315.2	20	78.8	1257.2	707.2	158
	M25	295.5	25	98.5	1257.2	707.2	158
0.45	Control	351	0	0	1183	858	158
	M10	315.9	10	35.1	1183	858	158
	M15	298.35	15	52.65	1183	858	158
	M20	280.8	20	70.2	1183	858	158
	M25	263.25	25	87.75	1183	858	158

The results of the compressive strength tests show an increase in strength in the mixes with 10% and 15% replacement with marble powder. This increase can be attributed to the fact that the marble powder helps to form denser mixes with less porosity. The mixes with 20 and 25% replacement percentages show a decrease in compressive strength, possibly due to the lack of cementitious material in the concrete.

The samples with a w/c ratio of 0.35 showed an increase in strength in the sample with 15% replacement (Figure 8). Similarly, at the same percentage of replacement but at the w/c ratio of 0.40, there is also an increase in compressive strength (Figure 9).

For the w/c ratio of 0.45, the compressive strength decreased compared to w/c ratios of 0.35 and 0.40 (Figure 10).

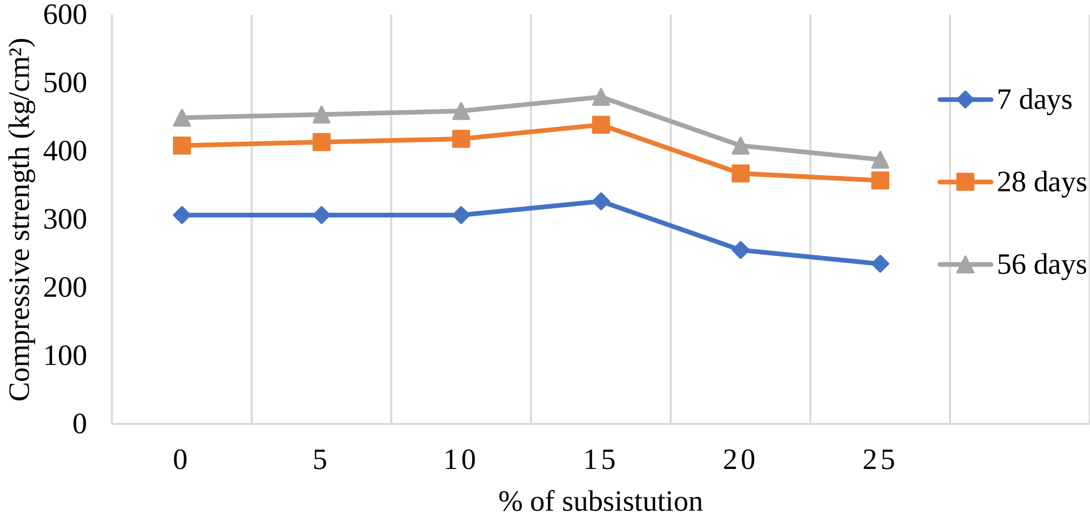

Figure 4. Compressive strength of concrete specimens with w/c ratio 0.35.

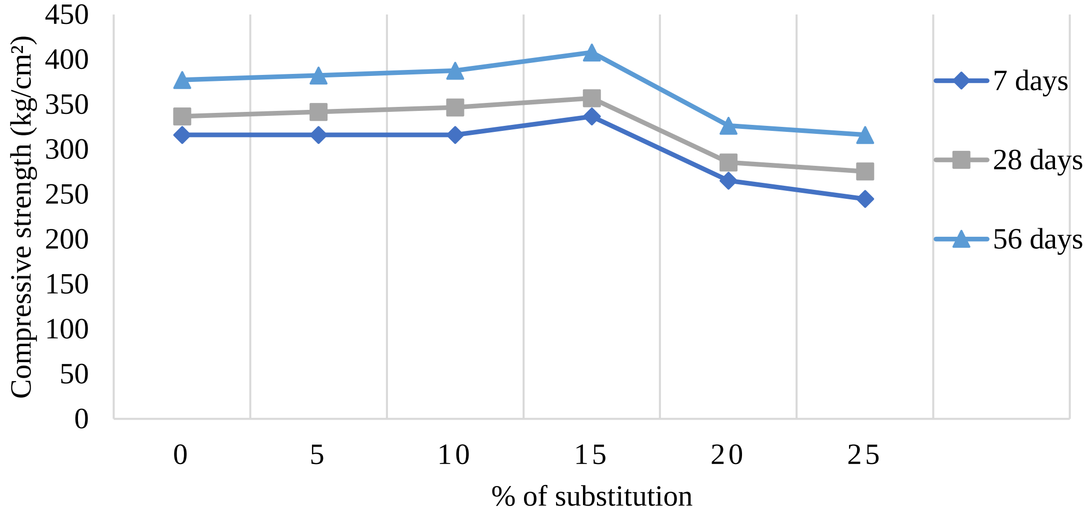

Figure 5. Compressive strength of concrete specimens with w/c ratio 0.40.

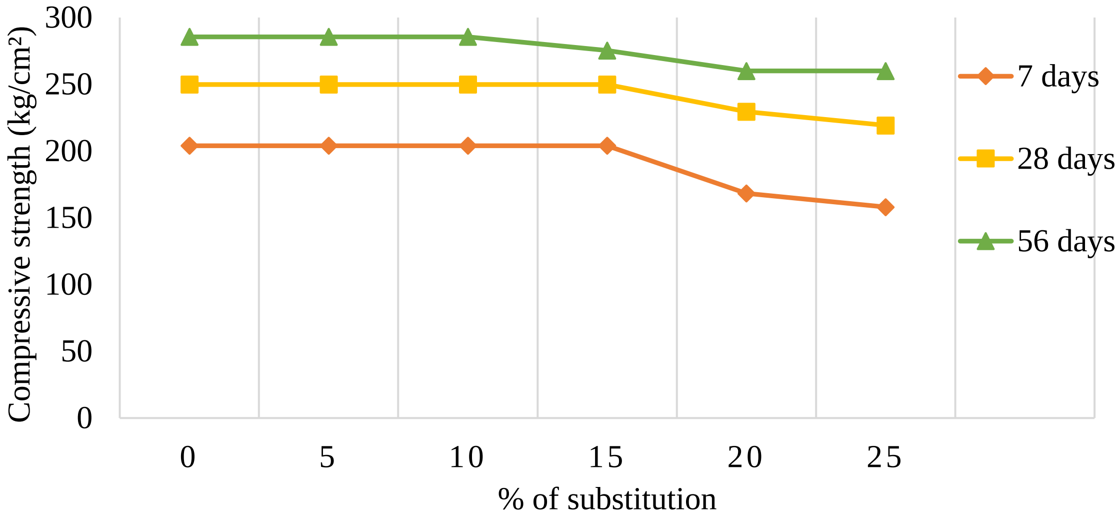

Figure 6. Compressive strength of concrete samples with w/c ratio 0.45.

Another research experimented with replacement of cement with marble waste at 0, 5, 10, and 20% and determined that the use of marble powder in concrete in the range of 10-15% increases the compressive strength. (Khodabakhshian, et al., 2018).
Wang, Y. et al. (2022) manufactured concrete by replacing cement with marble powder in proportions of 0%, 5%, 10%, 15%, 20%, and 25%, in samples of 150 mm cubes, performing compressive strength tests at 3, 7, 14 and 28 days of age, obtaining the following results: the control sample presented strengths of 23.8, 29.8, 33.1 and 35.0 MPa at 3, 7, 14 and 28 days respectively, the 5% samples at 3 days obtained a lower compressive strength than the original sample, the sample with 10% marble powder from 3 to 14 days, as well as the 5% sample, had a lower strength, but at 28 days it was 35.4 MPa, increasing by 1.14% with respect to the original sample. The other substitutions (15%, 20%, and 25%) showed up to 21.14% (28 days) lower compressive strength than the sample without marble powder.
Talah, Kharchi, and Chaid (2015) found that one can substitute marble powder for cement and have a gain in compressive strength if one has vibration to remove air in the fabrication of specimens. Ghorbani, S. et al. (2018), Mostafa Shaaban (2020), Babouri, L., et al., (Khodabakhshian, et al., 2018), and Wang, Y., et al. (2022) found that the range of substitution of marble powder for cement so that the compressive strength is not affected is 0 to 10 %.
From this section, it can be concluded that up to 10% of marble powder can be substituted for cement so that the compressive strength of the concrete is not affected. According to the test results, the compressive strength is affected when the marble powder substitution is greater than 10%.

2.4 Marble powder, concrete, mortar, and superplasticizers

Water-reducing additives (plasticizers) and high-range water-reducing additives (superplasticizers) contribute to increase durability and provide a reduction in the amount of water of at least 5%, decreasing the w/c ratio, and superplasticizers, at least 12%, and up to 40%.
Corinaldesi, Moriconi, and Naik (2010), in a reference sample, substituted 10% cement with marble powder and, in a second option, substituted 10% sand; in addition, an acrylic-based superplasticizer additive was added at a proportion of 0.5% of the weight of the cement, as shown in Table 6.
Three cubes obtained from 40 x 40 x 160 mm bars of each mixture were manufactured for compression tests at 3, 7, 28, and 56 days of curing.

Table 6. Proportions of mortar with superplasticizer.

Mix	**Ref**	**10% Cement**	**10% Sand**
A/C	0.48	0.49	0.53
Water (kg/m³)	220	200	240
Cement (kg/m³)	450	405	450
Sand (kg/m³)	1350	1350	1215
Marble powder (kg/m³)	0	45	135
Superplasticizer additive (kg/m³)	2.25	2.02	2.25

Both samples reported higher compressive strength at early ages. At 28 days of age, the reference sample obtained higher strength; however, the use of the plasticizer provided an increase in compressive strength compared to the study carried out without the additive. (Figures 2 and 11).

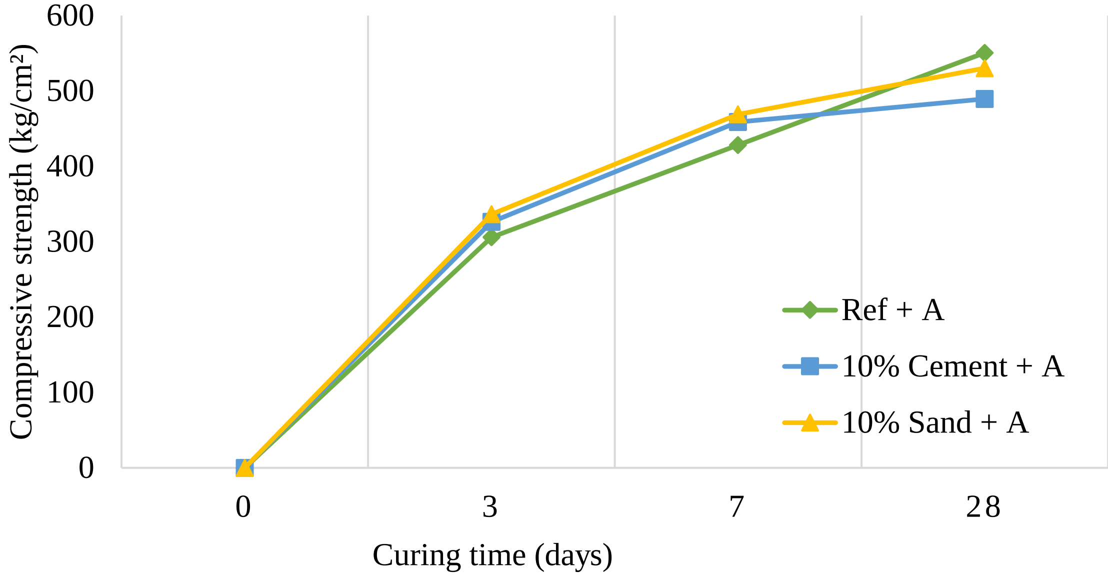

Figure 11. Compressive strength in relation to curing time in mortars with superplasticizer admixture.

In summary, when a superplasticizer is used in concrete, an increase in compressive strength is achieved. It can be said that marble powder can be substituted for cement in an amount greater than 10%, and a superplasticizer is applied to compensate for the resistance.

2.5 Previous experimental studies to elaborate bricks with marble powder.

Santos, Villegas, and Betancourt (2012) conducted a study proposing a series of dosages having marble powder as a base, the amount of cement in the samples varied, and the amount of water did not change (Table 7).

Table 7. Results of bricks based on marble powder. (Santos, et al., 2012)

Sample No.	Cement %	Water (c+RM) %	Resistance (kg/cm²)	Absorption %
1	8	15	45.83	17
2	11	15	81.56	16
3	14	15	82.76	18

Cylinders of 15 cm in height and 7.5 cm in diameter were manufactured, as well as 5 cm cubes. They concluded that the shape of the bricks did not affect the results.

The results show that there is a significant influence on strength with an increase from 8 to 11% cement, but at a percentage higher than 11%, there is no increase in strength.

The results show that the absorption did not change as a function of the amount of cement.

Morales-Olán et al. (2015) propose the fabrication of a block of 14 x 20 x 40 cm section made with marble powder, tepezil, cement, and water. The dosage is shown in Table 8. The mixtures were compacted by vibration and pressing and were dried in the sun for 48 hours.

Table 8. Composition in percentage of materials in the evaluated mixtures.
(Morales-Olán , et al., 2015)

Material	M1 %	M2 %
Marble Waste	55	35
Tepezil	31	51
Cement	6	6
Water	8	8

The results obtained in the water absorption test show that sample 1 absorbs less water than sample 2. As for the compressive strength tests, sample 1 performs better than sample 2, as shown in Table 9.

Table 9. Percentage of water absorption and compressive strength of samples.
(Morales-Olán , et al., 2015)

Sample No.	Water absorption %	Resistance (kg/cm^2)
1	19.43 ± 5.55	38.40 ± 1.84
2	23.91 ± 0.25	21.46 ± 3.25

With the results presented, sample 1 complies with the necessary characteristics indicated in NMXC-441-ONNCCE-2013 to work as a construction material for non-structural use.
Another study carried out to produce bricks with marble powder was conducted by Nevárez and Rangel (2014). Table 10 shows the dosage used for the production of reference bricks, cured in the traditional way and saturated in water. Tables 11 and 12 report the results of the brick compression tests, with two options of cement quantity, 12 and 15%.

A preload of 100 kg/cm^2 was applied to all samples during the mold filling process for one minute, but the author does not explain the preloading process in his paper.

Table 10. Dosages that passed the compressive strength test.
(Nevarez & Rangel, 2014)

Component	Mixing at 12% cement	Mixing at 15 % cement
Marble powder	10 kg	10 kg
Cement	1.2 kg	1.5 kg
Sand	2 kg	2 kg
Water	2 l	2 l

Table 11. Result compressive strength of brick samples at 7, 14, or 28 days of curing 15% cement. (Nevarez & Rangel, 2014)

Sample No.	7 days of curing (kg/cm^2)	14 days of curing (kg/cm^2)	28 days of curing (kg/cm^2)
1	122.70	89.12	89.99
2	138.50	Witness	Witness
3	140.70	119.29	Witness
4	136.60	86.05	87.47
5	144.30	Witness	88.00
6	129.90	86.46	88.96
7	109.70	88.00	87.88
8	149.90	86.79	88.57
9	130.9	86.61	86.20
10	100.4	87.79	86.16

Table 12. Compressive strength results with 12% cement. (Nevarez & Rangel, 2014)

No. Dyas	Compressive strength (kg/cm^2)
7 days	107.00
14 days	107.15
28 days	95.55

For the case of 12% cement in the samples, it is concluded that the highest compressive strength occurs at early ages, i.e., at the age of 7 days, while for the age of 14 and 28 days, the strength decreases compared to 7 days, but the magnitude is maintained between 14 and 28 days. For the case of 15% cement, the compressive strength decreases compared to the12% samples at the age of 7 days, but at the ages of 14 and 28 days, it increases, which indicates that for the amount of cement in small percentages, the strength increases at early ages and the higher percentages increase the strength at advanced ages.

Betancourt et al. (2015) elaborated a brick with Portland Cement Compound type I, drinking water, river sand, and marble powder in order to observe the behavior of different proportions and shapes of the samples, cubes of 5 x 5 x 5 x 5 cm, cylinders of 7.5 diameter and 15 cm high and tablets of 5 x 10 cm; the results of the compression tests are presented in Tables 13, 14 and 15 respectively.

Table 13. Compressive strength in cubes of 5 x 5 x 5 x 5 cm elaborated with marble powder base. (Betancourt Chávez, et al., 2015)

Mix #	Cement %	Lime %	Water %	Compressive strength kg/cm^2
1	25	0	20	76.60
2	22.5	2.5	20	60.00
3	20	5	20	52

Table 14. Compressive strength, in cylindrical elements of 7.5 x 15 cm elaborated with marble powder base. (Betancourt Chávez, et al., 2015)

Mix	**Cement**	**Lime**	**Wáter**	**Compressive strength**
#	**%**	**%**	**%**	**kg/cm²**
1	25	0	20	67.90
2	22.5	2.5	20	56.24
3	20	5	20	48.00

Table 15. Compressive strength of 5 x 10 cm tablets with marble powder and sand base material, pressed at 70 kg/cm². (Betancourt Chávez, et al., 2015)

Sample	**Cement**	**Sand**	**Wáter**	**Compressive strength**
	%	**%**	**%**	**kg/cm²**
1	8	0	20	28
2	10	20	20	76
3	10	30	20	90

Tables 13, 14, and 15 show the compressive strength results of cubes, cylinders, and tablets manufactured with marble powder in its highest percentage. The tables show the percentages of cement, sand, and water only, and the percentage that is missing to reach 100% in each piece is what corresponds to the marble powder.
The elements with a higher amount of cement showed better results in compression. The shape of the element does not significantly influence the results. With respect to the results in Table 15, it is observed that, by adding sand and compressing the sample, the compressive strength increases (Betancourt Chávez et al., 2015).
For the above dosages, it was considered that, of the weight of marble powder to be used, the percentages of cement, lime, sand, and water were used as indicated in tables 13, 14, and 15.
Moreno et al. (2020) manufactured bricks with a mixture based on marble powder, cement, water, and river sand (AR), they made 4 more mixtures, taking as a basis the dosage shown in Table 16.

Table 16. Dosage of marble brick with river sand (AR). (Moreno Juárez, et al., 2020)

Material	**Quantity**
Marble powder	15 kg
Cement	2.25 kg
River sand	3 kg
Water	7 l

In the first mix, river sand was added; in the second mix, 100% of the river sand was replaced by crushed limestone sand (AT); in the third mix, 100% of the river sand was replaced by silica sand (S); in the next mix, 66% of the river sand was replaced by silica sand (SR); in the last mix, 66% of the river sand was replaced by silica sand (RS); and the rest of the aggregate was replaced by silica sand (RS). The compression results at 28 days of curing, according to each mix, are shown in Figure 12.

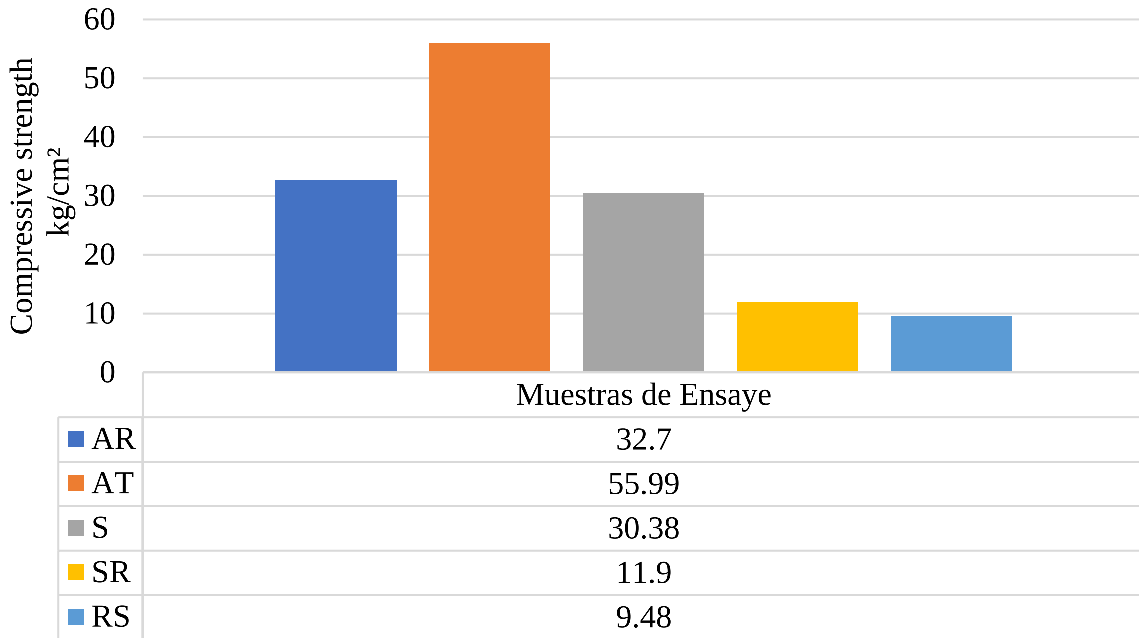

Figure 7. Compressive strength of test specimens. (Moreno Juárez, et al., 2020)

With the results presented, the AT mix performed better in compression (Figure 12) but does not have sufficient strength to work as a structural brick according to NMX-C-404-ONNCCE-2012. In Pakistan, Khan et al (2021) analyzed the performance of clay brick with partial substitution of marble powder at percentages of 0%, 5%, 10%, 15%, 20%, 25%, and 30%.
Three different brick factories in the region participated in the study; the results obtained were similar in each of the participating companies. They performed efflorescence, thermal conductivity, compressive strength, porosity, absorption, and density tests.
The density of the bricks in the original sample without marble powder was 1.55 g/cm³ and decreased as the percentage of substitution increased until it reached 30%, with a density of 1.27 g/cm³. The samples did not show efflorescence. The porosity of the samples also increased according to the percentage of marble powder substitution, from 12.6% to 52.71%, this due to the release of Carbon Dioxide (CO_2), in addition, the Calcium Oxide (CaO), being expandable, causes porosity in the sample, therefore, it is also reflected an increase in the absorption of the samples from 18% to 36%. Given the increase in porosity in the bricks, the compressive strength is also affected considerably, decreasing the compressive strength from 18.06 MPa to 4.83 MPa. Khan et al. (2021) comment that Turkish and European standards indicate that a clay brick should have a minimum strength of 7 MPa, so a substitution of up to 20% marble powder for clay meets the compressive strength standard for brick. Due to the increased porosity of the bricks, the thermal conductivity decreased from 0.99 to 0.86 W/mK, and it is concluded that with this result, the pieces would work as thermal insulation.
Santos, Villegas, Betancourt (2012) and Khan et al. (2021) found good results in the compressive strength of bricks at low marble powder substitution contents and at higher percentages, the strength decreases, Morales-Olán et al (2015) show results where marble powder is combined with Tepezil, and it is shown that the higher the marble powder substitution, the higher the strength. Nevárez and Rangel (2014) have high compressive strengths in their bricks as long as there is a preload in the manufacture of the bricks, Betancourt et al. (2015) found that the compressive strength of the samples is proportional to the amount of cement, i.e., the more cement, the higher the strength. Moreno et al. (2020) in their research, used different types of sand, resulting in the best performance of limestone sand.

As a conclusion of this section, it is determined that marble powder bricks can be used as non-structural elements and as thermal insulation.

3. CONCLUSIONS

As a conclusion of this review, it can be mentioned that marble powder can be used in construction either to replace cement, to replace fine aggregate, or to manufacture non-structural bricks. It is a topic with a lot of potential where good results can be obtained if the research is deepened.
Marble powder as a partial substitute for cement in proportions no greater than 10-15% is shown to maintain or offer an increase in compressive strength in mortars, concrete, and brick manufacturing.
The addition of superplasticizers showed an increase in compressive strength in conventional concrete mixes, and the partial substitution of marble powder to cement does not affect the compressive strength in this condition.
Marble powder as the main agent for brick making, supplemented with sand and cement, is feasible for non-structural use in residential masonry construction.
On the other hand, reducing the amount of cement used in concrete and mortars projects a cost reduction because the difference in commercial value with respect to marble powder is greater in cement. This implies that using marble powder in the manufacture of bricks reduces the cost of the pieces.
The energy required in cement production is about 1.18 GJ/ton. Therefore, replacing 15% of cement substitution with marble powder reduces energy consumption by almost 1.05%.
With the reduction of cement content, the carbon footprint would show a reduction, so its use would show a positive impact on the environment.
For the manufacture of bricks, it is observed that if a compaction of the material is used in the manufacturing process, a higher compressive strength is achieved, it is also concluded that using crushed sand instead of river sand helps the strength of the pieces.
In the case of concrete, it has been proven that the loss of strength is proportional to the increase of marble powder substitution. It was shown that the maximum percentage of marble powder substitution by cement is 10 %, so that the resistance is not affected.
For the application of marble powder in mortars, it is concluded that it is similar to the application of marble powder in concrete or bricks, i.e., the compressive strength with low percentages of marble powder is not affected.
Based on the above, it is possible to continue studying the application of marble powder in mortars, concrete, and brick manufacturing. In the manufacture of bricks, it is only necessary to find the right dosage so that the pieces can be used as structural. To achieve this, it is necessary to continue studying this topic and find the right dosage and aggregates.

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