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Use and effect of fly ash in concrete: a literature review

Uso y efecto de las cenizas volantes en el concreto: una revisión literaria

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ABSTRACT: Concrete production is characterized by a significant demand for energy and raw materials. The construction, maintenance, and demolition of engineering works cause excessive polluting waste that requires costly disposal. For this reason, alternative reusable materials that improve the mechanical properties of concrete, such as fly ash, are currently being investigated as an effective solution to reduce problems related to environmental impact. This paper analyzed 80 articles indexed in different databases such as ScienceDirect, IOPscience, Scielo, Ebsco, Scopus, SpringerLink, ProQuest, Dialnet, and Semanticscholar, which were not older than seven years since publication, to conduct an updated systematic review of the use, effect, and influence of fly ash on concrete. The methodologies and designs used to obtain the optimum percentages of 5, 10, and 15% were reviewed, analyzing mainly the results obtained when fly ash is used in concrete. Finally, according to the review carried out, it was concluded that fly ashes improve the mechanical and physical characteristics of concrete, and that the optimum dosage is 10% in substitution of ordinary Portland cement applied in simple concrete.

RESUMEN: La producción de hormigón se caracteriza por una importante demanda de energía y materias primas. La construcción, el mantenimiento y la demolición de obras de ingeniería generan un exceso de residuos contaminantes que requieren una costosa eliminación. Por este motivo, actualmente se están investigando materiales alternativos reutilizables que mejoren las propiedades mecánicas del hormigón, como las cenizas volantes, como solución eficaz para reducir los problemas relacionados con el impacto medioambiental. En esta revisión bibliográfica se analizaron 80 artículos indexados en diferentes bases de datos como ScienceDirect, IOPscience, Scielo, Ebsco, Scopus, SpringerLink, ProQuest, Dialnet y Semanticscholar, cuya antigüedad de publicación no superaba los 7 años, para realizar una revisión sistemática actualizada del uso, efecto e influencia de las cenizas volantes en el hormigón. Se revisaron las metodologías y diseños utilizados para la obtención de los porcentajes óptimos del 5, 10 y 15%, analizando principalmente los resultados obtenidos cuando se utilizan cenizas volantes en el hormigón. Finalmente, según la revisión realizada, se concluyó que las cenizas volantes proporcionan una mejora de las características mecánicas y físicas del hormigón, y que la dosificación óptima es del 10% en sustitución del cemento Portland ordinario aplicado en un hormigón simple.

1. Introduction

Concrete is the second-most-used building material. One of its main components is cement; its production, which dissipates large amounts of fossil fuels, generates approximately 7% of global CO_2 emissions, contributing negatively to the increase in environmental pollution [1]. For this reason, cement production and consumption must be reduced, as it emits large amounts of greenhouse gases [2]. Failure to reduce cement production leads to an overexploitation of the materials used for the manufacture

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of concrete, causing a negative impact on the environment, since the current production of 25 billion tons of concrete already generates sustainability problems. The problem of shortage of stone materials is already occurring in some countries, such as Malaysia, as it is known that both sand and gravel are one of the world's most exploited resources; estimates suggest that between 32 and 50 billion tons are extracted every year [3].

This is why the construction industry seeks policies to avoid the scarcity of these resources, proposing using fly ash as a supplementary cementing input to reduce pollution due to cement production and uncontrolled decomposition of agro-industrial wastes [4]. Because of this, solutions are sought to reduce this type of problem, making it feasible to partially replace cement with fly ash (FA), which, as studied, reduces carbon dioxide emissions [1].
In this sense, the use of FA, associated with the disposal of industrial waste, is one of the main alternatives to mitigate environmental pollution [4]. FA are amorphous aluminosilicate materials that may be non-cementitious in their natural form, but when they react with calcium hydroxide and water, they form cementitious compounds, positioning themselves as a much more environmentally friendly solution than conventional Portland cement concrete, since they offer several advantages such as reduced heat of hydration [5], better frost resistance, and even energy savings [6], limitation of CO_2 emissions, reduced use of natural resources and hazardous waste management [7].

Similarly, with the use of fly ash (FA), mechanical and physical properties such as workability, strength, and durability are improved [8]. An active area of study is related to the properties of green concrete manufactured with partial replacement of cement by FA, [9] taking into account different combustion temperatures that can determine pozzolanic behavior. Causing a positive impact on concrete [10], several experimental investigations demonstrate the optimization of fly ash-based green concrete properties, incorporating other additions such as polypropylene fibers and/or coconut shell residues, which, when working together, result in a significant reduction in slump and density of concrete, higher modulus of elasticity, and better compressive, flexural, and tensile strength [11].

On the other hand, it is investigated how feasible it is to produce high-volume concrete (HVFA) and how it improves its strength by replacing cement with large mass proportions of FA ranging from 40 to 70% [12]; it is also well-known that due to the exponential growth of industrial sectors, the demand for thermal energy of nations increases rapidly, resulting coal as the main energy material. FA is the result of the combustion of such material, as the furnace expands along with the smoke; due to this high production rate, research related to the innovative use of this type of waste material is carried out all over the world [13]. Likewise, some relevant studies show that the use of FA generates significant and positive contributions, favorably reducing the evolution of hydration heat [14].

The FAs that are most commonly used as pozzolanic materials added to Portland Cement concrete are low in calcium, and these are class C and F according to ASTM C618. Class-C FA is mainly used to produce permeable concrete by adopting the mixture dosing method described in the ACI 522 R-10, where its incorporation has been shown to reduce the total voids in this type of concrete, which is mainly attributed to the micro-filling effect of fly ash and the addition of plasticizer, which has caused a cohesive action, thus reducing the total voids in permeable concrete [15]. Class-C FAs are mainly used to intensify the durability property of concrete, indirect tensile strength, elastic modulus, reduction in the cracking process, and increase tensile yield coefficients [16]. On the contrary, the Class-F FA showed through control tests a gradual increase in strength over a period of time and generated a greater capacity for water absorption and permeability to chloride [17].

Traditionally, building materials have been tested for durability, strength, and lightweight. In order to reduce the self-weight of concrete, the use of sintered AF is being implemented as a partial replacement of fine aggregate in concrete [18], so this method is becoming increasingly important; this is due to the prevention of a future shortage of sand and natural aggregates [19], so FA becomes a solution to solve the environmental problem of CO_2 emission [20].

In contrast, there are also different experimental methods to improve the properties of concrete, thus distinguishing the use of mixed recycled aggregates from different plants and the replacement of cement and/or aggregates by fly ash [21] but the substitution of FA as a fine aggregate is distinguished because it results in a more environmentally friendly method that steadily decreases drying shrinkage relative to ordinary concrete [22]. It is also necessary to highlight that microspheres (FAM) are a type of FA obtained by the coal combustion process. FAMs are sphere-shaped with gaps and have minimal density compared to water, and are also distinguished by their function of achieving collision in the porosity of concrete [23].

Ultrafine fly ash is another type that is acquired through a dry and closed separation process, which improves the strength and workability properties of concrete [24]. Instead, considering the size, we can find nano ash, obtained from macro to nano through a ball milling process, significantly reducing pores and gaps in the concrete [25].

We can also distinguish the fly ash of large volume applied in the concrete mixture, which maintains its initial composition and improves its physical and mechanical properties [26].

Moreover, there are several types of concrete in which the use of FA has been identified, such as geopolymers, which were introduced to reduce cement consumption and reduce carbon dioxide emissions, as well as other concrete used such as self-compacting, high volume, recycled, shotcrete, and lightweight [27].

The purpose of this article is to review the most recent and up-to-date research on the use of fly ash in concrete. In addition, the results of this review are analyzed and discussed to provide new knowledge and information on the applications of FAs in particular.

2. Methodology

The review was conducted using a total of 80 articles from different databases such as ScienceDirect, IOPscience, Scielo, Ebsco, Scopus, SpringerLink, Proquest, Dialnet, and Semanticscholar. We found 1 article in 2014, 2 in 2015, 7 in 2016, 8 in 2017, 11 in 2018, 17 in 2019, 23 in 2020, 6 in 2021, and 3 in 2022. The keywords used for the search were fly ash and fly ash concrete. All articles no older than 7 years and including the search filters corresponding to the various databases, such as thematic area, type of document, type of publication, and type of source, among others.

For better detail, Table 1 shows the distribution of the articles, taking into account the database and the year of publication; Table 2 describes the search criteria, the filters applied, and the selection of the articles used in the present research, and Figure 1 indicates the process of searching and selecting publications. The search was finally closed on June 10, 2022.

3. Results and discussion

To review the results and discussions, information was collected from various studies, comparing the procedures and criteria of research carried out by different authors, as shown in Table 3. Seven sections were classified, to exchange opinions on the use, influence, importance, and effect of fly ash on concrete.

3.1 Fly ash as a mitigator of environmental pollution

The main cause of the emission of large quantities of greenhouse gases is a high demand for energy and raw materials, which triggers a series of problems related to environmental impact, which is increasingly harmful to human beings. Concrete is one of the building materials that emits the most carbon dioxide into the environment, with production projected to increase until 2050, especially in developing countries. For this reason, alternatives that can mitigate these problems and that are environmentally friendly are being studied, considering the partial replacement of concrete components with FA as one of the most optimal solutions at present. Empirical studies show that FA has a synergistic effect on concrete, contributing to reducing the aforementioned environmental impact conflicts, thus valuing the development of structural concretes that are much more sustainable than conventional ones [72, 73].

On the other hand, there are cementitious materials such as fly ash that seek to contribute to environmental sustainability by contributing improvements to physical properties of the concrete mix, demonstrating through experimental programs that this type of composite mix results in eco-friendly concrete with optimum mechanical properties [74].

3.2 Origins of fly ash

It was in 1930 that the term "fly ash" began to be used, and in 1937, it was reported to be used in concrete in North America. The interest in FA grew and became evident since, over the years, FA represented 16% of the manufacture of concrete. The study of FM took importance in the construction industry because it favorably modified the properties of concrete, such as compressive strength, tensile, bending, and many more characteristics that are investigated through scientific articles until today. [75] FAs originate in the coal combustion process and occur mainly in thermoelectric power plants or industrial boilers. Previous research has shown that to know if fly ash should be used in a particular case, it will be necessary to measure its reactivity through characterization tests such as fluorescence and X-ray diffraction, optical and scanning electron microscopy, and X-ray photoelectron spectroscopy, among others. Taking into account the degree of reactivity, FA can have the ability to replace cement in concrete without affecting its mechanical strength and optimizing physical properties such as durability, workability, and heat of hydration [76].

Some additional aspects that must be considered to classify FA as suitable for use in the manufacture of concrete are the effective reaction of aluminosilicates with

Table 1 Articles distributed by database and year of publication

Database	Year of publication									Total
	2014	2015	2016	2017	2018	2019	2020	2021	2022	
Dialnet								1		1
IOPscience				3	8	5	10	3		31
Proquest		In	1	2	1	5	1			10
Scielo			2	1	1	3	1			8
ScienceDirect			1	1	1		1			4
Scopus		1	2				1	1	3	8
Ebsco						1	8	1		10
Semantic Scholar	1		1	1			1			4
Springer Link		1				3				4

Table 2 Search criteria and selection of articles used in this research

Database	Year of of search	Keywords	Number of documents search results	Filters applied		New search results	Selection of scientific articles
				Affair/ Area	Other		
Dialnet	2021	Fly ash concrete	95	-	Document type: Journal article	71	1
IOPScience	2017-2021	Fly ash concrete	500	-	Type of publication: Articles Open access	422	31
IProquest	2016-2020	Fly ash concrete	38 738	Civil engineering	Limit to: full text Source type: scientific journals Document type: Article Language: English	434	10
Scielo	2016 2020	Fly ash concrete	63	Engineering	Type of: literature: Article	34	8
Science Direct	2016-2020	Fly ash concrete	26 226	Engineering	Article type: Research articles Publication title: Cement and concrete compounds	551	4
Ebsco	2019-2021	Fly ash concrete	2 590	Fly ash	Limit to: full text in pdf Font type: publications	63	10
Scopus	2014-2022	Fly ash concrete	28 534	Engineering	Article type: Research articles Publication title: Cement and concrete compounds	101	8
Semantich Scholar	2014-2020	Fly ash	512 000	Engineering	Type of publication: Journal article Has pdf	351	4
Springer Link	2015-2021	Fly ash concrete	11 665	Engineering	Content type: Article Subdiscipline: Civil Engineering Open access	95	4

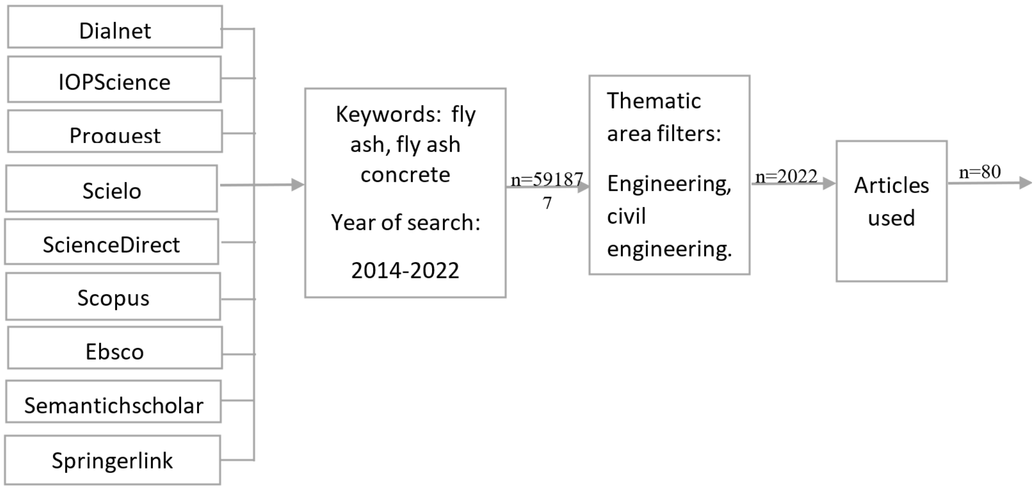

Figure 1 Process of searching and selecting publications

Table 3 Use of fly ash in concrete

Partial Replacement by	Cement [28–37];	Fine aggregate [22, 38].	Coarse aggregate [39]
Optimal percentage	10%	20-50%	20-50%
Improved properties	Physical and mechanical properties: Temperature variation Tensile strength, compression and bending; Durability; Relative dynamic modulus of elasticity; Workability [40–46].		
Tuition	C and F [37, 47].		
Types	Microspheres [23]; Ultrafines [24]; Nano ash [25]; Alkaline activated. [48]		
Use	High-volume fly ash [49, 50]. Incorporation of fly ash in geopolymer concrete [51–54]. Incorporation of fly ash in self-compacting concrete [55–60]. Incorporation of fly ash in high-volume concrete [61]. Incorporation of fly ash in recycled concrete [43, 62]. Incorporation of fly ash in sustainable concrete [63]. Incorporation of fly ash in shotcrete [64]. Incorporation of fly ash in light concrete [65–67]. Incorporation of high-resistance fly ash [68]. Incorporation of fly ash in green concrete [69]. Incorporation of fly ash in hydraulic concrete [70]. Incorporation of fly ash in aerated concrete [71].		

calcium hydroxides and the formation of cement hydrates in the passive phases [76].

As for the chemical composition of fly ash from thermal power plants, the main compounds are mainly aluminosilicates, silicon oxide, aluminum and iron oxide, among other metals. If FA has a low calcium oxide (CaO) content, this represents an advantage in terms of its efficiency in suppressing the expansion produced by the silica-alkali reaction in concrete. The compounds found in Friedreich's ataxia can be diverse; However, among the most common are carbon, glass, and minerals, while by the shape of their particles, we find cenospheres and plerospheres [76].

Stored fly ash isolated from moisture recognizes unburned coal, also called unburned coal, as the main contaminant. To obtain a grade estimate, it will be necessary to determine the loss on ignition. In most cases, the higher the percentage, the lower the specific yield. In previous years, studies indicated that optimum concrete performance was achieved by incorporating AF with a loss of ignition of less than 3.2%; however, recent studies have shown that 15.7% yields the same or even better results, making the use of AF with this loss on ignition percentage very feasible. The most outstanding advantages found were better workability of fresh concrete, higher compressive strength of up to 20%, greater durability, and high sulfate resistance [77].

3.3 Classes of fly ash

According to the ASTM standard, two types of fly ash (FA) used in concrete are distinguished, which are types C and F. Class-F ashes are those produced by coal exposed to high-energy heat, such as, for example, bituminous and anthracite coals, and according to previous research, they usually contain about more than 15% calcium oxide;

while class- C ashes are of subbituminous type that commonly contains more than 20% calcium oxide and are characterized by their cementitious properties [37].

Several analyses show a difference between class C and F ashes since, based on research on their chemical composition, class C ashes were found to have a high calcium content. In contrast, class-F ashes have a much lower index, meaning that class-C ashes have a higher amount of calcium aluminosilicates and higher reactivity. This means that class-C ashes have a higher amount of calcium aluminosilicates and higher reactivity compared to class-F ashes, which can be verified during the short setting time of concrete; on the other hand, class F (FA) fly ash has a low calcium content and high amounts of quartz, mullite, and magnetite, as well as having a higher silica and aluminum content than class-C ash [47].

3.4 Types of fly ash

Microspheres

Fly ash in the form of microspheres is the result of a mineral transition during coal combustion; they are hollow spherical particles with a density much lower than that of water. There are different types of microspheres, including the cenospheres, which are composed of aluminosilicates and are mainly used in concrete. This type of FAM is collected on the surface of sedimentation ponds, extracted by suction or mechanically, and then subjected to a drying process; the FA content from coal combustion ranges from 0,1 to 3,8% by weight [23].

The shape of this type of FAM is very variable since it can be perfectly spherical or completely irregular. It has a non-homogeneous structure composed of closed and open pores; Its surface may be spongy or rough. In addition, it is appreciated that the morphological changes of the microspheres can be variable since this depends on the combustion of charcoal [23]. Hollow microspheres can be used as an aeration additive in concrete, as a way to reduce porosity and the degree of accumulation of waste, achieving a reduction in porosity of up to 10% [23].

Ultrafine

It is important to note that to consider FA as a good cementitious agent, the origin of the combustion of previously pulverized coal must be taken into account, since the finer the particle size, the finer it is, and the more it can develop a behavior similar to that of cement, [24], considering it as a densifying agent to fill microscopic voids, according to ASTM C618, it indicates a maximum percentage of 34% retained in sieve number 325. In addition, the pozzolanic reaction of an FA, in most cases, depends on additional parameters such as the amorphous content and its chemical and mineralogical composition [24].

Ultrafine FA is obtained from a dry and closed separation process. It is commonly used as a replacement for cement in concrete. The use of this type of ash positively influences the fluidity, durability, resistivity, chloride coefficient, and the alkali-silica reaction of concrete. Workability with ultrafine FA can be improved by up to 15%, and compressive strength can reach approximately 70 MPa in 28 days [24].

Nano ash Alkaline activated

To convert the ash from micro to nano, it is necessary to subject them to a grinding process for an estimated time of two hours, and an analysis must be carried out in order to corroborate the size and distribution of the particles, in addition to being subjected to mechanical tests such as compressive strength, tensile strength by division and modulus of rupture [25]. Adding these ashes will consist of penetrating them and fusing them with the concrete components, which might reduce the percentage of porosity and make the concrete much denser.

One of the identified disadvantages of using this type of FA is the high cost of this material in many parts of the world; however, it was found that the reduction in particle size provides greater compressive strength compared to conventional concrete [25].

Alkaline activated

FA are alkaline activated and undergo a chemical process, giving rise to a dense structure that provides high early mechanical strength and good resistance to atmospheric agents; the most commonly used alkaline solutions are sodium silicate, sodium hydroxide, potassium hydroxide, calcium hydroxide, etc. All this increases reactivity and makes it a suitable material to replace cement. Although the benefits and advantages of incorporating this type of FA have been demonstrated, the cost of this type of catalyst makes it a valid option only for specific cases. Another way to activate FA is by adding chemicals from powder, ball mill, limestone, and water [48].

Among the recognized benefits are the low chloride permeability rate, low transport of aggressive agents, increased durability and greater long-term strength. A notable improvement in apparent electrical resistivity has also been identified, reaching values of up to 60 MPa, while for standard concrete, the rates are between 45 MPa and 50 MPa [48].

In recent studies carried out in Latin American countries, including Colombia, resistance values higher than 26.1%

were reached after 28 days of curing, compared to standard concrete. On the other hand, better mechanical behavior and greater resistance to water penetration were also recognized [78].

3.5 Properties and advantages of fly ash in concrete

FAs are produced in the plant, originate through a combustion process, are characterized by having pozzolanic properties and spherical grain shape, and also have the function of replacing cement in the concrete mixture, following the respective physical and mechanical parameters. In other countries, it is classified as inorganic waste resulting from the cremation of pulverized carbon developed in power plants, and its size ranges from 0.01 to 100 mm in the form of spheres [40, 41].

Among the most notable characteristics of fly ash (FA) is improving the mechanical and physical properties in concrete manufacturing, such as compressive strength, flexural strength, and division tensile strength, as well as improving the performance and durability of concrete mixtures [41]. In addition, its use helps environmental sustainability and cost reduction. According to Sivasankaran *et al*. [42], the percentages with which FA reuse is sought range between 6% and 30%; this is similar to that stated by Szcześniak et al., mentioning that the use of FA in concrete mixtures provides beneficial modifications in its properties, with doses of 10 to 33% fly ash. The process shows an increase in initial strength and high endurance over a long period [40].

On the other hand, several properties of the incorporation of fly ash in different types of concrete, such as polymeric concrete, were recognized, where the percentage of replacement fluctuates between 6.4% and 25%, causing an improvement in compressive strength and flexural strength, in a period of time of 14 days [41]. Regarding recycled concrete, the substitution is approximately 50%, retaining its heterogeneous properties [43]. In the case of using a dose higher than 25%, the results related to the increase in compressive strength were obtained over a time period of 29.58 and 87 days. [42]. According to previous studies, in self-compacting concrete (HAC), three types of dosages are used: 5%, 15%, and 35% in partial replacement of cement in a period of 28 days, proving that the most optimal dosage is 15%, observing an improvement in bending strength observing an improvement in flexural strength. [44] On the other hand, ready-mix concrete, used mainly in paving, uses a dosage of 30%, replacing Portland cement, preserving its compressive strength and improving its [45] physical properties. Finally, self-compacting concrete in replacement doses of 35% causes positive effects on its properties such as indirect traction, etc. [46].

3.6 Use of fly ash in concrete

High-volume fly ash

This type of ash is commonly used in engineering works involving large volumes of concrete, such as dams, reservoirs, water intakes, etc. It has long been identified that one of the biggest problems of constructions involving large amounts of concrete is related to the cracking of their structures caused by the heat of hydration. The main contribution of high-volume FAs is the reduction of cracks caused by the heat of hydration [49].

Other characteristics that distinguish large-volume FAs are reduced vacuum ratio, water absorption of concrete, improved durability, increased fluidity, greater resistance to aggressive agents, better rheological properties, higher thermal conductivity (up to 18% compared to conventional concrete), lower temperature variation, and increased compressive strength [49].

Tests carried out in different places, such as Taiwan, have shown a decrease in fall between 160 and 260 mm; in addition, no dispersion index was found, and the elastic modulus improved markedly, while the drying shrinkage is inversely proportional with respect to the addition of FA; finally, a set time of about 7 hours was estimated [50]. The incorporation of this type of FA contributes to manufacturing a much cheaper, ecological, and more durable concrete; however, in addition to requiring a large amount of fly ash, it is necessary to add a high-end water reducer in order to preserve the properties of the concrete; likewise, it is recognized that large-volume FA has a great influence on the setting time, So it is necessary to have a correct and adequate control, especially in the demolding time [50].

Fly ash as a replacement for cement

The reuse of this type of ash in concrete as a substitute for cement has become increasingly relevant in recent years thanks to its pozzolanic composition, since different investigations confirm the positive impact on the improvement of its main properties in the long term, being used, in most cases, doses of 10%, 20%, 30%, 40% and 50% class F FA, Observing an improvement in a period of time of 7, 28 and 56 days [28].

The substitution of FA as a cementitious material is a method recently known in several parts of the world, especially in countries such as India, since multiple thermoelectric plants generate tons of FA, which is why the reuse of FA is implemented, developing benefits such as improving the durability of concrete [29].

The quality of FA depends on different factors such as the coal combustion process and the quality control of its basic components; in addition, the fineness of its particles must meet the requirements and conditions specified in ASTM C-430, and must also be subjected to density tests. To achieve proper yield from these ashes, tests indicate that a 10% dose must be incorporated and ASTM C-618 compliant [30].

A type of fly ash increasingly used for engineering purposes is Vietnamese fly ash, which is used in optimal dosages of 10% and 20%, where an improvement in its mechanical property of flexural strength of reinforced concrete beams compared to control beams is observed without the addition of fly ash. It is also necessary to mention the addition of fly ash reduced the risk of steel corrosion in concrete [31]. While the large-volume FA improved the resistance and flow properties, achieving a value of 32.4 MPa and a porosity of 0.48 in 28 days. [32]

For the performance and workability of concrete, cement can be replaced by fly ash in an optimal dosage, which is obtained through tests and quality control of materials, improving its properties and maximum resistance. The tests are carried out on samples in the form of concrete cubes, with a curing age over a time period of 3,7,14,28,56, and 90 days. It is noted that in the time period from 7 days to 56 days, better conditions were obtained in the strength properties of concrete [33]. Among the main experimental investigations, it was recognized that the fineness of FA influences the strength, toughness and fracture of concrete; there are three types of fineness that pass through sieves n ° 175, n ° 250 and n ° 32, when these are replaced in doses of 10% and 20% by weight with respect to the cementitious material, the results are highly beneficial [34]. Likewise, waste applied in concrete mixing is an approach in construction that reduces environmental problems by reusing FA by replacing cement in doses of 0% to 30% over 28 days [35]. Other studies indicate that the substitution of FA in concrete based on crushed limestone of high absorption, also called low-quality concrete, manages to improve its mechanical properties in doses of 20% and 40% [36].

All these studies agree that this type of ash as an additional material to cement in the manufacture of concrete should consider doses that do not affect the strength, but, on the contrary, improve its physical and mechanical properties, and also mitigate the environmental damage caused by construction materials. These doses include percentages of 2.5%, 5.0%, 10.0%, and 15%, obtaining results through destructive tests at 7, 14, 28, and 90 days, giving a conclusion that the maximum percentage of fly ash used should be 10%, since if a higher dose is used, strength and other properties can be seriously compromised [37].

Fly ash as a replacement for aggregates

Fly ash as a replacement for fine aggregate

The use of fly ash as a substitute for fine aggregate (sand) in concrete mixing is an improved option for the shortage of fine aggregate in different parts of the world. For this reason, the impact generated by the substitution of this material is studied, where the strength-weight and cost-resistance ratio applied in the concrete mixture is evaluated using doses of 0%, 20%, 35%, and 50% FA as a replacement for fine aggregate in a period of time of 28 days. It is also taken into account that when using fly ash as a replacement for fine aggregate, its particles have to go through mesh No. 4, that is, the size of its particles must be less than 4.75 mm. It was observed that with this method, an improvement in mechanical properties and a significant reduction in costs were obtained. Another identified benefit of using FA as a replacement for fine aggregate in concrete mixtures is the decrease in shrinkage; to reach this conclusion, several studies were previously conducted with the substitution of FA in doses of 0,15,25,35 and 45%, indicating that there is a notable variation in the decrease in shrinkage by drying of concrete, with the most optimal dose being 25% [22, 38].

Fly ash as a replacement for coarse aggregate

Studies conducted in Taiwan recognize that the mixture of concrete with the replacement of coarse aggregate by FA increases mechanical strength and improves its properties, such as workability and durability, within 28 days, following the parameters specified in the respective standard, taking into account the specific weight, the average density and its granulometry where in order for the fly ash to replace the coarse aggregate its particles have to pass through mesh No. 1 1/2" to No. 3 1/2", i.e., the size of its particles must be between 37.5 mm to 90 mm [39].

3.7 Use of fly ash in various types of concrete

Thermal power plants use pulverized coal as fuel and generate large amounts of FA as a by-product. A clear example is India, which has around 125 thermal power plants; they produce approximately 120 million tons of FMD per year and are expected to produce 170 million tons by the end of 2021 [79]. One solution to mitigate this problem of elimination and ecological damage is through technological advances applied to construction, where concrete acquires modifications through the incorporation of additives, such as fly ash, in order to find the optimal replacement level of Class C and F FA [79].

Incorporation of fly ash in geopolymer concrete

The behavior of geopolymer concrete at elevated temperatures can be improved by using newly developed lightweight non-granulated aggregates made entirely of FA as a replacement for conventional natural aggregates [51]. Being applicable (14-15 cm), but with a relatively fast setting time (below 60 minutes), concluding that having a smaller nominal size in the coarse aggregate, it will have a better resistance in its different properties [52].

In recent decades, the search for an environmentally friendly concrete triggered the research and development of an ecological concrete called fly ash geopolymer (FA) concrete, where properties such as workability in the fresh state and compressive strength at 7 days are analyzed, finding that the FA ratio, with a temperature and curing time of 70°C and 48 hours, respectively, it produces higher compressive strength [53].

Since geopolymer concrete has the potential to completely replace concrete in different applications, such as precast units and green building technology, significant relevance is attributed to FA fineness and the proportion of alkaline solutions in the mechanical properties of FA-based geopolymer concrete [54], as it achieves greater concrete strength.

Incorporation of fly ash in self-compacting concrete

The objective of studying the effects on the properties of self-compacting fresh concrete (SCC) through the use of FA as a partial replacement of cement together with superplasticizers as an additive, is due to the problem of mega-production of CO2 as a by-product of cement manufacturing that generates intense environmental pollution and must be adequately controlled. It is found that replacing 30% of the cement content with FA is the most suitable mixture to produce concrete with high cement content: workability and flow capacity of SCC [55]. In a self-compacting concrete incorporating a high volume of FA, the sorptivity is expected to be different, as specified by the ASTM C1858 method; in addition, the influence of the high-volume FA content is determined according to the sorption capacity of the self-compacting concretes [56].

On the other hand, it is intended to significantly increase the constructive and technical properties of SCC, with a minimum content of binders, by developing theoretical and practical principles for the design of the dispersed particle size distribution of high-strength SCC [57] mixtures, in which several types of dispersed modifiers are used, including fly ash (FA) of thermal power plants. In addition to studying the impact of the FA mixture on the aeration structure and selected physical and mechanical properties of the SCC mixture [58]. This was achieved by replacing ordinary Portland cement with FA in several fractions (10% and 20%) and with various percentages (5%, 10%, 15%, 15%, 20% and 25%) by weight of cement as a filler material; obtaining that with the addition of FA in proportion to 15% replacement, the tensile strength and bending were improved. [59] This is why, in order to use fly ash as a replacement for cement in SCC, the influence of properties must be taken into account [60].

Incorporation of fly ash in high-volume concrete

Ultra-high performance (UHPC) concrete is a revolutionary technology concrete, which includes better properties than other types of concrete; however, due to a large amount of micro silica used, there is, as a consequence, a significant increase in cost compared to ordinary concrete. Thus, in places like Colombia, through previous studies, it was concluded that, despite the low quality of local fly ash, they could be used as a replacement for cement, taking into account the size of their particles no larger than 0.6 mm and using the optimal addition of 10% it is possible to reach compressive strength values of 150 MPa, without any prior heat treatment [61].

Incorporation of fly ash in recycled concrete

Recycled concrete is a material with the potential to create a sustainable construction industry. A solution for the control of the deformation of recycled concrete is proposed by adding FA, concluding, according to previous studies, that the replacement of 50% of FA increased the rupture modulus of recycled concrete [43]. The influence of FA in recycled concrete was determined from different tests that served as indicators [62].

Incorporation of fly ash in shotcrete

In New Australia, the key technology for the tunneling method is shotcrete. The right amount of FA for a shotcrete mixture can reduce crack generation and compensate for shrinkage, improving the capacity of shotcrete and reducing construction costs. For ordinary shotcrete, it is suggested that the optimal dose by weight of FA replacing cement is about 9% [64].

Incorporation of fly ash in light concrete

The analysis of radioactivity and thermal decay of FA is motivated by the high existence of environmental contamination by ash residues in thermal power plants used in the production of light concrete. This analysis focuses on comparing the radioactivity analysis of fly ash from a thermal power plant for compliance with international standards and requirements for use in lightweight concrete [65]. In this sense, some studies were carried out with the substitution of cement by FA, in proportions of 10%, 20%, and 30% by weight, with the objective of improving the quality of this type of concrete. The results indicated that the percentage with which the best results were obtained was 30%, with values of 12.68 and 15.4 Mpa for compressive and tensile strength, respectively [66]. In addition, it should not be forgotten that the particle size of FA and grinding time affect the strength of lightweight concrete, since the most recommended is the effect of FA after 5-10 minutes of mechanical grinding with light aggregate concrete ash [67].

Incorporation of high-strength fly ash

To design a high-strength concrete with a value greater than 90 Mpa and good workability, the variation of the percentage of mineral additives and the respective guidelines must be taken into account. Fly ash (FA) plays an important role in the long-term strength of concrete and reduces early strength gain. On the other hand, the addition of FA increases the workability of the mixture. It has been found that mixing mixed concrete produced satisfactory results with intermediate workability and higher strength compared to others [68].

Incorporation of fly ash in green concrete

It is known that the substitution of FA for more than 0.06 of the binder by weight reduces the compressive strength at an early stage, so it is only applicable in non-structural or semi-structural concretes, a solution is to reduce the water/binder ratio by adding at the same time superplasticizers to preserve workability. With the optimal percentage, even with 0.80 of the binder replaced by FA, the compressive strength of concrete can reach more than 40 Mpa after 7 days and more than 60 Mpa after 28 days [69]. To eradicate the damage caused by the burning of shells of agro-industrial products and emissions from coal-fired power plants, priority was given to investigating the efficiency of the replacement ratios of this type of ash in the fresh and hardened properties of concrete mixtures, showing that FA improves mechanical and physical properties compared to the standard mixture of ordinary cement [72].

Incorporation of fly ash in hydraulic concrete

There were 45,630 tons of waste generated as FMD for the ninth month of 2019 in the Tashkent region, Republic of Uzbekistan, and ash disposal of 2554 tons at the New-Angren thermal power plant [70]. These sample values show that per year, only 0.12-0.13 of FMD and slag waste is used by consumers for various purposes, as approximately the remaining 0.87-0.88 of waste accumulates in landfills and pollutes the environment. As an adequate solution to economic and environmental problems, the use of FA from the New-Angren thermal power plant as a microfill of a raw hydraulic concrete mixture is presented as a solution, indicating that the use of NATPP large-tonnage FA in concrete technology is a task that managed to solve the priorities of the further development of the economy and proved to be one of the strategic ways to solve the environmental problem, looking to implement this method in more countries with this type of problems [70].

Incorporation of fly ash in aerated concrete

Due to its insulation properties, aerated concrete is an alternative wall material that can be used in tropical buildings,. It also has good thermal conductivity and sound absorption coefficient compared to conventional concrete. The use of FA also influences its mechanical and insulation properties, resulting in cellular concrete with 20% FA having a density of about 2000 kg/m3 with a maximum compressive strength of 13.24 MPa. It was found that the thermal conductivity (k) of cellular concrete increased by 20% FA compared to the mixture without FA. Finally, it was found that the use of FA in cellular concrete has the ability to improve thermal conductivity and sound absorption [71].

4. Conclusions

Thanks to the corresponding systematic review, a better understanding of the use and influence of fly ash in concrete has been achieved, focusing on the design of a mixture with the replacement of fly ash to improve the mechanical properties of structural concrete, also increasing maximum strengths. Considering the standard mixture, the relevance of the impact of this type of cementitious mixture in the construction industry and taking as a reference the results and opinions of the research carried out by the different authors on the subject, the following conclusions have been reached:

It is recognized that using fly ash in concrete modifies mechanical, hydraulic, elastic, and thermal physical properties and even significant cost reduction. The physical and mechanical properties of concrete are important to this review because it is possible to observe favorable results. In addition, fly ash becomes a much more sustainable cementitious product than ordinary concrete; by reusing the FA thrown in landfills, it is possible to reduce the pollution generated by them.

The main indicators that will determine the optimization of fly ash as a material to be used in concrete are attributed to its reactivity and the percentage of loss of ignition, since, depending on the degree indicated by the corresponding tests, the substitution capacity of fly ash can be verified without compromising mechanical properties such as compressive strength.

Two types of fly ash are distinguished as those of class C and F, which are suitable for use in concrete; each of them differs by the content of calcium aluminosilicates, with class C, with a much higher index than class F; This characteristic, according to empirical studies, was determined thanks to the setting time and the corresponding reactivity index.

There are different types of fly ash, the most used being microspheres, ultrafine, nano ashes, and large-volume ashes; the size of their particles ranges between 0.2 and 200 microns in diameter. Each of them is distinguished by improving various properties of concrete, such as microspheres achieving better aeration performance, while ultrafine ash in partial replacement of cement manages to improve workability and compressive strength by up to 15%; on the other hand, nano ashes significantly reduce porosity and, Finally, large volume ash reduces the proportion of voids and provides greater durability and better fluidity in the concrete.

The use of fly ash in concrete as a partial replacement of cement or fine or coarse aggregate in doses of 10% to 50% can modify the properties of the concrete in a period of 7, 28, and 56 days, concluding that the optimum percentage is 10%, achieving an improvement in compressive strength and complying with the provisions of ASTM C-618. Resistances of the standard sample and the experimental sample are compared, obtaining results for a specific standard of 275 kg / cm2, at 62,478 MPa and with FA replacement of 276.77 kg / cm2 to 66,756 managing to identify an improvement of approximately 1%.

Finally, it is concluded that taking into account the environmental aspects, the use of fly ash in concrete is highly beneficial, useful and recommended, because they have a positive effect on the environment, since its purpose is to reduce the damage caused by the release of carbon dioxide produced by the main sources of raw materials used in construction. From the review, it can be affirmed that with the correct reuse of this type of ash, it is possible to obtain eco-friendly and sustainable concrete with better physical and mechanical properties. It is recommended that future studies evaluate a cost-benefit analysis to validate if it is economically favorable.

5. Declaration of competing interest

We declare that we have no significant competitive interests, including financial or non-financial, professional or personal interests, that interfere with the complete and objective presentation of the work described in this manuscript.

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7. Author contributions

In the present work, the author J. Lozano, contributed to the original idea, responsible for the development of the article contributing by 30

8. Data availability statement

For this research, data were collected electronically through the different databases, taking into account a time of no more than 7 years, with the closing date of the search being June 10, 2021.

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