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Review

A Review on the Effect of Mechanical Properties and Durability of Concrete with Construction and Demolition Waste (CDW) and Fly Ash in the Production of New Cement Concrete

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Abstract: The search for new alternative materials for employment in the construction industry is necessary for more sustainable development. The construction demolition waste (CDW), as well as by-products generated by initiatives, such as slag, fly ash (FA), palm oil fuel ash (POFA), metakaolin (MK), silica fume (SF), and rice husk ash (RHA), are objects of studies in several segments of the civil construction sector. The addition of these wastes to the materials currently used to produce concrete and mortar can be one of the significant efforts to achieve more sustainable construction. The use of these wastes in the construction sector can bring considerable benefits in terms of costs, energy efficiency, and environmental and ecological benefits. Over the years, many types of research have been developed aiming at the possibility of a practical use of CDW as an aggregate and industrial by-product (FA, POFA, MK, SF, RHA) as pozzolans. Based on recent studies, this paper reviews the current state of knowledge about the production of concrete with partial replacement of natural aggregates by recycled aggregates from CDW and the use of fly ash (FA) as pozzolan in partial replacement with Portland cement. This work discussed the following concrete properties: compressive strength, water absorption, chloride penetration, carbonation, and modulus of elasticity.

Keywords: concrete; construction and demolition waste; fly ash; mechanical properties; carbonation

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1. Introduction

The increased rate of industrialization and urbanization due to economic and population growth has made the construction industry one of the segments that most consumes natural resources and generates solid waste that negatively impacts the environment. According to Mehta and Monteiro [1], during the most recent 100 years, the total populace has developed from 1.5 to 6 billion people, with almost 3 billion living around cities. It is estimated that the global world population will reach around 10 billion by 2060, which can be attributed to the technological, medical, and logistical advances that have improved living and health standards since the Industrial Revolution [2,3].

Concrete employed in the construction of cities plays a crucial role in socio-economic development. Still, it also has a rather significant adverse effect on the environment and the depletion of natural resources. Over the years, infrastructures have been basically built with concrete, steel, and wood, as well as glass, which are considered the primary materials used in contemporary construction [4]. However, in volume, the most significant manufactured product in the world today is concrete [1], and it is also considered to be the second most consumed material on Earth after water [4].

The construction industry is responsible for significant environmental impacts due to the extraction of raw materials and a considerable portion of the waste generation that negatively influences the environment [5,6]. It is also responsible for generating large amounts of carbon dioxide (CO_2) generated by the cement industries and by the burning of fossil fuels used in the equipment employed in the extraction and processing of raw materials.

The extraction of raw materials, the processing of materials for civil construction, the construction of buildings, as well as renovations and demolitions, generate solid waste that, when disposed of improperly, can cause various problems, such as the proliferation of disease-carrying agents, the degradation of springs and permanent protection areas, the obstruction of drainage systems, silting up of rivers and streams, and the occupation of roads that degrade the urban landscape [6]. Aiming to use natural resources in a more sustainable way, several researchers have been seeking alternative uses for the solid waste from construction and demolition as a by-product for reuse in the construction industry as brick waste [7,8], ceramic [9,10], glass [11,12], from rubber [13,14], from concrete [15,16], and mixed waste [17,18].

Studies verifying the feasibility of using construction and demolition waste (CDW) as a partial replacement for natural aggregate for concrete production have presented relevant results. The different compositions of CDW directly influence the mechanical properties and durability of concrete [19]. Limbachiya, Meddah, and Ouchagour [20], Lotfy and Al-Fayez [21], and Poon, Kou, and Lam [22] observed that the replacement of coarse aggregate with recycled coarse aggregate at levels lower than 30% does not have a significant adverse effect on concrete performance when compared to natural concrete. According to the authors, CDW, as a more porous aggregate, has a high-water absorption capacity. This water adhered to the recycled aggregate can be used as an internal curing agent, especially for concretes with fly ash that requires longer wet curing for the pozzolanic reaction.

However, the significant variability of existing waste, with different compositions, and physical and mechanical properties, can present negative results due to increased porosity, roughness, and water absorption, which leads to higher a/c ratios, making the cement paste weaker and more porous [19,23–25]. Other studies evaluate the mechanical bonding in the Interfacial Transition Zone between the mortar and the substrate [19,26], which ultimately decreases the compressive strength of the material [10], which limits the use of recycled aggregate with a percentage higher than 30% in structural concrete [27].

The construction sector is also responsible for the generation and release into the atmosphere of large amounts of carbon dioxide (CO_2). Asia alone produces more than 80% of cement in the world and, as a consequence, releases approximately 80% of the CO_2 generated by Portland cement production [4]. According to Meyer [28] and Aprianti [29], the reduction of Portland cement production would be one of the alternatives to reduce the environmental impact. Another way would be the use of by-products generated by industrial processes, agricultural waste, and recycled materials. Among the various types of products that can be used, there is fly ash, which is a by-product generated by thermoelectric plants powered by mineral coal. According to Acar and Atalay [30], many thermoelectric plants were built in the world in a period of 80 years due to the growing demand for electricity generation. It is estimated that the annual global production of fly ash varies between 0.75 and 1 billion tons. Other works have already been performed, employing the fly ash and recycled aggregate in concretes simultaneously [5,17,31–37].

Limbachiya, Meddah, and Ouchagour [20] and Lima et al. [31], observed that the use of fly ash as a partial replacement for Portland cement in the production of concrete improves its durability as well as contributes to the reduction of CO_2 emissions. For a deeper understanding of the influence of fly ash in concrete, Payá et al. [38], Sakai et al. [39], Moon et al. [40], and Shaikh [33] investigated the role of this by-product in cement hydration, as well as the pozzolanic reaction process.

Dabhade, Chaudari, and Gajbhaye [5] verified a slight increase in axial compressive strength in concretes with recycled aggregate and with 10% of fly ash compared to concrete with recycled aggregate only. Lima et al. [31] concluded that the addition of fly ash in concretes with recycled aggregate, in general, improves workability as well as mechanical and durability properties, reducing the harmful effects of recycled aggregate.

The scope of this investigation was to gather and analyze the published information about the effects on the mechanical properties and durability of concretes with construction and demolition waste (CDW) and fly ash (fly ash). Based on this study, it was sought to identify the most suitable composition of concrete mixtures with construction and demolition waste and fly ash to reach a consensus on the most appropriate contents of these wastes to achieve results of mechanical properties and durability closer to the reference concretes. To seek a deeper understanding of the effect of fly ash in concretes with a recycled aggregate, a microstructural analysis was performed in the transition zone of the interface between the aggregate and the paste.

2. Importance of the Study

Considering the search for a solution for the appropriate disposal of waste generated by the construction industry segment, many studies have been developed with the objective of reusing this waste as by-products in order to reduce the consumption of natural resources and, consequently, reduce the negative impacts that this waste can cause to the environment.

In concrete, Portland cement is responsible for 74–81% of total CO_2 emissions, while coarse aggregate is responsible for 13–20% of CO_2 emissions. Fine aggregates generate less equivalent CO_2 as they are not crushed. The mixing of the conventional concrete process with Portland cement ranged only between 0.29 and 0.32 t CO_2-e/m^3. It was found that the addition of fly ash is able to reduce between 13 and 15% of CO_2 emissions in concrete mixes [41]. Large amounts of waste from construction and demolition are generated every day by the construction industry, which, inappropriately deposited, can bring great harm to biodiversity. The use of these recycled aggregates in partial replacement of natural aggregates can be essential for the concrete eco-efficiency, as well as producing significant economic advantages [42].

There are already many studies focusing on the reuse of waste from construction and demolition (CDW), as well as waste generated by cement industries, such as fly ash (FA), for the production of mortar and concrete. However, there are few studies employing combined wastes, such as CDW and FA for new concrete production.

Analysis of publications focusing on the production of concrete with a combined use of CDW and FA was performed, initially in English, between January 2007 and December 2021. The databases investigated were ANTE (Abstract in New Technologies and Engineering), ASTM International, Aluminium Industry Abstract, and ACS Journals Search. The keywords used for the search were "concrete" + "fly ash" + "construction and demolition waste" or "concrete" + "fly ash" + "waste concrete aggregate" or "concrete" + "fly ash" + "recycled aggregate". A total of 259 published articles were found, and their distribution by year is shown in Figure 1.

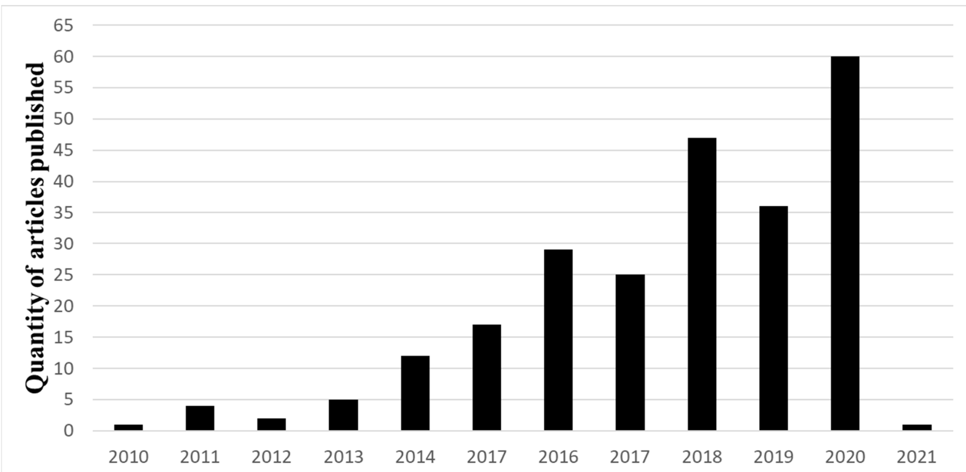

Figure 1. Number of articles published on the use of construction and demolition waste (CDW) with fly ash in concrete production.

Considering the different types of waste generated in the construction and demolition process, as well as the significant variability of these wastes, it is imperative that studies be conducted for a better understanding of the behavior of concretes with combined wastes. In this regard, this literature review is essential to have a more profound knowledge of the use of these wastes in the production of new cement concretes.

The main objective of this work is to establish an innovative concept in order to minimize the effects caused to the environment, which are: reduction of CO_2 emissions caused by cement industries and reduction of natural aggregates extraction from the environment.

3. Factors That Influence the Properties of Concrete with Recycled Aggregate and Fly Ash

3.1. Properties of Construction and Demolition Waste That Influence New Concretes

According to Meddah [4], recycled concrete aggregate is the most abundant waste due to the availability of its origin, which comes from the continuous demolition of old buildings and sidewalks. According to Morales-Martíns et al. [43], recycled concrete coarse aggregates that are composed of original aggregate and adhered mortar contain impurities, such as clay bricks and crushed ceramic materials, and gypsum, which contribute to the existence of contaminants. These adhered products negatively influence the physical and mechanical properties of concrete produced with the recycled coarse aggregate [44,45]. Many studies have announced the contrasts between the characteristics of recycled concrete aggregates compared to natural aggregates [46–49], since the physicochemical and mechanical properties of recycled aggregates influence the properties of concrete [50,51], which are presented in the following.

3.1.1. Bulk Density and Water Absorption

Verian et al. [52] observed in their studies that there is a correlation between the water absorption of coarse aggregates and their density because the higher the absorption, the lower the density. The results observed by the authors Verian et al. [52] for recycled coarse aggregates were 14.50%, 12.50%, 12.44%, and 12.10% for water absorption, while for the bulk density, it was 2.05 kg/dm^3, 2.18 kg/dm^3, 2.21 kg/dm^3 and 2.28 kg/dm^3, respectively. For natural coarse aggregates, the water absorption was 2.30%, 1.98%, and 1.70%, while the bulk density was 2.69 kg/dm^3, 2.74 kg/dm^3, and 2.78 kg/dm^3, respectively. The same behavior was verified in recycled and natural sands. In natural sand, the absorption was approximately 3.0% and 2.11%, while the specific mass was approximately 2.63 kg/dm^3 and 2.68 kg/dm^3. Agrela et al. [53] observed the correlation between the concrete content and the dry density of the saturated surface. The results obtained by the authors were: concrete with absorption of 2.48%, 5.1%, 7.49%, 10.2%, and 12.5% have a saturated surface dry density of 2.59 kg/dm^3, 2.35 kg/dm^3, 2.15 kg/dm^3, and 2.08 kg/dm^3, respectively.

Kisku et al. [51] also observed, based on their studies, that the presence of the old mortar contained in the recycled aggregate increases the absorption capacity and decreases the specific mass of recycled aggregates compared to natural aggregates. According to da Silva and Andrade [17], the evaluation of water absorption is an essential point that should be considered because the durability performance of concrete is a property of the pervasion qualities of materials, considering the trustworthiness of concrete against aggressive agents.

There are many studies that use different types of waste as aggregate for the production of concretes whose water absorption and bulk density are quite varied. Table 1 presents some comparisons of bulk density and water absorption.

Table 1. Bulk density and water absorption of different types of construction and demolition waste.

Recycled Aggregate	Bulk Density (kg/m^3)	Water Absorption (%)	Authors
Brick	974–2548	5.96–8.6	Sharba et al. [54], Zachariah et al. [55], Dang et al. [56]

Table 1. *Cont.*

Recycled Aggregate	Bulk Density (kg/m^3)	Water Absorption (%)	Authors
RCA [1]	2265–2560	4.0–6.92	Yang et al. [57], Jian and Wu [58], Sahoo and Singh [59]
MRA [2]	1250–2340	5.0–8.79	Martínez et al. [60], Cantero et al. [61], Silva et al. [17], Robalo et al. [42]
Rubber	539–1050	0.9–1.7	Kasmi et al. [62], Yang et al. [57], Feng et al. [63]
Glass	800–880	0.002–0.4	Omoding et al. [64], Balan et al. [65], Yang et al. [66]

[1] RCA—recycled aggregate concrete, [2] MRA—mixed recycled aggregate.

The glass waste had the lowest percentages of water absorption, which ranged between 0.002 and 0.04% when compared to bricks, rubber, and glass. These percentages were also observed in the studies of Penacho, Brito, and Veigas [67]. However, the recycled concrete and mixed aggregates absorbed the most water, ranging from 4.0 to 8.79%. Cantero et al. [61] observed in their studies that the percentages of absorption of these materials varied between 4.49 and 10%. The bricks presented the most significant variation in bulk density (974 to 2548 kg/m^3), and this is due to the characteristics of the clays as well as the preparation and burning temperature. The rubbers also present bulk density varying between 539 and 1050 kg/m^3. Agrela et al. [53] recommend a classification into three groups for recycled aggregates from construction and demolition, based on the following proportions:

1. Recycled concrete aggregate for mixtures containing less than 10% ceramic and more than 90% concrete;
2. Mixed recycled aggregate for mixtures containing less than 30% ceramic and between 70 and 90% concrete;
3. Ceramic recycled aggregate for mixtures containing more than 30% ceramic and less than 70% concrete.

Based on their studies, the authors concluded that recycled aggregate with many ceramic particles causes an increase in water absorption and a decrease in the density of recycled aggregate. However, Robalo et al. [42] suggest the classification of recycled aggregates by their dry density, resulting in four classes:

(a) Class A—dry density between 2400 and 2600 kg/m^3;
(b) Class B—dry density between 2100 and 2300 kg/m^3;
(c) Class C—dry density between 1800 and 2000 kg/m^3;
(d) Class D—dry density lower than 1800 kg/m^3.

The classification was generated from a relative decrease in compressive strength of concrete with recycled aggregate obtained through the study of Robalo et al. [42], and some researchers. According to Robalo et al. [42], this classification allows for the estimation of the minimum compressive strength of the concretes based on the substitution content of recycled aggregate.

All wastes present variations in bulk density and water absorption. This variation is closely linked to the feasibility of the compositions of materials contained in the waste (RCA, RMA), the type and combination of materials for production (glass, rubber), as well as the selection, handling, and firing processes of ceramic materials.

3.1.2. Interfacial Transition Zones (ITZ)

Recycled aggregate is formed of two Interfacial Transition Zones (ITZ), one between the natural aggregate and the old cement matrix and the other between the old cement matrix and the new cement matrix [68–70]. A schematic diagram of the Interfacial Transition Zones (ITZ) in recycled concrete aggregate is presented in Figure 2.

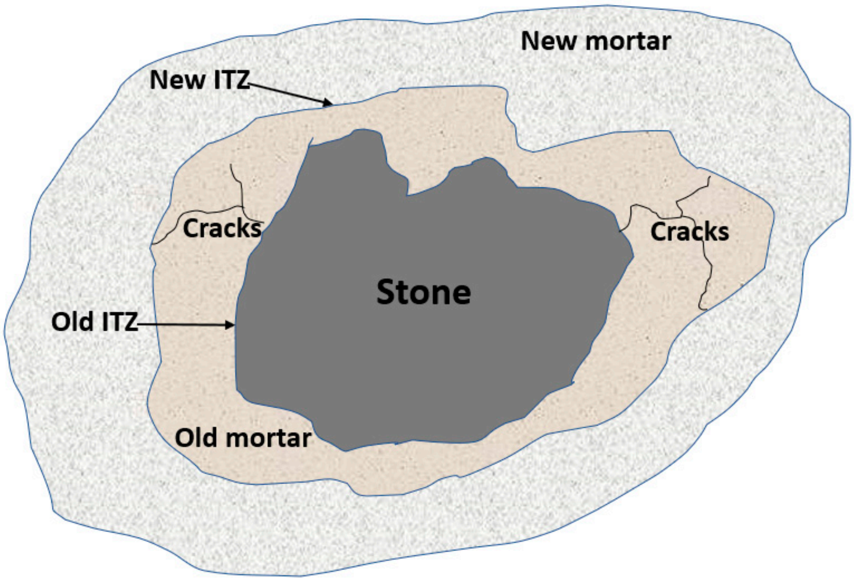

Figure 2. Schematic diagram of the old and new ITZ.

The old ITZ makes the microstructure of the concrete more brittle due to higher porosity and cracking; thus acting as the weakest link [49]. The method of crushing the source concrete has been observed in order to reduce the density of cracking in the old Interfacial Transition Zone (ITZ) [49]. According to Xiao et al. [69], the thickness of the old and new ITZ are in the same order of magnitude, with the new ITZ being thicker. It has been found that the increased ratio of mechanical properties, with respect to the modulus of elasticity and strength, of the old ITZ to the cement matrix, results in higher strength but lower ductility [71]. Zhao et al. [26] and Zhang et al. [72] suggest a third ITZ in the recycled aggregate.

The first ITZ is between the new aggregate and the new mortar, the second ITZ is located between the old mortar and the new mortar, and the third ITZ is between the old mortar and the new aggregate. According to the authors, the third ITZ presents stability in its mechanical properties; however, the addition of recycled aggregate in partial replacement of natural aggregate in concrete, Zhao observed in his studies, not only decreases the mechanical properties, such as mechanical strength and modulus of elasticity, but also decreases its durability, including chloride resistance. According to Zhang [72], the ITZ is characterized by its high porosity, high water permeability, and high diffusion coefficient. Consequently, the ITZ allows the ingress of harmful substances from the external environment, and the reaction between SO_4^{2-} and C-S-H tends to form first in the transition zone between the paste and the substrate, providing an earlier expansion in this zone than in other phases of the material. This expansion over time may be the key to understanding the macroscopic deterioration of concrete under external sulfate attack.

One of the methods employed to improve the microstructure of recycled concrete aggregate is the coating of aggregates with pozzolanic materials [73], and the Pozzolanic material that will be discussed next is fly ash.

3.1.3. Effect of the Recycled Aggregate Size on Strength and Elastic Modulus Properties

Kang and Weibin [74] developed a study to assess the impact of the recycled aggregate diameter on the mechanical properties of concrete (compressive strength and modulus of elasticity). The authors use three different diameters (5–15 mm, 15–20 mm, and 20–30 mm) of recycled aggregate. In this study, two types of recycled aggregate were used, one being crushed in the laboratory and the second crushed in a large crushing plant. It was observed that the larger the diameter of recycled aggregates, the greater the compressive strength. According to the authors, strength gain is related to the lower mortar content adhered to larger diameter aggregates when compared to smaller diameter aggregates. It was observed that the control concrete elastic modulus was higher than the concrete elastic modulus with a recycled aggregate. However, the authors noted that concretes' modulus of elasticity with different diameters of recycled aggregate is closely linked to a variation in compressive strength performance. Musa and Saim [75] analyzed the compressive strength of concrete with natural coarse aggregate of different sizes (10 mm and 20 mm). The same behavior was observed by the authors, that the larger the particle size, the greater the compressive strength.

3.2. Fly Ash

The size and shape of the fly ash particles have a relevant effect on the binder properties (cement-waste ash). The pozzolanic reactivity is directly related to the fineness of the fly ash because the more significant the surface area, the higher the Pozzolanic Index [76,77]. Studies show that the smaller the fly ash particles, the higher the mechanical strength [77,78]. Furthermore, according to Blissett and Rowson [79], the chemical composition of fly ash has traditionally been the basis for evaluating its suitability for use as a cement replacement material. Another inherent factor in the properties of fly ash is, besides the physical and chemical characteristics, the crystalline structure in the hydration process [80].

There is a classification established by Ramachandran [81] for fly ash based on the amount of CaO. Fly ash with CaO contents below 10% is classified as pozzolanic material. Fly ash that has contents equal to or greater than 10% is classified as cementing materials. According to the author, fly ash consists predominantly of silicon oxide (SiO_2), calcium oxide (CaO), in addition to aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3). The amount of SiO_2 and CaO in the system influences the composition of the hydrate, as the greater the amount of SiO_2, the smaller CaO/SiO_2 ratio of the hydrates, that is, the lower the alkali–silica reaction due to the lower alkalinity of the pore solution [82]. According to Garzia et al. [83], an alkali–aggregate reaction, more precisely an alkali–silica reaction, can cause damage, such as the appearance of micro-cracks in concrete as well as loss of mechanical integrity properties and durability, which may even compromise the functionality of a structural part.

According to Mehta [84], the pozzolanic fly ash reaction compared to Portland cement is slower. Fly ash Oxides, when reacting with water and $Ca(OH)_2$, result in a layer of C-S-H around the particle, making it difficult to access the innermost oxides. As a result, the hydration pozzolanic reaction forms more slowly; thus slowing down the resistance development. Concretes with fly ash addition, in partial replacement to Portland cement, may have lower mechanical strength compared to conventional ones at younger ages. However, the fly ash addition in partial replacement to Portland cement tends to reduce the effect of the alkali–aggregate reaction, which occurs between cement alkalis and reactive aggregates in the presence of moisture.

3.2.1. Effect of Fly Ash on the Compression, Tensile and Flexural in Concretes

When fly ash, cement, and water are mixed, silica (SiO_2) and alumina (Al_2O_3) progressively react with calcium hydroxide ($Ca(OH)_2$), which is formed by the cement hydration process; thus producing the calcium silicate hydrate, known as secondary C-S-H. This reaction reduces the calcium hydroxide content and consequently reduces the concrete compressive strength. However, the cement hydration process allows the SiO_2 and Al_2O_3 reaction from the fly ash. The fly ash pozzolanic reaction depends on the $CaOH_2$ concentration, so it can be stated that the higher the $Ca(OH)_2$ concentration, the higher the pozzolanic reaction rate [85]. The production of secondary C-S-H at older ages will depend on the $Ca(OH)_2$ concentration, as the higher the concentration, the longer the pozzolanic reaction time [86]. The flexural strength exhibits similar behavior to the compressive strength. Tensile strength, on the other hand, depends on the shear zone of the interfaces between the paste and the substrate, which, in turn, improves with curing time. This improvement is closely linked to the fly ash pozzolanic reaction [85].

3.2.2. Bulk Density and Water Absorption

The Brazilian Standard NBR 12653/2014 classifies fly ash as class "C", which is produced by burning mineral coal in thermoelectric power plants. However, the international standard ASTM C618:2012 classifies fly ash in "C" and "F". Class "F" is produced by burning anthracite or bituminous coal and presents the exact limits of chemical compounds as the Brazilian standard (Table 2). Class "C" is produced by burning lignite or sub-bituminous coal that contains a combination of chemicals (SiO_2 + Al_2O_3 + Fe_2O_3) between 50% and 70%.

Table 2. Chemical characteristics required by ABNT NBR 12653: 2014 class "C" and by international standard ASTM C618:2012 class "F".

Properties (%)	ABNT NBR 12653:2014	ASTM C 618:2012	
		Class C	Class F
SiO_2 + Al_2O_3 + Fe_2O_3	≥70.0	≥50.0	≥70.0
SO_3	≤5.0	≤5.0	≤5.0
Humidity (%)	≤3.0	≤3.0	≤3.0
Loss to fire	≤10.0	≤10.0	≤10.0
Alkalis available in Na_2O	≤1.5	≤1.5	≤1.5
Retained in the sieve 45 µm	≤20%	≤34%	≤34%

Studies show that there is a significant variation in the number of oxides within the same class of fly ash. This variation is associated with its origin (characteristic of the coal) as well as the different forms of the process (calcination). Table 3 presents the variations of the oxides present in fly ash according to the literature.

Table 3. Range of oxides present in fly ash, as presented in the literature.

Oxides	Class C (%)	Class F (%)	Authors
CaO	16.28–29.21	0.87–13.52	[25,76,87–94]
SiO_2	27.05–37.67	49.2–70.70	[25,76,87–94]
Al_2O_3	13.44–21.07	16.36–33.7	[25,76,87–94]
Fe_2O_3	4.42–6.58	2.87–14.72	[25,76,87–94]
MgO	1.48–6.22	0.08–4.57	[25,76,87–94]
K_2O	0.35–1.25	0.58–2.16	[25,76,88,89,91–94]
Na_2O	0.33–1.91	0.0–2.82	[25,76,88,91–94]
Na_2Oeq	0.50–1.43	1.16–4.24	[76,87–89,93,94]
SO_3	1.43–7.65	0.25–1.47	[25,76,87–89,91–94]
LOI	0.12–15.73	0.49–4.01	[25,76,87–90,92,94]

Based on the Texas Department of Transportation database, the oxide content variations of approximately 5500 fly ash samples from 36 plants in and outside Texas were analyzed, and authors Du and Lukefahr [95] observed that the oxide contents of ASTM class F fly ash were more variable than those of class C fly ash. The authors observed that the main differences between class C and class F fly ash are CaO and SiO_2, and class C fly ash has high CaO content, being mainly compounded with more than 25%. The CaO concentration in class C fly ash is higher than in class F fly ash, which was also observed by Oey et al. [96]. Already, according to the authors, Al_2O_3 and Fe_2O_3 showed very close results. According to Aboustait et al. [97], most of the particles of Class C fly ash have the highest contents of CaO + MgO + Na_2O + K_2O than those of Class F fly ash. On the other hand, most of the particles of Class F fly ash have higher contents of SiO_2 + Al_2O_3, which is mainly due to the higher SiO_2 content in the particles of Class F fly ash.

Oey et al. [96] performed an alkali–silica reaction durability index analysis to verify the performance of fly ash in concretes, SiO_2, Fe_2O_3, Al_2O_3, CaO, and equivalent alkali contents were used for calculation purposes. The alkali–silica reaction is an internal reaction between alkalis, such as Na^+ and K^+, and hydroxyl ions (OH-) of the cementitious material and reactive silica in some aggregates, and the product of the reaction is an alkaline silica gel that has a high capacity to absorb water molecules from pore solution as well as from external sources [98]. The durability index of class C fly ash showed an average of 24.6, while that of class F fly ash was 51.3 [95]. According to Du, Lukefahr, and Naranjo [95], the use of fly ash in concrete can be more viable and productive if its durability index is considered.

According to Wright, Shafaatiann, and Rajabipour [93], for a reduction of the alkali–silica reaction expansion to occur, for class C fly ash with 27.3% CaO, it was necessary to replace 31% Portland cement, while for class F fly ash with 13.5% CaO, 18% replacement content was required. The reduction of the alkali–silica reaction occurs due to the decrease in alkalinity ([OH-]) of the pore solution, significantly decreasing the ionic diffusion coefficient of mortars, which is due, in part, to the reduction of porosity when Portland cement is replaced by fly ash of a lower density, and, in part, due to the pozzolanic reaction promoted by the high temperature and alkalinity of the system [94].

3.2.3. Physical and Mineralogical Properties of Fly Ash

According to the Brazilian Standard NBR 12653/2014 and the international standard ASTM C618:2012, the physical properties should be in accordance with the requirements established according to Table 4.

Table 4. Physical requirements for fly ash established in Brazilian (NBR 12653/2014) and international standards (ASTM C618:2012).

Properties (%)	ABNT NBR 12653:2014	ASTM C 618:2012	
		Class C	Class F
Retained in the sieve 45 μm (% max.)	34	34	34
Pozzolanic activity Index at 28 days (% min.)	75	75	75
Required water (% max.)	110	105	105

A high amount of coarse particles (Ø > 1 μm) causes an irregular distribution of the material and leads to high macroporosity [99]. However, finer particles tend to reduce water absorption due to the refinement of the capillary pores of the concretes [17].

Due to the employment of more advanced characterization techniques, such as scanning electron microscopy (SEM) imaging as well as energy-dispersive X-ray spectroscopy (EDS), it is possible to identify the morphology and the chemical hydration products formed. These techniques are widely employed for performing visual analysis to observe numbers and ranges of chemical compositions [17,92,99,100]. Through these applied techniques, it was observed that the fly ash used in the study of da Silva and Andrade [17] presented spherical and flat shapes while the Portland cement presented irregular and rough shapes.

For higher levels of fly ash incorporation, the workability of concrete increases due to the spherical and smooth shape of the particles that influence the rheological properties of the cement paste, causing a reduction in the water requirement [101]. By scanning electron microscopy (SEM), Tosun-Celikoglu et al. [92] noted that the particle size of class F fly ash is finer than that of class C fly ash particles.

The automated scanning electron microscopy (ASEM) technique employed by Aboustait et al. [97], allowed us to verify that the fly ash particles larger than 5.0 μm were more spherical than the smaller particles, and the particles with sizes between 0.1 and 1.0 μm were the least spherical. The authors also noted that class C fly ash seems to show a wider range of size distribution than those of class F. Furthermore, the pozzolanic reactivity is directly proportional to the fineness of the fly ash, as the finer the fly ash, the higher the Pozzolanic Index [76,102]. Tkaczewska [102] observe in his study that the finer fly ash (0–16 μm) increases the degree of depolymerization of SiO_4, which is responsible for the increase of pozzolanic reactivity.

The X-ray diffraction (XRD) technique is fundamental for knowing the crystalline structure and microstructure of a material to understand its properties. Silva and Andrade [30] used XRD on a fly ash particle for sample analysis. The authors observed a high concentration of quartz, calcite, and muscovite/illite as crystalline phases and amorphous phase content throughout the fly ash particles. Ma, Hu, and Ye [103] also used XRD in their studies, where they observed that the main crystalline phases of fly ash were quartz (SiO_2) and mullite ($3Al_2O_3$, $2SiO_2$).

Durdzinski et al. [104] observed that the fly ash in studies was made of glassy material of amorphous nature, and because of that, the constituent materials largely include chemical reactions. According to the authors, fly ash with elevated amorphous substance is more viable in increasing the pozzolanic reaction.

4. Influence of Fly Ash Replacement in Concretes with Construction and Demolition Waste (CDW) in Concrete Properties

Feasibility studies of the use of construction and demolition waste (CDW) as a substitute for natural aggregate for the production of concrete in small quantities show promising results. However, the significant variability of existing waste, with different compositions, and physical and mechanical properties, can present adverse effects due to increased porosity, roughness, and water absorption that leads to higher w/c ratios, making the cement paste weaker and more porous [19,23–25]. To minimize the adverse effects regarding the significant variability of CDW, many studies have been adding fly ash as a partial replacement for Portland cement and will be presented as follows.

4.1. A General Overview

Many studies have investigated the influence of the use of fly ash and CDW on the physical–mechanical properties of concretes, showing that the results improve the mechanical properties and durability in ages longer than 28 days, as presented in Table 5.

Table 5. Some recent studies on the mechanical and durability properties of concrete with fly ash.

Properties	RCD Types	Replacements	Authors
Compressive strength	RCA [1]	(RA [4], 0% 50% 100%) (FA [5], 0% 30% 60%)	Kurad et al. [37]
	MRA [2]	(RA [4], 0% 25% 50% 75% 100%) (FA [5], 0% 15% 20% 25% 30%)	da Silva and Andrade [17]
	RCA [1]	(RA [4], 0% 100%) (FA [5], 0% 20% 30%)	Sunayana and Barai [34]
	RCA [1]	(RA [4], 0% 25% 50%) (FA [5], 0% 10%)	Shaikh [33]
	RCA [1]	(RA [4], 0% 50% 100%) (FA [5], 0% 25% 35% 55%)	Kou and Poon [32]
	RMA [3]	(RA [4], 0% 30% 40% 50%) (FA [5], 0% 15%)	Zong, Fei, and Zhang [7]
Tensile strength	MRA [2]	(RA [4], 0% 25% 50% 75% 100%) (FA [5], 0% 15% 20% 25% 30%)	da Silva and Andrade [17]
	RCA [1]	(RA [4], 0% 25% 50%) (FA [5], 0% 10%)	Shaikh [33]
	RCA [1]	(RA [4], 0% 50% 100%) (FA [5], 0% 25% 35% 55%)	Kou and Poon [32]
	RCA [1]	(RA [4], 0% 100%) (FA [5], 0% 20% 30%)	Sunayana and Barai [34]

Table 5. *Cont.*

Properties	RCD Types	Replacements	Authors
Modulus of elasticity	RCA [1]	(FA [4], 0% 100%) (FA [5], 0% 20% 30%)	Sunayana and Barai [34]
	RCA [1]	(RA [4], 0% 50% 100%) (FA [5], 0% 25% 35% 55%)	Kou and Poon [32]
Carbonation coefficient (k)	RCA [1]	(RA [4], 0% 50% 100%) (FA [5], 0% 25% 35% 55%)	Kou and Poon [32]
	RCA [1]	(RA [4], 0% 20% 40% 60% 80%) (FA [5], 0% 10% 20% 30%)	Geng and Sun [35]
	MRA [2]	(RA [4], 0% 25% 50% 75% 100%) (FA [5], 0% 15% 20% 25% 30%)	da Silva and Andrade [17]
Sulfate resistance	RMA [3]	(RA [4], 0% 30% 40% 50%) (FA [5], 0% 15%)	Zong, Fei, and Zhang [7]
Permeability to chloride ions	RCA [2]	(RA [4], 0% 25% 50%) (FA [5], 0% 10%)	Shaikh [33]
	RCA [2]	(RA [4], 0% 30% 60% 100%) (FA [5], 0% 15% 30%)	Sim and Park [36]
Water absorption	MRA [3]	(RA [4], 0% 25% 50% 75% 100%) (FA [5], 0% 15% 20% 25% 30%)	da Silva and Andrade [17]
	RCA [1]	(RA [4], 0% 25% 50%) (FA [5], 0% 10%)	Shaikh [33]
	RMA [3]	(RA [4], 0% 30% 40% 50%) (FA [5], 0% 15%)	Zong, Fei, and Zhang [7]

[1] RCA = recycled concrete aggregate; [2] MRA = mixed recycled aggregate; [3] RMA = recycled masonry aggregate [4] RA = recycled aggregate; [5] FA = fly ash.

In general, the addition of fly ash in partial replacement of Portland cement presents a positive influence with respect to mechanical strength and durability in concretes with recycled aggregate from construction and demolition when compared to concretes with recycled aggregate and without fly ash at higher ages of healing. Kamal et al. [105] analyzed sample data where more than a thousand pieces of information was extracted from the literature, and through the nonlinear model, the effect of fly ash on the resistance properties of concrete was investigated. The study involved high cement replacement content by fly ash (up to 70%), different water/binder ratios, and a 90-day curing period. The authors observed, through mathematical models, that there is a good correlation between compressive strength and the water/cement ratio in cured concrete up to 90 days without fly ash, but no correlation was verified between compressive strength and water/binder ratio in concrete with cured fly ash up to 90 days. A good correlation was also verified between compressive strength and tensile and bending strength. According to the authors, compressive strength can be calculated through mathematical models constructed through the suggested methodology.

According to Limbachiya, Meddah, and Ouchgour [20], whenever recycled aggregate (RA) is added to concrete with 30% fly ash in partial replacement to natural aggregate, regardless of the content to be replaced, the tendency of durability and mechanical strength is to decrease, and shrink drying is increased.

According to Limbachiya, Meddah, and Ouchagour [20], as the content of substitution of natural coarse aggregate by recycled concrete aggregate increases (ARC), the strengths (compression and traction), and the modulus of elasticity decrease. On the other hand, shrinkage by drying increases. It is a consensus among all authors that the use of recycled aggregate in concrete decreases the mechanical properties and durability, but with replacement levels below 30% of natural aggregate by the recycled aggregate, the adverse effects are not so significant. The addition of fly ash in small proportions in concretes with recycled aggregate tends to minimize the adverse effects, but the impact of fly ash is observed in concretes with higher ages, where, according Lorca et al. (2014), the fly ash reacts with calcium hydroxide released by the cement hydration product in older ages.

Some studies have developed mathematical models to estimate the mechanical strength of concrete with pozzolanic materials as well as with recycled aggregate [105–107]. Shakr Piro et al. [105] used five different models to estimate the compressive strength of concrete with carbon nanotubes. Therefore, the artificial neural network model, M5P tree model, nonlinear regression model, and multilinear model have been used. The variables used in the model were curing time in days, coarse aggregate content, water/binder ratio, cement intake in kg/m^3, and carbon nanotube. As a methodology, the authors used information such as the reference concrete compressive strength and concrete with different contents of carbon nanotube. Based on sample data with 282 records analyzed statistically, the authors developed a multiscale model to estimate the compressive strength of the concretes. Another very relevant study developed by the authors [107] was the analysis of the correlation between compressive strength and electrical resistivity of concrete slag residue. The models used for this study were the multi logistic regression model, complete quadratic model, M5P tree model, and neural network. Barkhordari et al.'s [106] mathematical models have been used to estimate the compressive strength of concrete with fly ash. The models used were super apprentice algorithm, simple average, weighted average, and stacking employed. The database contained information from 270 samples that were collected and preprocessed. Next, some recent research on the use of fly ash in concretes with recycled aggregate will be presented.

4.2. Mechanical Properties

4.2.1. Compressive Strength

Thus, concretes with the addition of fly ash in partial replacement to Portland cement may present lower compressive strength compared to conventional ones in the smallest ages. Below will be a few studies of the combined effect of different levels of fly ash and with 50% recycled aggregate in the compressive strength in concrete at 28 days of curing (Figure 3).

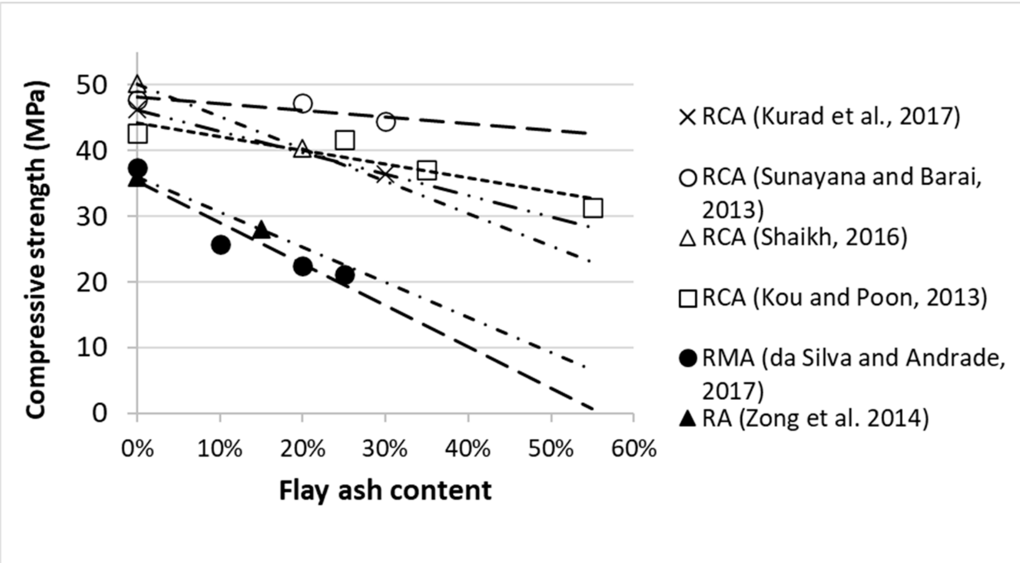

Figure 3. Compressive strength of concrete with: recycled aggregate of concrete (RCA), mixed recycled aggregate (RMA), and ceramic bricks (RA). Data from Zong et al. [7], da Silva and Andrade [17], Kou and Poon [32], Shaikh [33], Sunayana and Barai [34] and Kurad et al. [37].

The addition of fly ash in partial replacement to Portland cement tends to reduce the compressive strength of concrete in the smallest ages. According to Mehta [84], this is because the oxides when reacting with water and $Ca(OH)_2$ form a layer of C-S-H around the particle making it difficult to access the oxides of the inner part. With this, the hydration heat of the pozzolanic reaction forms more slowly making the development of resistance slower.

According to Kurad et al. [37], the actual decrease in the combined fly ash effect and recycled aggregate concrete (RCA) on compressive strength is less than the sum of the individual fly ash effect and RCA, especially after 28 days of cure. According to the authors, one of the factors that led to this behavior is the pozzolanic reaction between silicon dioxide (SiO_2) of fly ash and calcium hydroxide ($Ca(OH)_2$) of RCA. With the increase of $Ca(OH)_2$ due to the increasing reason for the incorporation of recycled aggregate, fly ash SiO_2 will have more Calcium Oxide (CaO) in the not hydrated particles of the old cement to produce more C–S–H, which is the main contributor to the development of concrete resistance.

In 2017, Kurad et al. [37] verified the effect of incorporating high volumes of recycled concrete aggregates and fly ash on the mechanical strength of new concretes. The authors produced concrete with axial compressive strength of 20 MPa at 28 days. At the same age (28 days) the concretes were crushed, and only after 10 months, the recycled concrete aggregate (RCA) was used in the mixture as coarse and fine aggregates for the production of new concretes. The sum of the main oxides of the fly ash used in this study (SiO_2 + Al_2O_3 + Fe_2O_3) was 86.1% of the total mass. The axial compressive strength designed for the original concrete was 37 MPa, and the slump of the cone was 80 $\pm$ 10 mm in all mixtures.

In this study, the authors replaced Portland cement with fly ash in the following proportions: 0%, 30%, and 50% of fly ash, and the binder consumption were 350, 235, and 140 kg/m^3, respectively. The authors produced concrete with 0% and 100% replacement content of natural aggregate by recycled sand. Some of the concrete mixtures were repeated with the addition of a 1% superplasticizer.

The authors observed that, in general, the replacement of natural aggregate with recycled aggregate (RCA) is prejudicial to the compressive strength. The incorporation of RCA as fine aggregate is more detrimental than its incorporation as coarse aggregate. The authors also observed that when incorporating fly ash in mixtures with recycled aggregate (RCA), the compressive strength of concretes has the tendency to decrease at early ages. However, the rate of increase of concrete strength is directly proportional to the rise in incorporation levels of RCA and FA.

According to Kurad et al. [37], the decrease of the combined effect of the joint employment of fly ash and RCA is smaller than the individual effect of the components, especially after 28 days of curing. According to the authors' study, one of the factors that led to this behavior is the pozzolanic reaction between the Silicon Dioxide (SiO_2) of the fly ash and Calcium Hydroxide ($Ca(OH)_2$) present in the RCA. With the increase of $Ca(OH)_2$ due to the increasing ratio of incorporation of recycled aggregate, the SiO_2 of the fly ash will have more Calcium Oxide (CaO) from the extra particles of the old cement to produce more C-S-H, which is the main reason for the development of concrete strength [37].

According to Corinaldesi and Moriconi [108], concretes with a recycled concrete aggregate present an improvement in the interfacial transition zone (ITZ) as a result of the internal curing effect due to water being returned by the recycled aggregate particles, which have high porosity, and in the C-S-H particles, probably contained in recycled aggregates coming from the old mortar [108]. According to the authors, recycled aggregates also have $Ca(OH)_2$ particles that should help improve the pozzolanic activity of fly ash. To analyze the TZs between natural aggregate and cement paste in conventional concrete and between recycled concrete aggregate and cement paste in RCA concrete and fly ash, the authors used the scanning electron microscopy (SEM) technique. The results showed that the ITZs of the concrete mixes made with fly ash and recycled concrete aggregates were better than those of the original concrete.

Corinaldesi and Moriconi [108] verified that the high amount of old cement particles increases the $Ca(OH)_2$ content, and the fly ash also contains large amounts of SiO_2. Soon the amount of CSH increments and fills the ITZ and works on the interfacial connection among aggregates and paste. This behavior was also observed by other authors [20,106,109].

In 2017, da Silva and Andrade [17] produced concretes with mixed recycled aggregate consisting of 8% ceramic, 13% natural aggregate, and 79% concrete. The sum of the main oxides of the fly ash used in this study (SiO_2 + Al_2O_3 + Fe_2O_3) was 80.6%. The Portland cement used in this research was similar to ASTM C 150 III, whose levels of substitution of natural coarse aggregate by recycled aggregate proportions employed in the experiment were 25%, 50%, 75%, and 100%, with 15%, 20%, 25%, and 30% of cement substitution by fly ash. The axial compressive strength of the reference concrete at 28 days was 54.1 MPa, and the slump of the cone was approximately 80 ± 10 mm in all mixtures. The w/binder ratios employed were 0.40, 0.45, 0.50, 0.55, and 0.65. Based on a nonlinear regression model, the authors observed that by replacing natural coarse aggregate with mixed recycled coarse aggregate, the growth rate of axial compressive strength of the concretes without fly ash between the ages of 28 and 91 days was low for the w/b ratio of 0.4. However, as the replacement content of Portland cement by fly ash is increased, the growth rate of compressive strength increases significantly, and as the w/b ratio is increased, this growth rate is even higher (Table 6).

Table 6. Influence of the ratio w/b in the growth rate of the concrete compressive strength 25% RCA.

Mix	Relationship fc_{91}/fc_{28}		
	w/b 0.4	**w/b 0.5**	**w/b 0.6**
R0F0	1.09	1.11	1.13
R25F0	1.09	1.11	1.13
R25F15	1.14	1.16	1.18
R25F20	1.17	1.21	1.27
R25F25	1.21	1.26	1.36
R25F30	1.27	1.34	1.46

According to da Silva and Andrade [17], the pozzolanic reaction between fly ash and $Ca(OH)_2$ in concretes with mixed recycled aggregate showed significant improvements in mechanical properties, tending to approach the reference concretes at older ages. The results verified in this study are in agreement with those observed by Kurad et al. [37].

The addition of fly ash in concretes with clay brick waste with a strength of approximately 10 MPa as coarse aggregate replacing natural coarse aggregate was the subject of a study by Zong, Fei, and Zhang [7]. The sum of the principal oxides in the fly ash (SiO_2 + Al_2O_3 + Fe_2O_3) was 86.91% of the total mass. The cement employed in this study was ordinary Portland cement. The proportions used in this study were 30%, 40%, and 50% recycled aggregate, and 15% fly ash. A high-performance polycarboxylate admixture was used for water reduction. The water content in the concrete was the standard amount of water required for reference concrete plus additional water based on the increased water absorption of the recycled aggregate. The authors observed a significant reduction in the density of the concretes with recycled aggregate compared to the reference concrete.. According to the authors, this behavior is related to the low density of the recycled aggregate of ceramic material. According to the authors, the reference concrete had a density of 2476 kg/m^3, while concretes with 30, 40, and 50% of recycled aggregate content presented 2352 kg/m^3, 2316 kg/m^3, and 2175 kg/m^3, respectively. According to the authors, the reference concrete had a density of 2476 kg/m^3, while concretes with 30, 40, and 50% of recycled aggregate content presented 2352 kg/m^3, 2316 kg/m^3, and 2175 kg/m^3, respectively. According to the authors, the reduction in density of the concretes with recycled aggregate is related to the low density of the recycled aggregate of ceramic material.

Fei and Zhang [7] observed that the reduction in mechanical strength was more significant in concretes with 50% recycled aggregate and 15% fly ash compared to the reference concrete, which was 44% at 28 days of curing. Based on the authors' results, the concrete with only 15% fly ash presents compressive strength of 48 MPa and flexural strength of 11 MPa. For concretes with 15% fly ash and 30, 40, and 50% recycled aggregate, the compressive strength was 42 MPa, 35 MPa, and 28 MPa, respectively, while the tensile strength was 4.8 MPa, 4.6 MPa, and 3.9 MPa, respectively. According to the authors, this behavior occurred because the recycled aggregate used in this study presents much lower strength than the natural aggregates.

In a general way, it can be noticed that the reduction in the mechanical strength of concrete when recycled aggregate is used is closely related to the type of waste. Recycled concrete aggregates tend to present higher mechanical resistance in comparison to recycled aggregates from clay bricks, and consequently present a higher strength decrease. The addition of fly ash in concretes with recycled aggregate has a very significant contribution because it produces an excellent pozzolanic reaction in the long term and has a pore filling effect due to the fine particles of the ash. The higher the content of adding fly ash in partial replacement to Portland cement, the lower the degree of reaction in the initial ages of cure [110].

4.2.2. Tensile Strength

Tensile strength showed behavior similar to compressive strength, although, according to a study carried out by Gonzalez-Corominas [111], if the curing process is steam, the tensile strength tends to improve. This behavior is closely linked to the addition of fly ash in partial replacement to Portland cement that results in a concrete with lower cement content, and consequently lower availability of calcium hydroxide in the concrete matrix (FILHO [112]), as shown in Figure 4.

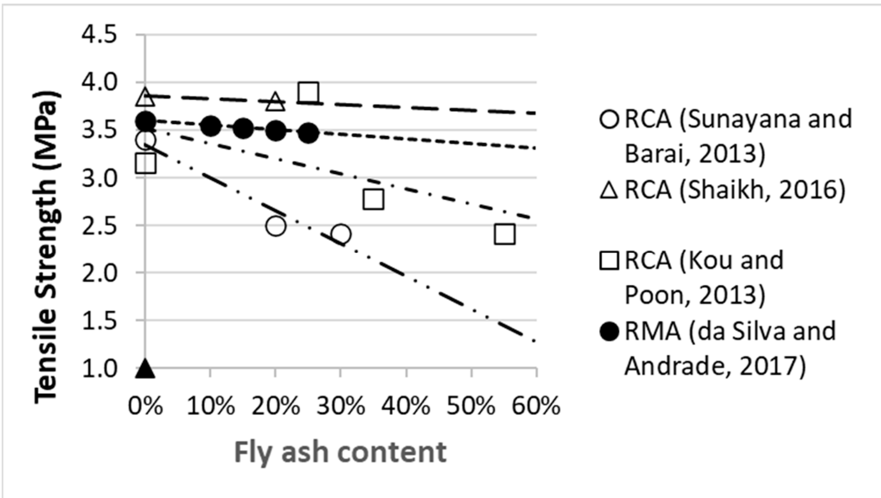

Figure 4. Results of tensile strength of concrete with recycled aggregate of concrete (RCA), mixed recycled aggregate (RMA), and ceramic bricks (RA) from some researchers. Data from da Silva and Andrade [17], Kou and Poon [32], Shaikh [33] and Sunayana and Barai [34].

Regarding the tensile strength, the results of several research studies are convergent. Kou and Poon [32] evaluated such property by employing replacement levels of 50% and 100% of natural aggregate by the coarse recycled concrete aggregate, with the addition of fly ash at three replacement levels (25%, 35%, and 50%) to the Portland cement ASTM Type I. The sum of the principal oxides of the fly ash employed in this study (SiO_2 + Al_2O_3 + Fe_2O_3) was 90.31%. The w/b ratio was 0.55, the slump was kept constant for all mixtures (120 mm), and the tensile strengths were estimated at ages of 28 days, 1, 3, 5, and 10 years. It was observed that the concretes produced with natural aggregate and fly ash in the proportions 0%, 25%, 35%, and 55% (R0F0, R0F25, R0F35, and R0F55) showed an increase in splitting tensile strength by 38.9%, 43.0%, 44.1%, and 39.8%, respectively, in the period between 28 days and 10 years. The concretes with 100% coarse recycled aggregate and fly ash in the same proportions showed an increase in strength of 57.8%, 62.5%, 67.2%, and 70.9%, respectively, in the period between 28 days and 10 years. After 10 years, the concrete with 100% coarse recycled aggregate and 25% fly ash (R100F20) presented the highest tensile strength. However, the concrete with 100% coarse recycled aggregate and 55% fly ash (R100F55) was the one that showed the highest resistance gain. According to the authors, this behavior is closely related to the incorporation of fly ash into the recycled aggregate, which improves the microstructure of the ITZ, which, in turn, increases the adhesion between the aggregates and the paste. Mehta and Monteiro [1] suggest that the concentration of calcium hydroxide crystals in the ITZ may be reduced by chemical reactions when a pozzolanic mixture or a reactive aggregate is present. The authors suggest that possible chemical interaction between calcium hydroxide and the calcareous aggregate is probably the reason for the increased tensile strength of concrete.

In another study, Kou et al. [113] produced concretes with different w/c ratios (0.45, 0.50, and 0.55), Portland cement ASTM Type I and fly ash whose sum of the principal oxides (SiO_2 + Al_2O_3 + Fe_2O_3) is 90.31%. The absorption of the recycled aggregate varied between 4.26% and 8.69%. In this study, the authors produced reference concretes with 20, 50, and 100% recycled aggregate content and concretes with 25% addition of fly ash in partial replacement of Portland cement and 0%, 20%, 50%, and 100% of recycled aggregate in partial replacement of natural aggregate.

According to the authors, the tensile strength at 91 days of concrete with 100% recycled aggregate for w/b ratios 0.50, 0.45, and 0.40 were 12%, 10%, 9%, and 10% lower than that of the reference concrete, respectively. By using the addition of fly ash as a partial replacement for Portland cement, the strength of concretes with 100% recycled aggregate increment by 3%, 6%, and 8%, respectively, contrasted with cement without fly ash. Kou et al. [113] suggest that such an increase in strength in the concretes with fly ash can be credited to the densification of the concrete because of the possible reduction in porosity and to the pozzolanic reaction of the fine fly ash particles.

The result of the influence of fly ash in concretes with mixed recycled aggregate in the tensile strength in concretes was produced by da Silva and Andrade [17], between the period of 28 days and 91 days. The authors observed that the addition of fly ash in concretes with recycled aggregate would, in general, constrict the adverse effects that the recycled aggregate may cause in the tensile strength of concretes.

The authors observed that the negative effect in concretes with 25% of RCA and with an increasing amount of fly ash was smaller than in concrete with 20% of fly ash when the content of replacement of RCA increased. This behavior is due to the reduction of concrete porosity due to the filling of voids by fly ash particles. The addition of fly ash in concretes with recycled aggregate, by containing very fine materials, has a pore plugging effect in the recycled aggregates and makes a denser paste, and consequently reduces the harmful effects of the incorporation of recycled aggregate.

4.2.3. Elastic Modulus

According to Neville [96], the elastic modulus of concrete depends on the elastic modulus of the aggregate and the volume proportion of the aggregate in concrete. Studies show that the elastic modulus decrease in concretes with fly ash and recycled aggregate in the early ages. Sunayana and Barai [34] and Kou and Poon [32] observed similar behavior of the elastic modulus of concrete produced with different fly ash contents and with 50% recycled aggregate, as shown in Figure 5.

However, the improvement in elastic modulus was observed in concretes with RCA in the older ages by some authors. Sunayana and Barai [34] used two groups of recycled concrete aggregate as coarse aggregate for the production of fly ash concretes. The first group of recycled concrete aggregate consists of a particle packing method (PPM), which consists of adopting a continuous particle size range between 4.75 mm and 20 mm because, according to the authors, the voids between larger particles are filled by the smaller particles to achieve the lower amount of voids in a concrete mix. The mixing method used for the production of concrete with recycled aggregate and fly ash was in the following steps:

(a) Mix for 15 s the natural aggregates and recycled aggregate;
(b) Add fly ash and mix for another 15 s;
(c) Portland cement is added and mixed for another 30 s;
(d) Add water and superplasticizer to the dry material and mix for another 60 s.

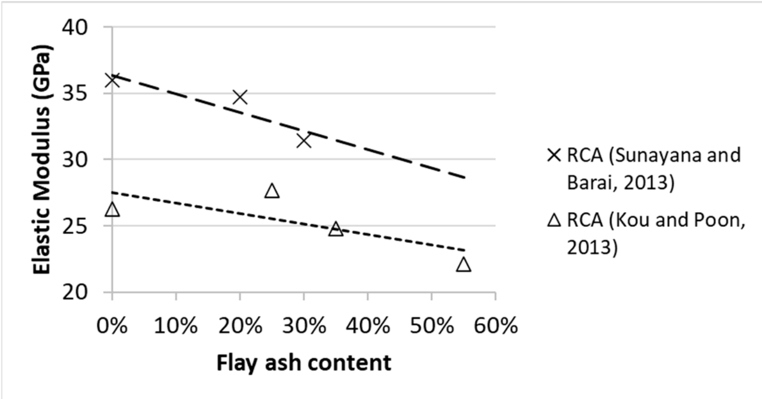

Figure 5. Elastic Modulus of concrete with recycled aggregate of concrete (RCA). Data from Kou and Poon [32] and Sunayana and Barai [34].

Cylindrical samples were fitted with a compressometer to measure the displacement at each load increment, which was subsequently converted to strain. The load was applied for three load cycles up to 1/3 compressive strength of similar cylinders and converted to strain. The stress–strain relationship in the linear elastic region was used to find the modulus of elasticity (E) and to minimize the effect of compressive strength. The parameter ($E/fc^{0.5}$) was found to be in the range of 4461–5507. Based on the authors' results, the reference concrete presented a compressive strength of approximately 43 MPa, while the concretes with 20 and 30% fly ash and RCA presented an average of 41 MPa and 42 MPa, respectively. The modulus of elasticity of the reference concrete was 36,000 MPa, while concretes with 20 and 30% fly ash and RCA had an average of 34,808 MPa and 31,340 MPa, respectively. The relationship between the modulus of elasticity and the compressive strength ($E/fc^{0.5}$) for the reference concrete was approximately 5505 and for the concretes with 20 and 30% fly ash and RCA, it was around 5443 and 4764, respectively.

Based on the results, the authors observed a 5 to 10% reduction in elastic modulus in concretes with NAC compared to natural aggregate for 20% and 30% of fly ash replacement presented a decrease for RAC + FA20 compared to NAC for the same w/b ratio of 0.45. This behavior is due to the lower elastic properties of recycled aggregate due to the presence of adhered mortar compared to natural aggregates.

Kou and Poon [32] produced concretes with coarse recycled concrete aggregate in the replacement of 50% and 100% of coarse natural aggregate. The PC used in this research was equivalent to ASTM Type I. The sum of the principal oxides of the fly ash employed ($SiO_2 + Al_2O_3 + Fe_2O_3$) was 90.31%, and the proportions of the addition of fly ash in replacement of PC were 25%, 35%, and 50%. The w/b ratio was 0.55, and the concrete was kept constant at 120 mm. The static elastic modulus was determined according to ASTM C 469 (2002) in specimens at 28 days, 1 year, 3 years, 5 years, and 10 years.

Based on the results, the authors observed that in the first year of curing, there was a gain in the elastic modulus for R100 R100F25, R100F35, and R100F5 mixtures of 7.2%, 7.9%, 11.2%, and 14.8%, respectively. However, at higher ages, the increase in percentages in the elastic modulus was much higher, corresponding to 31.3%, 33.9%, 40.7%, and 46.1%, respectively, between 28 days and 10 years. The authors also observed that, compared to the control mixture, the utilization of a considerable quantity of recycled aggregate in the concrete diminished the modulus increment following 10 years of curing.

According to Neville [114], the modulus of elasticity increases with concrete strength, but the growth in the concrete modulus of elasticity is smaller than the growth in compressive strength. The elastic modulus of concrete is closely linked to the elastic modulus of the binder matrix and aggregates. As recycled aggregate presents lower stiffness when compared to natural aggregate due to its composition and highly porous internal structure, it is expected that the higher the content of recycled aggregate substitution for natural aggregate, the lower the concrete elasticity modulus will be [42]. In the study by Kou and Poon [32], a good correlation was observed between compressive strength and modulus of elasticity for all concrete mixes with recycled concrete aggregate and fly ash. That is, as the compressive strength increases, the modulus of elasticity increases. For this analysis, the authors employed an equation based on ACI 318-08 to estimate the modulus of elasticity in terms of the compressive strength of natural concrete.

Thus, since the elastic modulus of concretes depends on the aggregate characteristics (considering the same properties for cement paste), it can be challenging to determine an adequate correlation between the elasticity modulus and concretes produced with recycled aggregate since the elasticity modulus of aggregates presents a significant variability, depending mainly on their type and origin.

4.3. Durability Properties

4.3.1. Water Absorption

According to Zhang et al. [115], there are several aggressive agents present in nature that contribute to the deterioration of the concrete structure, reducing its service life, whose action is associated with climatic and environmental conditions, such as CO_2, Cl^-, O_2, and H_2O. In addition, $Ca(OH)_2$ gives concrete high alkalinity, maintaining the pH of the mixture between 12 and 13, but it is a leachable product and in contact with CO_2 present in the environment, and relative humidity of approximately 60–80% initiates the carbonation process, which reduces the pH to values close to 8–9, leaving the concrete exposed to chemical attacks. Limbachiya, Meddah, and Ouchagour [20] produced concretes with 0%, 30%, 50%, and 100% ratio of natural coarse aggregate to recycled concrete aggregate and with 30% fly ash in place of Portland cement CEM I 42.5 N. The mixtures were classified into three grades according to the 28-day design compressive strength (C20, C30, and C35 considering a 28-day design compressive strength of 20, 30, and 35 MPa, respectively).

The method employed for testing water absorption in concretes by the authors consisted of measuring the rate at which water, through a known surface area, flows into the capillary network of concrete pores with a fixed scale of 10 min. The estimation of volumetric flow is obtained by measuring the length of flow along a capillary of known size. The initial surface absorption (ISA) of the various mixtures was determined in 150 mm cubes.

The authors observed that the initial surface absorption (10 min) versus RCA content for all investigated mixtures showed an increase in the initial surface absorption (ISA) as the replacement content of the recycled concrete aggregate was increased. However, the authors observed that concretes with 30% fly ash in partial replacement of Portland cement showed a reduction in water absorption when compared to concretes without fly ash. According to Limbachiya, Meddah, and Ouchagour [20], this behavior is linked to the pozzolanic reaction and the pore structure refinement that reduces the water flux. The same behavior was verified by da Silva and Andrade [17].

To analyze the water absorption in concretes with recycled aggregate and 10% ultrafine fly ash (UFFA), Shaikh [48] used 10% ultrafine fly ash (UFFA) and two levels of substitution (25% and 50%) of coarse recycled aggregate from construction and demolition waste (CDW) in partial replacement of natural aggregate. The CDW used was constituted of approximately 78% concrete, 13% bricks, 2.3% asphalt, and 5.7% other materials. The water absorption of the recycled aggregate was 4.88%. The sum of the fly ash oxides (SiO_2 + Al_2O_3 + Fe_2O_3) was 95.5%, with a surface area of 2.51 m^2/g. Concrete water absorption over a period of 6 h was adjusted by linear regression, and, to describe the absorption, the slope of the equation was used. The absorption rate (mm) for the investigated concretes at 7, 28, and 90 days.

Based on the analysis through linear regression based on R^2 values greater than 0.98 for all mixtures, the authors observed that the water absorbed in the concrete increased as recommended in Fick's first law equation [33]. The concretes with recycled aggregate presented higher water absorption than the reference concretes. According to Shaikh [33], the rate of water absorption through concrete is a function of the permeability of the pore structure where, due to capillary increase, the rate of water percolation is controlled mainly in unsaturated concretes. Based on the results obtained the authors noticed that as the age of cure increases, the rate of water absorption of recycled aggregates decreases. This behavior is related to the continuous hydration reaction and the formation of calcium silicate hydrate (C-S-H), which generally fills the micropores in the matrix [33]. It was also found that the addition of 10% UFFA significantly reduced the water absorption rate of concretes containing recycled coarse aggregate and natural coarse aggregate at all ages [33]. The high pozzolanic activity, the secondary C-S-H due to the pozzolanic reaction of ultra-fine fly ash (UFFA) with calcium hydroxide (CH), as well as the fineness of fly ash, may have significantly contributed to the reduction of water absorption [17,116].

In general, studies have shown that recycled aggregates are, for the most part, more permeable than natural aggregates. The higher the replacement level of natural aggregate by the recycled aggregate, the greater the water absorption. The addition of fly ash in concretes with recycled aggregate reduces the negative effect that the recycled aggregate causes in the concretes due to the refinement of the porous capillary network that makes these concretes denser, improving their mechanical resistance and reducing the flow of water through the concretes.

4.3.2. Chloride Ingress

The chloride ions do not cause significant damage to concrete itself, but they contribute to corrosion of reinforcement in structural elements and can negatively affect the serviceability and safety limit states [31,117]. Sim and Park [36] performed chloride ion penetration tests on concrete with recycled concrete sand, whose water absorption was 6.45%. The sum of the principal oxides of the fly ash employed in this study (SiO_2 + Al_2O_3 + Fe_2O_3) was 30.3%, with high CaO content (61.2%). The water/binder ratio was equal to 0.485, and the replacement contents of natural sand with recycled concrete sand were 30%, 60%, and 100%. The addition of fly ash in replacement of Portland cement CEM I was 15% and 30% by weight. The authors analyzed the depth of chloride ion penetration measured at different cure times compared to the addition of fly ash at the ages of 21 days and 56 days.

Based on the results, it is observed that the penetration of chloride ions at 21 days reduces significantly according to by how much the partial replacement of cement by fly ash is increased. For the concrete, at 56 days, the reduction was not so significant when compared to the reference concrete. According to the authors [36], the concretes with recycled aggregate for applications in structural elements obtained sufficient resistance to chloride ion penetration, and the resistance can be maximized by the addition of fly ash. Similar behaviors were observed by other authors [31,112].

Shaikh [33] used the method proposed by ASTM C1202 31 for the mitigation of chlorides in concretes with ultrafine fly ash and coarse aggregate from construction and demolition waste. The authors analyzed the effects of ultrafine fly ash (UFFA) on the permeability of chloride ions in concrete containing coarse recycled aggregates. The authors observed that for reference concretes (OPC), as the age of the concrete increases, the penetration of chloride ions decreases. By replacing the natural coarse aggregate with recycled coarse aggregate (RCA), there is a significant increase in chloride ion penetration compared to reference concretes (OPC). However, when adding 10% ultrafine fly ash (UFFA) in partial replacement of Portland cement, it is observed that there is a significant improvement in permeability at all ages. It is also observed that the addition of 10% UFFA will, in general, expand the chloride ion resistance of recycled aggregate concretes since, according to Shaikh [33], it serves to promote hydration and block the capillary spaces in the concrete matrix.

Thus, the chloride ions will penetrate the concretes with recycled aggregate more quickly due to a higher permeability rate in function of the capillary pores in the matrix of the cement and recycled aggregate. The addition of fly ash in concretes with recycled aggregate fills the capillary pores of the recycled aggregates making a denser concrete, and consequently improves the resistance of concretes to chloride ion penetration.

4.3.3. Carbonation Depth

Carbonation has a significant influence on concrete durability because this reaction reduces the pH of the water in the pores of the cement paste from approximately 12.6 to 8.3 [114]. When the low pH reaches the surface of the reinforcement, the thin passivation layer of oxides that is strongly adhered to the steel in the presence of moisture is destroyed, causing the beginning of the corrosive process [114]. According Khunthongkeaw et al. [118], mortars with fly ash contents lower than 30% have carbonation proposals similar to the reference mortars. Thus, it is crucial to know the resistance to carbonation of concretes with recycled aggregate and fly ash so that these concretes can be used in structural elements.

Geng and Sun [35] used recycled concrete aggregate as sand with a fineness modulus equal to 2.7. The fly ash employed in this study presented a sum of 88% in its principal oxides (SiO_2 + Al_2O_3 + Fe_2O_3). The w/b ratio was 0.40, and the levels of substitution of natural sand for recycled sand were 20%, 40%, 60%, and 80% by weight, and the levels of substitution of ordinary Portland cement for fly ash were 10%, 20%, and 30% by weight. To perform the carbonation depth tests, the accelerated carbonation test was employed at a temperature of 20 $\pm$ 5 °C, with a relative humidity of 70 $\pm$ 5 and a carbon dioxide (CO_2) concentration of 3%. The carbonation depth was measured after 7, 14, and 28 days of exposure to CO_2. The authors compared the carbonation depth between the reference concrete (FC0), concrete with 40% replacement content of natural sand by recycled sand (FC14), and concrete with 40% replacement of natural sand by recycled sand combined with 10% (FCF1), 20% (FCF2), and 30% (FCF3) of replacement of Portland cement by fly ash, respectively.

In the first 7 days of curing, all concretes, with the exception of LC14 (4 cm), have practically zero carbonation depth. After 14 days of curing, the LC0 concrete remained with a carbonation depth close to zero. Concretes LCF2, LCF3, LCF1, and LC14 presented carbonation depths of 0.24 cm, 0.26 cm, 0.49 cm, and 0.78 cm, respectively. At 28 days of cure, the authors observed that the LC0 and LCF2 concrete had very similar carbonation depths (0.48 cm). The LCF3 concrete has a carbonation depth greater than the LCF2 concrete, which was 0.98 cm and 0.75 cm, respectively. The LC14 concrete has a carbonation depth of 1.49 cm.

Carbonation depth of the concretes with recycled sand and fly ash is lower than the concretes with only recycled sand. According to Geng and Sun [35], the effect of cement replacement by fly ash on carbonation depth reveals that carbonation initially decreases and then increases with a replacement rate from 10% to 30%, and then reaches the minimum at 20%. However, according to the authors, the amount of cement decreases with increasing fly ash replacement content, which leads to a decrease in the alkalinity of the pore solution, which is unfavorable for the carbonation resistance capacity of the concrete. This behavior was also observed by Limbachiya, Meddah, and Ouchagour [20] and Silva and Andrade [17]. Khunthongkeaw, Tangtermsirikul, and Leelawat [100] and Silva and Andrade [17] suggest that this behavior may be related, in addition to the reduction of calcium hydroxide (CH) due to the reduction of cement content, to the pozzolanic reaction of the fly ash, which predominates in the refinement of the pores, since there is a slowing of the initial hydration process [35]. Limbachiya, Meddah, and Ouchagour [20] also state that the reduction of the initial CaO content in the cement matrix leads to a decrease in the pH of the concrete, which will contribute to accelerating the carbonation rate.

Silva and Andrade [17] evaluated the resistance to CO_2 of concretes with fly ash and mixed recycled coarse aggregate subjected to accelerated carbonation with a CO_2 concentration of 3%, moisture content between 65 and 75%, and a total exposure period of 23 weeks. The first measurement of carbonation depth was at 15 days of exposure, and the other measures were taken every 30 days. They observed that the carbonation coefficient (adjusted according to Fick's second law) tends to be higher in concretes with recycled coarse aggregate and fly ash compared to reference concretes. This analysis was performed with reference concrete (R0F0), concrete with a 25% replacement of natural coarse aggregate by recycled coarse aggregate (R25F0), concrete with a 25% replacement of natural coarse aggregate by the recycled coarse aggregate, and 30% addition of fly ash in partial replacement of Portland cement, for a w/b ratio of 0.50.

The relationship between K (mm/month$^{0.5}$) and t (months) was analyzed in all concretes and based on the authors' results. All concretes presented in the carbonation coefficient with increasing time of exposure to CO_2. This behavior was observed in all concretes. In the first 15 days of exposure to CO_2, the reference concrete was a carbonation coefficient of 4.9, while the R25F0 and R25F30 concretes were a carbonation coefficient of 5.9 and R25F30. At 145 days of exposure to CO_2, the reference concrete was a carbonation coefficient of 3.97, while the concretes R25F0 and R25F30 were a carbonation coefficient of 3.98 and R25F30. According to the authors, the carbonation process is straightforwardly associated with the exposure time of the specimens to CO_2, and the carbonation coefficient will, in general, balance out after some time. Similar behaviors were observed by Meddah and Ouchagour [20], Khunthongkeaw, Tangtermsirikul, Leelawat [113], and Atiş [119].

In general, it is found that with a partial replacement of Portland cement with fly ash, the CH decreases and makes the concrete more vulnerable to CO_2 penetration. However, the pozzolanic reaction of the fly ash in the pore refinement, which occurs in concretes with higher ages, contributes to the carbonation resistance. Thus, it is possible to observe in the studies that initially, the carbonation resistance is lower at early ages, and as the age increases, the carbonation resistance is improved.

4.3.4. Microstructural Analyses

Microstructural analyses are essential to verify the products formed due to the chemical reactions between the components of the cement matrix and the aggregates, especially on the ITZ. Li, Xiao, and Zhou [120] observed the ITZ employing scanning electron microscopy (SEM). The authors investigated the properties of two groups of concretes: in the first (A) part of the mixing, water was mixed with a pozzolanic powder consisting of fly ash, silica fume, and blast furnace slag for 60 s in order to produce a paste with a relatively low water/binder ratio; then recycled concrete aggregate (RAC) was added to the paste and mixed for another 60 s to coat the surfaces of the recycled aggregate; finally, the remaining water, sand, and Portland cement were added to the mixture and mixed for another 120 s. The second group (B) mixtures were performed in a conventional way and without the pre-mixing of the recycled aggregate.

Microstructural analyses were performed on the concretes RC04A and RC04B to verify the influence of different types of the mixture on the ITZ of the two concretes that present the same proportions of materials. For concrete production, recycled aggregate from an old cement sidewalk was used, whose apparent density was 2.497 g/cm^3 and water absorption of 4.6%. The amount of binder and water was established at 500 kg/m^3 and 220 kg/m^3, respectively. A superplasticizer was added in a fixed amount of 0.8% to the binder in all mixtures. The density (in g/cm^3) of the fly ash, silica fume, and blast furnace slag were 2.38, 2.20, and 2.75, and specific surface area values (in m^2/kg) were 410, 20,000, and 240, respectively.

According to the authors, the RC04A concrete has a denser ITZ, and the hydrates are mainly composed of uniform CSH gel. With the new mixing technique, the pozzolanic coating layer forms a barrier that prevents water penetration. Workability is improved, and the ITZ is strengthened. On the other hand, concrete RC04B showed a crack with a length of 30–40 μm (perpendicular to the ITZ), and a large amount of CH crystals was observed in the ITZ. According to the authors, the occurrence of the cracks may be due to the water absorption from the paste by the recycled aggregate. After the water evaporation, it was verified the occurrence of voids that correspond to the cracks in the ITZ. Thus, it can be observed that different mixing techniques can contribute to making the material denser and with fewer cracks. The use of recycled aggregate without pre-mixing, resulting in a weaker ITZ, was also verified by Poon, Shui, and Lam [68] and Sidorova et al. [121].

To evaluate the ITZ bond, Juan-Valdéz et al. [122] produced concretes with 50% replacement of natural aggregate with mixed recycled aggregate whose composition was 44.11% stone, 33.56% bricks, tiles, sanitary ware, 17.51% stone with mortar, 0.44% asphalt, 0.75% glass, 3.48% gypsum, and 0.16% other materials. The authors used a Hitachi S-4800 scanning electron microscope with tungsten as the X-ray source, a Si/Li detector, and a Brucker XFlash 5030 EDS analyzer to verify the EDX elemental mappings. It was found that aggregates (natural and recycled) developed ITZ with satisfactory properties [122]. According to the authors, this result was due to the wetting of the recycled aggregate before its addition to the concrete mixture. Thus, it can be seen that saturation of recycled aggregates results in beneficial effects regarding the improvement of concrete microstructure, making a denser paste that improves ITZ properties.

5. General Analysis

In general, construction and demolition waste can be used in the production of concrete components, mortar, paving blocks, subfloor, and masonry in urban infrastructures such as sidewalks and curbs. These materials can also be used in the regularization and gravel of unpaved streets, as well as in the base, sub-base, and reinforcement of the pavement subgrade. The use of waste (recycled aggregates) and fly ash (binder), although there are many studies, has still been little used in the construction industry, as it requires the systematization of quality control technology, public policies, standards, and technical specifications for use on a large scale. Based on what was exposed in this review, it is possible to estimate the practical application of this waste in some segments of civil construction, as shown in Table 7.

Table 7. Possible to estimate the practical application.

Usage with 20% of Fly Ash	Replacement Rate		
	0–25%	25–50%	>50%
Structural cement concrete (20–25 MPa)	X		
Non-structural cement concrete (<20 MPa)	X	X	
Permeable cement concrete	X	X	
Mortars	X	X	
Paving (base, sub-base, and sub-bed reinforcement)	X	X	X

For use in paving, some basic requirements, such as particle size composition, maximum characteristic dimension, and shape index, are necessary. For cement concretes, the minimum required control requirements are particle size composition, water absorption, and control of contaminants, such as chlorides, sulfates, and non-mineral materials.

6. Conclusions

Considering the several works published in the literature, the following considerations can be drawn:

- There are already several studies exploring the most suitable composition of concrete mixtures with construction and demolition waste and fly ash to reach a consensus on the most appropriate contents of these wastes to achieve results of mechanical properties and durability closer to the reference concretes;
- Although there is an intense debate regarding the use of construction and demolition waste for the production of new concretes due to the significant variability of this waste, many researchers agree that small amounts of substitution of natural aggregates by recycled aggregates are quite feasible;

- The addition of fly ash as a partial replacement for Portland cement in concretes with recycled aggregate from construction and demolition waste, besides improving the adverse effects caused by recycled aggregates in terms of mechanical properties and durability, can contribute significantly to reducing CO_2 generation in the environment;
- The use of this solid waste in the production of concrete and mortar will make a significant contribution to reducing the consumption of natural resources as well as reducing production costs.

7. Suggestions for Further In-Depth Studies

In view of the current holes in the past studies, the accompanying suggestions are proposed for future exploration:

- There is a need for an establishment of methodologies for cost evaluation per m^3 of concretes with recycled aggregate and fly ash;
- A study of the mechanical properties and durability in concretes with recycled aggregate and fly ash under different environmental conditions;
- Further investigations are necessary to determine ranges for an adequate w/b ratio for concretes with recycled aggregate and fly ash, given the variability of the physical–chemical characteristics of such materials;
- As the curing temperature directly affects the chemical reactions of fly ash activation, an evaluation of the mechanical properties and durability of concretes with recycled aggregate and fly ash is necessary;
- Life cycle analysis (LCA) that includes the recycling or reuse process to incorporate the product in the construction process is needed in order to give information for the decision-making process.
- Prediction of compressive strength of concrete modified with fly ash: applications of neuro-swarm and neuro-imperialism models;
- Systematic multiscale models to predict the compressive strength of fly ash-based geopolymer concrete at various mixture proportions and curing regimes;
- Soft computing techniques: systematic multiscale models to predict the compressive strength of HVFA concrete based on mix proportions and curing times;
- ANN, M5P-tree, and nonlinear regression approach with statistical evaluations to predict the compressive strength of cement-based mortar modified with fly ash;
- Characterizing and modeling the mechanical properties of the cement mortar modified with fly ash for various water-to-cement ratios and curing times;
- Model technics to predict the impact of the particle size distribution (PSD) of the sand on the mechanical properties of the cement mortar modified with fly ash;
- Compare the cost and environmental effect of the use of demolition construction waste for the production of new concrete.

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