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A bibliographic review of concrete obtained by alkaline activation and the specific case of the municipal solid waste incineration slag

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Abstract: The present bibliographic review work focuses on the approach and study of historical processes of slag resulting from the incineration of municipal solid waste, namely: An introduction to the history of Roman civilization and its building habits in the region of Pozzuoli, its engineering and architecture; Alkali-activated ligands, their Zeolitic compositions, geopolymers, chemical reactions and their crystalline phases, amorphous materials and the composition of aluminosilicates; Chemical and structural characterization of alkaline-activated materials and elements; Hybrid cements considered binders containing a percentage of OPC and another percentage of an aluminosilicate precursor and activated alcaline; Origin and treatment of municipal solid waste as well as incineration processes; Hybrid cements containing municipal solid waste incineration slag; An approach to the alkali activation of ligands with slag from municipal solid waste incineration. Finally, a conclusive top-down analysis of these issues.

Keywords: Alkaline Activation, Incineration Slag, Municipal Solid Waste, Portland Cement

Introduction

The first known uses of pozzolans date back to the Roman Empire, when it was discovered that volcanic ash from the region of Pozzuoli, near Vesuvius, when finely ground and mixed with lime, produced a strong and durable mortar. The first explorations started in that region, but were extended to other volcanic areas of Lazio and Campania and later throughout the Mediterranean basin, making use of the different colors of the material, which vary according to their origin. Vitruvius, the Roman engineer and architect who lived in the 1st century BC, had already described four types of pozzolana (black, white, gray, and red) and their uses.

Once their binding properties were discovered, the Romans made extensive use of pozzolans to produce opus caementicium (cementizio), a type of mortar created by mixing pozzolans with lime (typically in a 2:1 ratio) immediately before the addition of water. This mortar is a powerful enough binder to build large structures, such as bridges, domes and long beams, and it has the unique characteristic of setting even when submerged. Extraordinary examples of its use are the dome of the Pantheon in Rome and the jetties of the Roman port of Cosa. The latter were built with pozzolanic mortar apparently placed on the seabed through long tubes that made it possible to fill the molds without mixing it with seawater. The resulting structure was so durable that three of the piers still remain, with their submerged structures in excellent condition, more than 2100 years after their construction.

The use of pozzolanic mortars was abandoned with the fall of the Roman Empire but it was resumed after the European Renaissance and it is at the origin of modern cements. The rediscovery of pozzolans is due to the work of Italian humanists having been promoted by the great Renaissance architects and builders, including Filippo Brunelleschi, who rediscovered the use of quick-setting pozzolanic mortars in the construction of domes and bridges.

The large-scale reintroduction of the use of pozzolans led to the search for alternative sources to natural ones, with multiple non-crystalline silica-rich materials having been found to show the same cementitious properties. Among the artificial pozzolans, calcined clays, fly ash and calcined diatomaceous earth stand out.

Pozzolans are rocks of volcanic origin consisting of a more or less homogeneous mixture of clayey materials, silts and sands, with greater or lesser aggregation, resulting from the alteration by atmospheric agents of volcanic materials rich in non-crystalline silica, especially pumice. Nowadays, the designation of pozzolana has been extended to materials either produced industrially or derived from fly ash or slag from industrial burning processes.

Due to their richness in vitreous silicates, pozzolans are considered acidic sedimentary rocks, with a high content of reactive silica (SiO2), capable of reacting with calcium hydroxide (Ca(OH)2), producing silicates of hydrated calcium (C-S-H), responsible for the mechanical strength of cement. The most common pozzolans are light in color, but depending on the metallic oxides content, their colors may range from whitish to dark gray, including red and pink varieties.

Alkaline-activated binders

The research on alkaline-activated cements had a somewhat relevant development- in the former Soviet Union, in the Scandinavian countries and in some countries of Eastern Europe (Torgal et al. 2007).

References point to Glukhovshy as the first researcher who emphasized the differences between the composition of Portland cement, C-S-H and Ca(OH)2, and the basic composition of Earth crust minerals, Zeolitic materials containing alkali metals (Glukhovsky, 1959). Davidovits later developed and patented alkaline activated cements, naming them geopolymers. Based on his investigations, Glukhovshy developed a new type of binder that he called “soil-cement”, with the word “soil” being used because it resembles a natural rock, and “cement” for its binding capacity (Pacheco and Jalali, 2009). They also reported that the polymerization process involves a chemical reaction in a high alkalinity medium, which generates Si-O-Al-O polymeric amorphous bonds, which follow an empirical formula Mn[-(Si-O2)Z-Al-O]n, wH2O- where n is the degree of polymerization, Z is 1, 2 or 3, and M is an alkaline ion, such as sodium or potassium (Davidovits, 1982; 1991).

It has also been reported that some geopolymers are similar to amorphous zeolites in which the crystallization stage has not been reached, due to a very rapid reaction during dissolution and condensation, or a very slow reaction when hardening occurs (Fernandez-Jimenez, 2005). It was also indicated that most investigations on alkaline-activated binders use inferior products such as blast furnace slag or fly ash, as these materials do not require milling or heat treatment operations (Roy, 1999), and that other researchers have evaluated the activation possibility of several aluminosilicate minerals (Xu, 2000).

Recent articles published by Mehrab Nodehi and Taghvagee (2021) on alkaline-activated materials and geopolymers, point to a major obstacle to sustainable development and sustainability in the Construction Materials Industry, due to the high increase of CO2 production, originating from the Common Portland Cement Production Industry, thus highlighted as a relevant emitter of greenhouse gasses, with approximately 8% of the total global annual production of CO2 (Arrigoni, 2020; Lehne, 2018) with reports also pointing to the use of almost 40% of energy production (Zhao, 2020).

Torgal and Jalali (2009) have also mentioned that ligands obtained by alkaline activation have been receiving increasing attention, either due to the need to reduce greenhouse gas emissions, or due to the need for binders that have a superior durability to that of Portland cement, indicating that reinforced concrete structures built with Portland cement have shown their “Achilles heel” regarding their durability, given that their expected lifespan was 100 years in the 50s, 75 years in the 70s and currently it is only 50 years.

Ligands obtained by alkaline activation are synthesized from aluminosilicate material with highly alkaline solutions and are known to be responsible for a lower emission level than Portland cement, to which it must also be added a high capacity to immobilize heavy metals, granting this type of binder an added value (Torgal and Jalali, 2009). Thus, for the building materials industry to become environmentally “friendly”, one of the most recent alternatives in this area can be seen in the emergence of alkali-activated materials and geopolymers (Nodehi and Taghvaee, 2021) through which Portland cement can be replaced by supplementary cementitious materials that have binding capacity and are generally recognized as the most promising waste-containing materials added to the mix, replacing cement and acting as binding agents (Nodehi and Taghvaee, 2021).

Historically, cementitious materials were selected and chosen to be used in the construction industry, due to their suitability and often favorable properties. Table 1 presents a historical review.

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Table 1. Historical review of some important events concerning cements obtained + alkaline activation and alkaline cements adapted from Roy, 1999; Torgal and Jalali. 2009; Amer, 2021.

AUTHORS	YEAR	DESCRIPTION
Hans Kuhl	1908	Slag cement and process of making the same (Deventer; Provis, 2014)
Kuhl	1930	Investigated setting behavior of slag in the presence of caustic potash.
Chassevent	1937	Measurement of reactivity of slag using alkalis (Chassevent, 1937)
Feret	1939	Slags used for cement (Feret, 1939)
Purdon	1940	Investigated clinker-free. Alkali-Slag Combinations.(Provis; Deventer, 2014)
Glukhovsky	1957	Synthesized binder using hydrous and anhydrous aluminosilicates.
Glukhovsky	1959	Basesteric and development of alkaline cements (Torgal; and Jalali, 2009)
Glukhovsky	1965	First called “alkaline cements” (Glukhovsky, 1965)
Davidovits and Cordi	1979	Term “Geopolymer” (Davidovits; Cordi, 1979)
Malinowski	1979	Characterization of millennial aqueducts (Torgal and Jalali, 2009)
Davidovits	1982	Mixture Kaolinite-limestone and dolomite with alkalis (Davidovits, 1982)
Forss	1983	Cement type F (slag cement of low porosity) (Forss, 1983)
Langton and Roy	1983	Characterization of materials in millennial buildings (Langton; Roy, 1983)
Davidovits and Sawyer	1985	Patent of the “Pyrament” cement (Davidovits; Sawyer, 1985)
Krivenko	1986	Systems R2O - RO - SiO2 - H2O (Krivenko, 1986)
Malolepszy and Petri	1986	Activation of synthetic slags GGBFS (Malolepszy and Petri, 1986)
Malek. et al.	1986	Forms of Slag cement-low level radioactive waste (Malek et al., 1986)
Davidovits	1987	Comparison of millennial and modern concretes (Davidovits, 1987)
Kaushal et al.	1988	Adiabatic cured nuclear wastes forms (Kaushal; Roy; Licastro, 1988)
Deja and Malolepsy	1989	Resistance to chloride attack (Deja and Malolepsy, 1989)
Roy and Langton	1989	Analogies of millennial concrete (Langton; Roy, 1989)
Majunbar et al.	1989	GGBFS activation - C12A7 (Majumbar; Edmonds, 1989)
Talling and Brandstetr	1989	Alkaline slag activation (GGBFS) (Talling; Brandstetr, 1989)
Roy et al.	1989	Rapid setting alkali-activated cements (Roy et al., 1989)
Wu et al.	1990	Early Activation of slag cement (Wu et al., 1990)
Roy et al.	1991	Fast setting of alkaline activated cements (Roy et al., 1991)
Roy and Silsbee	1992	Review of alkaline activated cements (Torgal; Jalali, 2009)
Palomo and Glasser	1992	Metakaolin with CBC (Palomo and Glasser, 1992)
Roy and Malek	1993	Slag Cement (Roy and Malek, 1993)
Glukhovsky	1994	Millennial, modern and future concretes (Glukhovsky, 1994)
Krivenko	1994	Alkaline cements (Krivenko, 1994)
Wang and Scrivener	1995	Microstructure of alkaline activated slag (Wang and Scrivener, 1995)
Shi (Shi, 1996)	1996	Pore structure and permeability of alkali-activated GGBFS
Fernández and Portas	1997	Kinetic studies of activated slag cements (Fernández-Jiménez; Portas, 1997)
Katz	1998	Microstructure of activated fly ash (Katz, 1998)
Davidovits	1999	Chemistry of geopolymeric technology (Davidovits, 1999)
Roy	1999	Opportunities activated cements (Roy, 1999)
Palomo et al.	1999	Activated fly ash cement for future (Palomo et al., 1999)
Gong and Yang	2000	Activated red mud/slag cement (Gong, 2000)
Puertas et al.	2000	Activated fly ash/slag cement (Puertas et al., 2000)

Collins and Sanjayan	2001	Activated slag concrete (Collins and Sanjayan, 2001)
Palomo and Palacios	2003	Immobilization of hazardous wastes (Palomo, 2003)
Grutzeck et al.	2004	Zeolite formation (Grutzek et al., 2004)
Feng et al.	2006	Sialite Technology (Feng et al., 2006)
Duxson et al.	2007	Geopolymer technology: State of the ar (Duxson et al., 2007)
Hajimohammadi et al	2008	One-part geopolymer mixtures (Hajimohammadi, 2008)
Provis and Van Deventer	2009	Geopolymers (2009)
Ravikumar et al.	2010	Activated concretes containing FA or GGBFS (Ravikumar, 2010)
Puertas et al.	2011	C-A-S-H gel model for activated slag cements.(Puertas F. 2011)
Shi et al.	2011	Hybrid alkaline cement (Shi et al. 2011)
Tãnzer et al.	2012	Durability of model for activated slag cements (Tãnzer R. 2012)
Lee	2013	Alkali-activated FA/GGBFS concrete cured at room temperature (Lee, 2013)
Prabir and Pradip	2014	Hybrid alkaline cement
Palomo et al.	2014	Hybrid alkaline cement
Yuan et al.(2014)	2014	Shrinkage compensation for alkali-activated slag concrete
Pradip and Prabir	2015	Hybrid alkaline cement
Thomas and Peethamparan	2015	Engineering properties of AAC. (Thomas and Peethamparan, 2015)
Ding et al.	2016	Mechanical properties of AAC:Stat-of-art (Ding et al., 2016)
Rafeet et al.	2017	Mix proportioning of FA/GGBFS based AAC (Rafeet et al., 2017)
Ibrahim et al.	2018	Characterization of ambient cured AAC utilizing nano silica (Ibrahim et al., 2018)
Koenig et al.	2019	Flexural behavior of steel and macro-PP fiber reinforced AAC (Koenig et al., 2019)
Zhang et al	2020	Fabrication and engineering properties of AAC: A review

Purdon (1940) in Belgium, used slag activated alkaline with sodium hydroxide, suggesting that the process was basically developed in two stages: a first in which there would be the release of silica, alumina and calcium hydroxide and a second in which there would be formation of hydrated calcium silicates and aluminates as well as regeneration of the caustic solution.

From the results obtained, this researcher concluded that the alkali metal hydroxides act as catalysts, so that, through the leaching of this alkali metal from the hardened binder, in amounts similar to those present in the initial mixture, it was possible to prove this theory. Through the results obtained and documented, they defended the possibility of using such residues, -quite available at the time, to reduce the need for Portland cement and reduce incorporated costs. In addition to that, the researcher Joseph Davidovits investigated, developed and patented the ligands obtained by alkaline activation of kaolin and metakaolin as precursors and fire resistant materials, which he later designated as “geopolymer” (Davidovits, Deventer; Provis, 2009).

Geopolymers are polymers because they have the ability to transform, polycondense, take shape and harden quickly at low temperatures (Davidovits, 1991). In addition, they are inorganic, hard, stable up to temperatures of 1250 °C and non-flammable, that is, they are geopolymers. In terms of structural ligands, this researcher considers it to be a modern adaptation of processes used by Romans and Egyptians, even going so far as to hypothesize, after studies on the pyramids of Egypt, that those constructions use ligands produced by humans instead of traditional natural stone.

Davidovits (1982) also found, from chemical and mineralogical studies, that the blocks are not made of natural limestone, but of a binder made from a mixture of limestone from Giza with NaOH, produced on site by mixing lime, sodium carbonate and water. According to analysis carried out, the natural stones are composed of fossilized sheets arranged parallel to each other, and in sedimentary layers. However, in pyramid blocks, these layers are randomly oriented, as it would happen in a traditional binder. X-Ray studies of samples from the various pyramids indicate that calcite ($CaCO_3$) is the predominant crystalline phase. Furthermore, an amorphous material composed of aluminosilicates and an analcite-type zeolite ($Na_2.Al_2O_3.4SiO_2.2H_2O$) was also detected in the microstructure (Torgal, 2007).

From these investigations (Davidovits 1982), research in this domain has increased exponentially, with a vast set of investigations focusing on the development of a sustainable binding agent, starting to consider the use and study of the physical properties of alkali activated materials, through the use of a variety of waste-based materials and activators. Several investigators have observed the existence of almost 40% of analcite-type zeolites in the composition of mortars discovered at Jericho in the Jordan River valley and at Tel-Ramad in Syria, dated to 7000 BC (Contenson and Courtois, 1979; Perinet et al., 1980; Davidovits and Courtois, 1981). Furthermore, Langton and Roy (1984; 1989) analyzed Roman mortars, having discovered analcite in the composition of these binders.

Campbell and Folk (1991) showed that the durability of ancient binders was due to the high level of zeolitic and amorphous compounds in their composition. The Belgian researcher Demortier (2004) published a more recent study in which very solid arguments are made in defense of - Davidovits' thesis, comparing the resonance spectra for silica and alumina from a sample of the pyramid of Kéops and another from a geopolymeric binder, revealing that the first contains about 15% of geopolymeric binder (Torgal and Jalali, 2009).

Besides that, for Granizo (1998), the presence of zeolites in several ancient cements suggests that they are the stable phase of a long-term conversion, meeting certain hydrothermal conditions, from the initial phases to the formation of zeolitic-type materials (Torgal, 2007). Much of the research on ligands obtained by alkaline activation is related to the activation of blast furnace slag, known as “alkali-slag cement” or “alkali-activated slag cement” (Pacheco and Jalali, 2009). Blast furnace slag is a byproduct of the production of iron ore, which has a- substantial amount of calcium in its composition that comes from the calcium carbonate used as a flux (Pacheco and Jalali, 2009).

Characterization of chemical and structural elements of alkali-activated materials

Some researchers confirm the existence of two distinct models of alkaline activation: in the first model, the reaction products are of the hydrated calcium silicate type (C-S-H), a good example being the activation of blast furnace slag, a material with a high percentage of oxide and calcium that can be activated with alkaline solutions of low or medium concentration. In the second model, a polymerization reaction is triggered from the material composed essentially of silica and alumina when activated in the presence

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of highly concentrated alkaline solutions (Torgal, 2007). Table 2 presents the main alkaline activators used by researchers. Additionally, figure 1 and figure 2 present the types of poly(sialates) produced and illustrate the alkaline activation processes, respectively.

Table 2. Main alkaline activators - adapted from Duxson, 2007

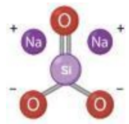
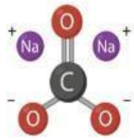
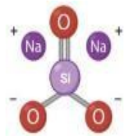
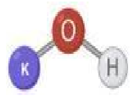
Alkaline Activators	**Structure**
The sodium hydroxide (NaOH), also known as caustic soda, is an inorganic compound that has a variety of uses in manufacturing including soaps, paper, dyes and petroleum products. As a strong base, it is corrosive in nature and can cause allergic reactions and skin irritations (Miller, 1987). It can be found in liquid and solid states that are colorless and odorless.	
Sodium silicate is a general name for any chemical compound that has sodium oxide, $(Na_2O)_n$, and silica, $(SiO_2)_m$, in it. It has a variety of applications in the construction industry which include sealing concrete cracks, dissolving agents in alkali-activated materials and an excellent accelerator (Hocking MB 2005). Commercially available sodium silicate has a pH of about 10 to 13, inversely related to silica content.	
Sodium carbonate is another inorganic compound that is soluble in water. With the formula Na_2CO_3, it has a high concentration of bicarbonate that increases the pH or leads to the dissolution of other matters within the medium (Speight JG 2017). This solid material can be produced from natural sources of trona and sodium carbonate brines, as well as the mineral nahcolite (natural sodium bicarbonate sources) (Haneke KE 2002) which commonly occurs as a decahydrate crystalline that later efflorescence and forms a white powder (Encyclopedia.com 2020).	
Sodium metasilicate is the main component of sodium silicate with Formula Na_2SiO_3. The production of sodium metasilicate is an energy-intensive process that requires the fusion of silica sand (SiO_2) with sodium carbonate (sodium carbonate) which occurs at around 1400°C (Kubba, 2018).	
With the KOH formula, **the potassium hydroxide** is a strong base that is marketed in **pallets**, flakes and powder that is known for its corrosive tendency to absorb moisture from the environment. The production of potassium hydroxide is done through the electrolysis of potassium chloride. Serious reactions, skin irritations and other dangerous side effects have been documented as a result of the contact with it (Torres-Carrasco et. al., 2019).	

Figure 1. Types of Poly(sialates) - Davidovits, 2005

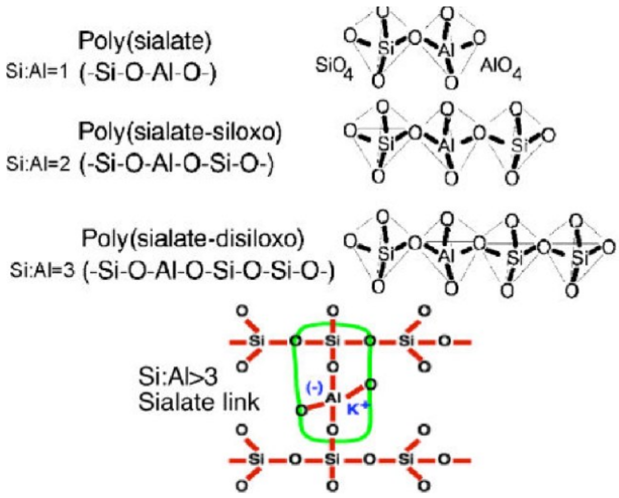
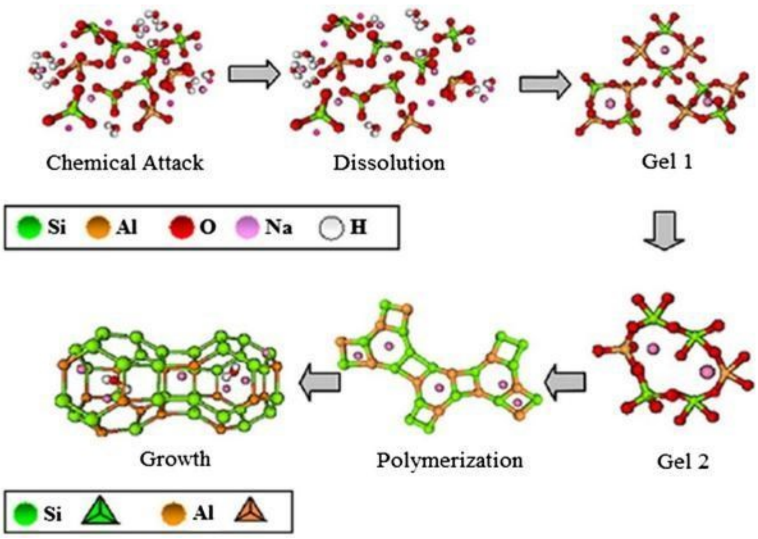


Figure 2. Alkaline activation processes - adapted from Duxson, 2007.



In the study of some results obtained on the characterization of ligands achieved by alkaline activation (Couto Oliveira n.d.) one sees that it is a hydration reaction of aluminosilicates with alkaline or alkaline-earth substances, namely hydroxides (ROH, R(OH)2), salts of weak acids (R2CO3, R2S, RF), salts of strong acids (Na2SO4, CaSO4.2H2O), or silicate salts of type R2.(n)SiO2, where R is an alkaline ion of type Na, K or Li, or alkaline earth such as Ca (Pinto, 2004; 2006). At first, the aluminosilicates must undergo a thermal treatment, involving the loss of water and the alteration of the coordination of the aluminum ion with the oxygen (Couto Oliveira n.d.). This procedure helps to enhance the results as the material thus shows greater capability of chemically combining.

As an effect of these changes, it can be noticed that the material loses a large part of its crystalline structure, remaining in a practically amorphous state, with high entropy (Chang, 1994). Thus, aluminosilicates are potential starting materials for alkaline activation, since they have a recognized thermal history. Among them are slags, which can be obtained in blast furnaces, fly ash, obtained by burning coal in thermoelectric power stations, volcanic ash, with natural heat treatment and tile or brick dust, which have been in industrial baking ovens. Obtaining amorphous matrices is reinforced by the cooling phase, as it is normally very fast and critical (Pinto, 2004; 2006; Couto Oliveira n.d.).

Metakaolin, which can also be activated alkaline, is obtained from kaolins, natural aluminosilicates, resulting from chemical changes in feldspathic rocks (meteorization). For that to happen, it is necessary that the kaolins undergo a heat treatment aiming at dehydroxylation and altering the aforementioned aluminum coordination. It should be noted that kaolins, as well as volcanic ash and certain fly ash, do not belong to the traditional line of mineral binders in which calcium, similarly to what happened with Portland cement, plays a leading role, since they generally have a low or practically zero calcium content (Pinto, 2004; 2006; Couto Oliveira n.d.).

In the alkaline activation process from kaolinitic precursors (metakaolin) the release of Al and Si elements is observed, while Ca and Si are released from precursors from blast furnace slag (Severo et al, 2013). Studies carried out prove that the degree of reaction in the metakaolin solutions activated with sodium silicate (NaSiO4) and sodium hydroxide (NaOH) is greater than if the metakaolin is activated only with NaOH. The fact that the silica present in the sodium silicate reacts faster than the silica in the metakaolin, may serve to prove this conclusion, since a greater proportion of the compound remains unreacted (Severo et al, 2013).

When studying the alkaline activation of metakaolin using an alkaline solution with sodium silicate, Pinto (2004) mentioned an increase in mechanical strength, either in compression, obtaining values from 30 to 60 MPa, or in traction by bending, obtaining values between 5 and 7 MPa. Fernandez-Gimenez and Palomo (2003) reported that the use of a solution composed of NaOH and sodium silicate as an alkaline activator, instead of only NaOH, causes an increase of 40-90 MPa only after one day of curing (Severo et al, 2013). In addition to these, other studies demonstrated that geopolymers produced with metakaolin and activated with NaOH and sodium silicate show an increase in mechanical strength when the Na2O/SiO2 molar ratio decreases (Severo et al, 2013).

The development of activated alkaline systems based on calcium-rich precursors has been monitored for over a century (Provis; Bernal, 2014; Nodehi and Taghvaee, 2021). In this system, precursors such as ground granulated blast furnace slag and Class C fly ash are used in a relatively mild alkaline condition (Garcia-Lodeiro, 2015; Nodehi and Taghvaee, 2021).

The participation of calcium in this system can be in the form of: (i) Ca (OH)2; (ii) replacing the cations within the mixture and linking it; or, (iii) reacting with dissolved aluminum and silicate species to initially form C-S-H gel (Nodehi and Taghvaee, 2021; Guo, 2010).

This addition of high calcium materials mainly alters the regulation time and the chemistry of the product (Nodehi and Taghvaee, 2021; Shi, 2019), where Al3+, Si4+, Ca2+, and Mg2+ are the main network modifiers in the reaction chain. These alkaline modifiers result in the formation of calcium aluminum silicate hydrate (C-A-S-H) (Nodehi and Taghvaee, 2021; Shi, 2019; Temuujin, 2009). Thus, the higher level of calcium leads to faster hardening of the C-A-S-H gel phase, lower set-up time (Nodehi and Taghvaee, 2021; Temuujin, 2009; Guo, 2019) and higher early strength (Nodehi and Taghvaee, 2021; Topark-Ngarm, 2015; Puligila, 2013).

This generation process has been reported to increase strength over longer periods of time if followed by curing under ambient conditions, similar to the ordinary Portland cement concrete system that develops hydrated calcium overtime (Nodehi and Taghvaee, 2021; Topark-Ngarm, 2015).

On the opposite side, however, higher drying shrinkage and cracking (Nodehi and Taghvaee, 2021; Collins, 2000), higher risk of steel corrosion through chloride ion exchange (Nodehi and Taghvaee, 2021; Sufian, 2014), and the loss of durability especially at high temperatures (above 300°C) (Nodehi and Taghvaee, 2021; Pan, 2018) have been reported for high calcium systems.

These adverse effects on the characteristic of alkali-activated materials are reported to be related to the molar ratio of Ca/Si, Al/Si, and the type and amount of activator, as well as the pH level of the medium, and as described by many investigators, the gypsum formation due to the presence of calcium (Provis; Bernal, 2014; Nodehi and Taghvaee, 2021; Deventer and Provis, 2009).

Hybrid alkaline cements

Recently, a new type of binder, known as hybrid alkaline cement, has been developed (Nath and Sarker, 2015; Palomo et al., 2014; 2013; Shi et al., 2011). These materials aim to combine the positive characteristics of ordinary Portland cement with those of alkali-activated materials, with two types of hybrid cements. The first includes the combination of a high proportion of aluminosilicate (above 70%) and Portland cement and the second is a mixture of aluminosilicate with another source of calcium, such as blast furnace slag. These materials are considered mixed Portland cements activated by alkali where the two gels coexist, C-S-H (product of Portland cement hydration) and N-A-S-H (product of alkaline activation of aluminosilicate) (García-Lodeiro et al., 2013).

The commercialization of this type of cement is considered highly viable due to its potential inclusion in construction taking into account its environmental, technical and economic advantages. However, the lack of policies, investment and marketing conditions delayed the success of the expansion of this technology. Based on the composition and calcium content of the solid precursor, three types of alkali-activated binder can be defined: (i) calcium alkali-activated ligands with high calcium content and, (ii) low calcium content and calcium intermediates. According to previous studies (Provis, 2014), alkali-activated binder with high calcium content are ligands with a Ca/(Si + Al) ratio of about 1, which is commonly a result of an alkaline activation of blast furnace slag. The main reaction product in this group is a calcium aluminosilicate hydrate, or C-A-S-H gel type with a disordered structure similar to tobermorite (Provis, 2014; Thomas, 2016).

The low calcium group binders are produced by alkaline activation of low calcium aluminosilicate materials (e.g. metakaolin or class fly ash). The main reaction product in these ligands is a structurally disordered three-dimensional sodium aluminosilicate hydrate (referred to as N-A-S-H or geopolymer) with a zeolite-like structure (Provis, 2014; Palomo, 1999; 2004; Davidovits 1991). These binders generally require heat or steam curing (e.g. at 60°C) to facilitate the dissolution of fly ash or metakaolin (Kovalchuk, 2007; Duxson et. al., 2007) and to influence the reactivity of the glass phase in aluminosilicate source materials (Provis, 2014).

Bearing in mind that the production of Portland cement currently represents 5% of CO2 emissions worldwide, such a rise in production implies a drastic increase in these emissions, which means a radically opposite stance to that recommended by the Kyoto protocol, which advocates the reduction of emissions in relation to the base year of 1990. And even though energy consumption for clinker production has already reached a level in terms of best practices at 3GJ/ton. According to Torgal and Said, 2008, a limit also seems to have been reached in the clinker/cement ratio. The world's largest cement producer reports having reduced carbon emissions from its cements from 0.767 to 0.685 tons of CO2 per ton of cement from 1990 to 2003 (Lafarge, 2003).

Currently, the cement industry produces cement additives with byproducts of cementitious characteristics, such as slag and fly ash, as a way of reducing both the level of emissions and their cost. (Gielen, 1997) states that cements with fly ash (25% replacement) are responsible for a level of carbon emissions of 0.67 ton of CO2 per ton of cement. Even so, it does not seem clear that this is the way to achieve substantial reductions in carbon emissions generated by the cement industry, and it is more likely that the solution may involve the development of “more environmentally friendly” materials. The present article, according to (Torgal and Jalali, 2010), aimed at analyzing the performance of ligands obtained by alkaline activation in terms of their carbon emissions (Torgal and Jalali, 2015).

The issue of carbon emissions from ligands obtained by alkaline activation has been the subject of some controversy. According to Torgal and Jalali (2010), Davidovits (1990; 1999) was the first author to comment on the low emissions of ligands obtained by alkaline activation of 0.184 ton of CO2 per ton of binder which, when compared to the Portland cement emissions, shows an improvement of 370%.

The analysis of the literature on the retraction of alkaline activated binders indicates this as one of the factors that influences the performance of this binder. The phenomenon of shrinkage has been widely studied for Portland cement-based ligands (Torgal and Jalali, 2009). However, it can be accepted that the mechanisms associated with it are, to some extent, similar, although not in the same order of magnitude as those that occur in alkaline-activated ligands.

The shrinkage is due to a phenomenon of volume decrease in part as a result of a decrease in the liquid phase. It is more appropriate to speak of retractions in the plural, because of the various elementary retractions that actually exist: a) Plastic shrinkage, which occurs before adjusting the mixture, by evaporating surface water (Wittmann, 1976; Torgal and Jalali. 2009); b) Shrinkage by drying, which occurs after the end of setting by evaporation of water in the pores (Torgal; Jalali. 2009); c) Autogenous shrinkage, also known as self-drying or chemical drying, defined as volume variation at constant temperature, without exchange of humidity with the outside, and due to the evolution of hydration reactions (Tazawa et al., 1995; Torgal and Jalali. 2009); d) Shrinkage due to temperature variation, similar to the exothermic reaction between water and Portland cement, an exothermic process also occurs in alkaline-activated binders, which will be associated with expansion phenomena that will lead to shrinkage when the temperature drops (Torgal and Jalali, 2009)).

The importance of shrinkage is generally associated with the decrease in the durability of the material under analysis due to the appearance of cracking and what this represents in terms of the ingress of aggressive substances into the material, and given its ability of resistance to provide a general idea of the quality of the material (Torgal and Jalali, 2009). The level of shrinkage is also extremely important, especially if this material can be used, for example, to repair concrete structures. In this case, the existing concrete will prevent this shrinkage, causing the appearance of stresses that can lead to the cracking of the connection zone (Asad, 1997; Torgal and Jalali, 2009).

The use of low-calcium fly ash allows for a longer setting time and better workability than high-calcium fly ash, which is less available and often has more variable characteristics. Through the use of low calcium fly ash, due to the reduced Ca content, however, the reactivity of the mixture is drastically affected to the point where another precursor with potentially higher calcium content is used or thermal curing becomes the only way to kick-start the chemical reaction (Thomas 2016; Palomo 1999).

Fly ash can be divided into materials with a high calcium content (class C) and low calcium content (class F), which are one of the most commonly used precursors in alkali-activated materials. Low calcium fly ash (class F) has been much more widely exercised as a major precursor in alkali-activated materials because of its availability and potentially better performance (Deventer; Provis, 2009). The use of low-calcium fly ash allows a longer setting time and better workability than high-calcium fly ash, which is less available and often has more variable characteristics. Through the use of low calcium fly ash, due to the reduced Ca content, however, the reactivity of the mixture is drastically affected to the point that another precursor with potentially higher calcium content is used or thermal curing becomes the only way to kick-start the chemical reaction (Shekhovtsova, 2018; Abdel-Gawwad, 2018).

Metakaolin results from the hydroxylation of kaolinite Si2O5,Al2(OH)4 that occurs around 750°C. Its main chemical components include silica (SiO2; 44.4-73%) and alumina (Al2O3,~14.5-47.43%), with a variable particle size of 1.20-38 μm and surface area of 2.16-22 m2/g (Torres-Carrasco, 2019; Rakhimova, 2019; Idir, 2020). Metakaolin is a key component especially used with low calcium alkali-activated materials that adjust the Si/Al of the binder. Metakaolin is reported to increase the polycondensation rate and effectively increase the reactivity of Class F fly ash to form denser nano and microstructures, achieving higher mechanical properties if cured at high temperature (Torres-Carrasco, 2019; Winnefeld, 2010).

In general, silica fume represents a pure silica material; whose use, in an alkali-activated mixture, is usually as charge. In this regard, the literature shows that the use of silica fume due to its small particles has an invariably positive effect on mechanical and durability properties of alkali-activated materials. This trend is aimed at providing more available Si content for further reaction of aluminosilicate sources in the mixture (Luukkonen, 2018), in addition to acting as a filler and reducing the permeability of hardened alkali-activated materials (Sun, 2018).

Municipal solid waste and its incineration

Waste is "any substance or object that the holder discards or intends or is obliged to discard" (Portuguese Decree-Law nº 178/2006, amended and republished by Decree-Law nº 73/2011). The rapid increase in the world population in the last century has generated a rise in municipal solid waste (MSW). Thousands of tons of MSW are produced each day (Hoornweg and Bhada-Tata, 2012; Cristelo et al., 2020). Municipal solid waste (MSW) has increased exponentially since the rapid world population and consumption habits growth. In 2018, 513kg were generated per capita in Portugal, which corresponds to 5281 million tons. In the EU, 492 kg of municipal waste were generated per capita on average (Matos; Sousa-Coutinho, 2022).

The incineration of urban solid waste (MSWI) is one of the main management processes of the entities associated with it and has been receiving increasing attention worldwide, hence the fact that many countries address the issue of the beneficial use of this waste, developing plans and strategic management regulations. The rise in MSW production is nowadays largely managed by the incineration method. Typically, this method is implemented through energy recovery in waste-to-energy plants. Basically, waste-to-energy plants burn waste that could not be recovered or recycled. MSW incineration generates energy, which can be transformed into electricity, hot water or steam. The incineration approach reduces MSW volume by about 90% (Matos; Sousa-Coutinho, 2022).

Municipal solid waste incineration (MSWI) gives rise to two main products, namely fly ash (FA) and bottom ash (BA). The (FA) is collected after the filtration process and carefully sealed to ensure there is no contamination of the local surroundings and then transported to hazardous landfills, treatment plants or salt mines. Since these locations are fully confined, the (FA) cannot leach into the environment (Matos; Sousa-Coutinho, 2022). However, significant volumes of fly ash (FA) and especially bottom ash (BA) are still produced by this method, against the unavoidable financial and environmental costs associated with exposure to these byproducts (Cristelo et al., 2020).

A common treatment of solid waste produced in urban areas is incineration, with an energy recovery bonus resulting from the caloric content of the waste, which allows the production of electricity, (principle of converting waste to energy (WTE), during the incineration process (Cristelo et al., 2020). This is a very effective procedure due to its ability to reduce waste volumes as well as the associated recovery through energy production (Cristelo et al., 2020). The need for WTE arose from the interconnected phenomena that are happening on our planet, that is, the need for energy and the problem of waste. As the global population continues to grow and living standards increase, dependence on fossil fuels as an energy source is becoming unsustainable as it is causing harmful effects such as exploitation, pollution and greenhouse gas emissions, threatening the sustainability of the planet (Lam, 2013).

Energy and waste systems policies share mutual concerns about environmental impacts that include greenhouse gas reductions, soil contamination and groundwater contamination. An example of this mutual concern is an energy and climate law introduced by Sweden in 2009, which integrates energy and climate policies as one. The problem of waste is now seen as a response to energy needs (Guziana 2014). The importance of the WTE is evident when considering the EU's energy policy, which includes two connected goasl for 2020 consisting of a 20% share in renewable energy sources and a 20% reduction in greenhouse gas emissions compared to 1990 levels. It is important to note that WTE is classified as a renewable energy source by the European Directive on Renewable Energy Sources, whose definition of biomass includes the biodegradable part of urban and industrial waste. In addition, these targets should act as steppingstones to further reductions in 2050. For example, the low carbon economy 2050 roadmap emphasizes the importance of electricity, which means the need for non-fossil fuel energy sources such as WTE.

Also, there are two other waste policies that promote WTE. One of them is the Landfill Directive, in which EU Member States have an obligation to reduce the amount of biodegradable municipal waste that goes to landfill. The other is the Waste Framework Directive, which promotes recycling and recovery. WTE is classified as recovery as long as the process meets certain levels of efficiency (Guziana, 2014). Although the volumes of bottom ashes (BA) and fly ashes (FA) are much lower than the total waste, representing a weight reduction of around 80% (Wei et al., 2011), their recycling by integration in any industrial process is an attractive possibility (Cristelo et al., 2020).

The WTE meets the two main objectives of waste management (Brunner & Rechberger, 2015). First, the protection of humans and the environment, such as emissions from incineration that are so technologically advanced that the compounds released into the air, water or soil are not threatening to humans or the environment. The second objective is the conservation of resources and the recovery of materials, which WTE processes by nature positively affect, since in WTE plants, urban solid waste contributes to energy recovery and suffers a reduction in its volume by 90% and its weight by 60%.

It is a process widely applied in several countries, but with emphasis in Europe where, according to information provided by the European Confederation of Waste and Energy (CEWEP), 492 WTE plants operate and contributed to the incineration of 70 MT, in 2017, with bottom ash being the main byproduct obtained during waste treatment, and classified as hazardous waste (EWC 19 01 11) or non-hazardous waste (EWC 19 01 12), depending on the concentration or not of hazardous substances. In the recent past, one of the concerns with MSWI was atmospheric pollution by dioxin (C4H4O2), furan (C4H4O) and heavy metals originating from MSW. Subsequently, emissions were drastically reduced through the implementation of APC devices to treat gases of a toxic nature using dry, semi-dry and wet scrubbing mechanisms. Later, the use of APC devices shifted the concern from air pollution to leachate from ash disposal in landfills, and RDF processes were reported to provide significant control over heavy metal release, reducing Pb to 52%, Cd to 73% and Cr to 63%.

In general, bottom ash is composed of Si, Al, Ca and Na oxides, and a small amount of heavy metals. And they undergo prior stabilization through an outdoor maturation treatment of 2–3 months, consisting of their carbonation and pH stabilization at values between 8–10 (Chimenos et. al., 2000).

Although BA is significantly less polluting than FA (Li et al., 2012; Liu et al., 2018), it still has a considerable content of heavy metals. In addition, there are several methods, already disclosed and commonly applied, to deal with MSW fly ash, namely the treatment and landfilling as a hazard, solidification and removal of heavy metals (Bie et al., 2016; Cristelo et al., 2020).

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The byproduct resulting from the maturation treatment is a bottom ash that is valued for engineering purposes. The main fields of application of BA as a secondary material are civil engineering, chemical engineering and the construction sector (Verbinnen 2016). Although the municipal solid waste incineration rate (MSWI) varies significantly from country to country and, more importantly, between different areas of the globe, it can reach 50-58% in some parts of Northern European countries (Dou et al., 2017) (Cristelo et al., 2020). According to EUROSTAT data, the incineration approach has been increasing in European countries. In 2017, European waste-to-energy plants treated around 96 million tonnes of MSW and around 19 million tonnes of MIBA were generated (CEWEP 2015). Several EU countries use MIBA as an alternative to non-renewable natural resources such as gravel and sand (Matos; Sousa-Coutinho, 2022). However, new applications of BA have emerged in recent years for their use as a precursor in cements obtained by alkaline activation (Silva 2017) due to their composition rich in silicates and aluminosilicates (Wei et al., 2011), making them an alternative to ordinary Portland cement (Matos; Sousa-Coutinho 2022).

Hybrid cement with MSWIS

According Lurdes Lopes (2019) in his approach on the production of a cementitious material based on MSWIS, pretreatment, such as grinding, is necessary, as shown in figure 3 - a fact also addressed by different authors. One article (Jiaqi Li, 2021) shows a critical overview of the pretreatment method that optimizes the use of MSWIS ash in cement/concrete and the influences of MSWIS ash on cement/concrete performance. Recent studies suggest that MSWIS ash can be used to produce concrete, bricks and other building materials with or without pretreatment of ash MSWIS (Haiying 2011; Tang, 2020). Many pretreatment methods have been applied to lower the content of chlorides, HMs, and or organic matters of MSWI ash (Jiaqi Li, 2021). The industrial pretreatment methods include water-washing, aging, magnetic separation, mechanical separations, and eddy current separation. The separation methods reclaim ferrous and non-ferrous metals (including precious metals, aluminum, and HMs (Biganzoli et. al., 2013). These industrial-scale separation technologies are mature and very commonly used (Jiaqi Li, 2021).

Figure 3. Working process of a ball mill usually used in the first stages of a laboratory analysis, as a pretreatment process of physical nature, consisting of the fragmentation of slags for the purpose of reducing the particle diameter (Lopes, 2019).

Water-washing is the most common industrial method to remove soluble salts, such as, NaCl, KCl,or CaCl2. From MSWI ash, more specifically FA (Jiaqi Li, 2021). This pretreatment is cost-efficient to remove chlorides, which trigger the corrosion of steel rebar and concrete mixers. However, water-washing typically can lower the chloride content down to 0,5 wt.% due to the presence of low-solubility chlorides (Mulder, 1996). Calcium oxychloride (CaOCl) is challenging to remove by only one time of washing. Mao et al. found that the influence of water-to-solid ratios on chlorides removal was less pronounced when the ratio was over three, and the replication of washing at this ratio was more efficient and water-saving than at a ratio of 20 (Mao 2020). Because water-washing is essentially a leaching process at high water-to-solid ratios, it yields leachates with HMs, reducing the HMs content of washed MSWI ash (Chimenos, 2005).

After appropriate treatments, MSWI ash, as a pozzolamic material, can potentially lessen the global shortage of SCMs. MSWI ash must be appropriately managed as SCMs in academic studies and practical applications. For example, MSWI ash must not be used to replace low-grade PC (Bie, 2016). Thus, such MSWI ash incorporated cement-based materials are considered products of the stabilization/solidification (S/S) process. These low-value products are more suitable as landfills with low toxic leachability or construction materials in niche markets (Quina 2014). Thus, the influence of unwashed ash on cement settings is complex; prolonged (Rémond, 2002) and shortened setting time (Shi, 2009) of raw ash-containing pastes have been reported. In addition, soluble Cl triggers steel-rebar corrosion. The metallic Al and Zn in raw ash cause the expansion and cracking of low-strength ash-containing pastes (Joseph et. al., 2020).

The low amorphous content and large grain size of BA may limit its reactivity in PC systems. Thus, raw ash contributes little to strength development. Even with the addition of alkaline activators (CaSO4 and Na2SO4), the compressive strength of hybrid cement with 40% MSWI mix ash is still~40% lower than OPC (Garcia-Lodeiro 2016). The low strength of blended cement incorporated with raw MSWI ash limits its wide use as standard-performance construction material despite its HMs immobilization advantage. These low-strength blended cement-based materials from the SS process are niche products (Quina, 2014). Thus, pretreatment of MSWI ash is suggested for its appropriate utilization as SCMs. The possible use of treated MSWI BA as SCMs depends on many factors, e.g., amorphous content, particle size, and compositions of PC and treated BA. Raw BA particle sizes are large; thus, milling and sieving are common processes. Jure et al. partially replaced OPC with milled BA, and the compressive strengths at 3-28 days were comparable to the 42.5R OPC group when the cement substitution was ‹ 20 wt.%. A 10% compressive strength reduction was observed at a substitution level of 30% at 28 days.

The leachability of the BA incorporated group met regulatory limits (Juric 2006). Similarly, Zhang and Zhao replaced 30 wt.% 42.5R OPC with wet-milled BA, while the blended group only exhibited similar or lower strengths compared to the pure OPC counterpart from 1 to 90 days (Zhang; Zhao, 2014). Bertolini et al. compared the influences of wet and dry-milling of BA on the mechanical properties of concrete (Bertolini, 2004). Concrete containing cement substituted with 30 wt.% wet-milled BA exhibited similar or higher compressive strengths compared to 52.5R OPC concrete from 1 day to 180 days, while concrete containing 30 wt.% dry-milled BA substitution exhibited 55% lower strength. The strength difference may be explained by the finer grains of wet-milled BA compared to dry-milled BA and the consumption of metallic Al and Zn. The incorporation of unwashed or other washed FA in mortars diminished compressive strength (Keppert, 2015). Higher cement replacement levels, e.g., 30 wt.%, also resulted in lower strengths, according to Bertolini et al. (2004).

Alkali-activated binders with MSWI

In the field of use of municipal solid waste incineration slags, such as alkaline activation binders, its application is recorded in 1930 (Investigated setting behavior of slags in the presence of caustic potash); by the German Engineer and Chemist Kuhl in 1937 (Measured reactivity of slag using caustic potash and soda solution); by Chassevent in 1940 (Investigated clinker-free cements consisting of slag and caustic soda or slag and caustic alkalis produced by a base and an alkaline salt); by Purdon in 1957 (Synthesized binder using hydrous and anhydrous aluminosilicates-glassy rocks, clays, metallurgical slags, etc. and alkalis, proposed Me2O-MeO-Me2O 3-SiO 2-H2). The cementing system, called "soil cement" binder (Batista, 2018) by Russian Glukhovsky (Shi; Krivenko; Della Roy, 2006). We can mention that, for slag, the development of alkaline-activated ligands made a significant contribution in 1940 with Purdon's study of blast oven slag activated with sodium hydroxide, having observed that hydroxides played a role as catalysts (Torgal, Castro-Gomes and Jalali, 2008). Years later, in 1957, Glukhovsky developed a study dedicated to the discovery of a new ligand based on low or no calcium aluminosilicate materials, naming it "cement soil" (Pacheco-Torgal, 2015; Shi; Krivenko; Della Roy, 2006).

Although there was an increase in scientific production on alkaline activation in the decades following 1990, it was only in the 21st century that new publications on the case appeared, increasingly with some approach on other slags, but with little approach to slags from the incineration of municipal solid waste MSWIS. One of the factors that some bibliography addresses about the weak insertion of MSWIS in current studies is, (Garcia-lodeiro, Palomo and Fernández-Jiménez, 2015) - that alkaline-activated ligands are divided into three categories. A) Materials with high calcium content (CaO-SiO2-Al2O3), B) Materials with low calcium content (SiO2-Al2O3) and C) Materials with intermediate calcium content. The most used material in category A is blast oven slag (SiO2+CaO≥70%), having as main reaction products calcium silicates hydrated with aluminum in its composition (C-A-S-H), followed by a series of secondary products that depend on the nature of the precursor, the activator and its concentration, in addition to the healing conditions and Ph (Garcia-Lodeiro; Palomo; Fernández-Jiménez, 2015; Bernal et al., 2014). And category B shows materials that are rich in silicon and aluminum and have a low calcium, such as some fly ash and metakaolin (Batista, 2018).

X-Ray diffractogram of the fly ash, in which it is verified that the fly ash presents different peaks of diffraction of crystalline phases, which, according to Provis et al. (2009) and Williams et al. (2010), are phases that arise during the burning of mineral coal at very high temperatures (1200-1600ºC) and in a highly oxidizing environment. Diffraction peaks are identified correspondents to crystalline phases of Quartz (SiO2), Mulita (Al6Si2O3) and Hematite (Fe2O3) (Azevedo et al., 2017). The diffractogram also presents a period between 10 and 40º (2ɵ), which indicates the presence of amorphous material, where in the vast majority, amorphous (reactive) amorphous aluminosilicates will react during ash activation with alkaline solutions (Tonholo et al, 2019).

X-ray diphratogram of metacaulim, where it is observed that the metacaulin presents a high crystallin, due to the presence of Quartz (SiO2), Anatásio (TiO2), Ilita {(K,H3O)(Al,Mg,Fe)2(Si,Al)4O10[(OH)2, (H2O)]} and Kaolinite [Al2Si2O5(OH)4] (MAURI 2009).

Figure 4. X-Ray diffractogram of the fly ash

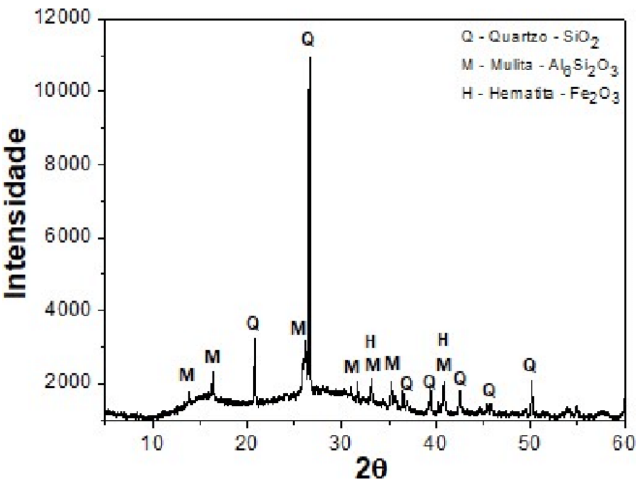
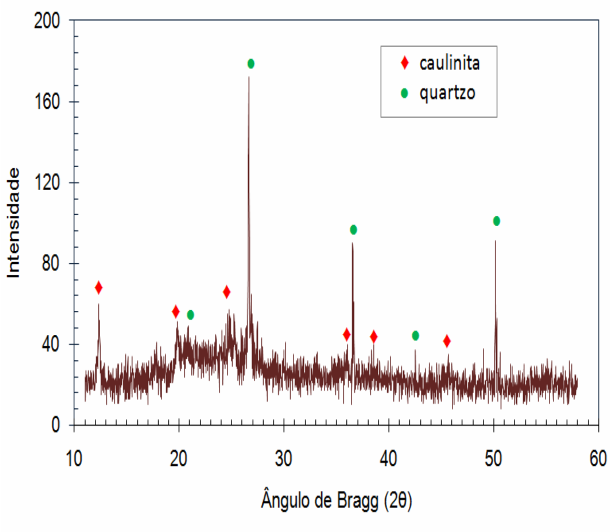


Figure 5. X-Ray diffractogram of metakaolin



In category C, the system type is hybrid in nature with combinations of agglomerates rich in allots and other reactive sources of calcium. This category allows the use and consequent recovery of residues and byproducts previously considered as little reactive, however, when combined with other materials they can generate good indicators as results (Batista, 2018). Its main reaction products are found in the combination of gels generated by systems with low and high calcium content, N-A-S-H and C-A-S-H, and in solutions with high pH, the solubility of calcium decreases and the Na+ ion can replace some Ca2+ ions in the formation of products, generating gels of type (N,C)-A-S-H. (Provis and Bernal, 2014; Batista 2018).

Final remarks

From the present research, the relevant remarks are drawn:

In the activation of slag with silicate and sodium hydroxide, the setting time depends on the activator composition. Researchers have observed initial and final setting times of 2 and 8 minutes, for an activator with 8% Na2O and Ms=1.25.

In slag activated with sodium silicate, researchers report very variable setting times, 2.75 to 4.25 hours for the beginning of setting and between 3.25 and 5.5 hours for the end of setting.

In slag activated with silicate and sodium hydroxide, researchers have observed a correlation between porosity and compressive strength, however, it states that only 70 to 80% of the variation in mechanical strength can be explained by the variation in pore volume, with the remainder due to chemical composition.

In slag activated with sodium hydroxide and carbonate and Portland cement binders, researchers have observed a much lower porosity than that of Portland cement.

In slag slurries activated alkaline with sodium hydroxide and sodium silicate with A/L=0.5, researchers obtained relatively low and increasing strengths of 8, 16 and 39 MPa respectively at 1, 7 and 28 days, however when using slag mortars (aggregate/gray=2) the strength made faster progress in the first days, with numbers at 9, 21 and 26 MPa.

In a study with concretes based on alkaline activated slag, with sodium hydroxide and sodium silicate and with A/L ratio=0.5, researchers obtained compressive strengths of 16 MPa, 36 and 46 MPa respectively after 1, 7 and 28 days and 6.5 MPa at the 28 day curvature.

In mortars with slag (aggregate/slag=2) and with an A/L ratio=0.51 activated with sodium silicate and sodium hydroxide, strengths of about 100 MPa in compression and 11 MPa in bending were obtained.

The pretreatment of MSWIS has shown that its application reduces the content of chlorides, heavy materials and some organic material issues, and that washing with water is a common method for removing soluble salts such as NaCl, KCl or CaCl2.

Wet grinding provides a basic environment for the dissolution of al-metallic aluminum in slag, and some comparative studies between the use of wet and dry grinding materials have shown that there is a greater performance in the compressive forces of mixtures containing wet grinding materials.

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