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Review

Development of cement industry, technology, and artistic applications: a historical overview of the Portuguese case within an international context

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ABSTRACT

The development of the cement industry and technology was a significant driver of progress in construction and artistic applications. Between the late 19th and 20th centuries, cement-based mortars and concrete were widely used in both utilitarian and artistic heritage, serving as structural materials and decorative ornaments. This paper presents a historical overview of the Portuguese cement industry within an international framework. It traces the evolution of modern hydraulic binders from the 18th-century experiments with clay-rich limestone and pozzolan to the 19th-century development of artificial hydraulic lime and major improvements in production processes, kiln design, and chemical analyses, resulting in the standardization of modern artificial Portland cement. These advancements shaped the adaptation and industrialization of cement in Portugal, and marked a gradual transition from natural to artificial cement around the turn of the century. Cement binders imported from England and France continued to dominate the Portuguese market well into the 20th century, even after national production began in the second half of the 19th century.

While current research on modern cement heritage often focuses on built structures, this study highlights the cultural significance of cementitious public art. It explores the transition from functional to artistic uses of cement, particularly during the 19th and 20th centuries, through selected case studies that reflect the different techniques and mortar formulations, as well as international influences on Portuguese cementitious heritage. An early example is the *Teatro Nacional de São João*, where ornaments created with cement-based mortars reinforced with steel bars and metal mesh reflect the influence of French engineering and the pioneering work of Joseph Monier. By contextualizing the Portuguese case within broader technological and artistic trends, this study contributes to a deeper understanding of cementitious heritage and emphasizes the need for further research on Portuguese cement-based artworks from the 20th century. The findings reveal compositional variations and applications that often relied on evolving techniques and experimental mortar formulations. Thus, understanding the material and technical evolution of cement-based mortars, as well as the cross-cultural exchanges that have shaped their use, is essential for the effective preservation and appreciation of this understudied part of modern heritage.

1. Introduction

Between the late 19th and 20th centuries, cement-based mortars and concrete emerged as one of the most commonly used materials in construction [1]. Chosen primarily for their versatility and final physical properties, they also provided a solution to post-war economic challenges, enhancing living standards by facilitating reconstruction, urban renewal, and infrastructure development [2–4]. As the industry progressed, cement binders became more readily available and cost-efficient, meeting the demand for economical and rapid construction without compromising quality [2]. Thus, the structural potential of cement has allowed its use in a multitude of utilitarian and artistic cultural assets of the modern era, namely buildings or structures, and decorative elements or public sculptures [3,5].

Although cement-based mortars and concrete were extensively used in modern construction and artistic production, their cultural value was only recognized later, largely in response to the dete-

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rioration and demolition of many high-profile 20th century buildings [1,3]. France was among the first countries to recognize the cultural significance of modern cementitious heritage, instituting measures for its listing and preservation in the 1940s, when the use of cement in architectural and artistic creations was becoming a common practice [3]. However, broader international acknowledgment and conservation efforts only emerged in the late 1980s, when heritage organizations across Europe and North America began addressing the vulnerability of modern heritage assets and implementing more comprehensive strategies to identify and protect modern heritage [3].

A significant proportion of cementitious modern heritage remains unrecognized, undervalued, and under-researched, but the growing interest in its safeguard and the conservation efforts within both academic and professional communities have since revealed the technical complexity of these materials [6]. The 19th- and 20th-century constant development of the cement industry and technology resulted in significant changes in binder composition and performance and in distinct properties characteristic of different technological periods [5,7]. Various hydraulic binders defined by the common term ‘cement’ have been produced since the second half of the 18th century, each exhibiting distinct properties according to its components, years, and place of production [5,7]. This continuous evolution has also introduced specific conservation challenges, as many early applications used construction techniques that were still experimental and mortar formulations that often lacked long-term durability and are now more prone to deterioration [4,6]. In addition to these challenges, unique national aspects must be considered when preserving these materials. Despite the similarity in the development of the cement industry across countries, local specificities in mortar composition can be found owing to the raw materials, additives, and aggregates available even in different locations within the same country [3,7].

The safeguarding and conservation of cementitious modern heritage present specific and complex challenges that arise due to their constituent material characteristics. Therefore, understanding this material diversity, which reflects broader industrial trends and local practices, is essential for the adequate preservation of modern cement-based heritage [1,4,5].

In this context, Portugal presents a relevant case for examining the adaptation and development of cement technology. While following broader international trends, it also introduced localized advancements and artistic expressions influenced by its sociopolitical context. The emergence of modern hydraulic binders in England and their dissemination across Europe and North America have prompted similar technological efforts in Portugal. Although industrial adoption began later, Portugal quickly integrated international practices, including the use of rotary kilns and the experimentation with new cement formulations, reflecting a global exchange of knowledge and techniques.

Despite the acknowledged importance of cement in modern construction and art, the specific historical development of cement technology and its artistic applications in Portugal remain understudied. Existing research has mainly focused on built heritage, giving limited attention to cementitious public art. The study of the artistic uses of cement-based mortars highlights the material’s versatility and its cultural and aesthetic significance, thereby broadening its understanding beyond functional construction. Shared conservation challenges faced across countries in preserving cement-based mortars from early industrial development emphasize the need for international collaboration. Drawing on collective expertise is crucial for developing more effective conservation strategies for this relatively understudied part of modern heritage.

2. Research aim

This article provides a historical overview of the development of the cement industry in Portugal and its artistic applications. It aims to trace the transition from natural to artificial cements and highlight the contributions of key individuals and companies to the industrialization of cement throughout the 19th and 20th centuries. Drawing on historical documentation and selected case studies, this research emphasizes the influence of European technological and artistic practices on Portuguese cementitious heritage, with particular attention to the use of cement in public art, a relatively understudied aspect of modern heritage. By analyzing compositional variations, evolving techniques, and improvements in mortar performance resulting from technological advancements, this study contributes to a better understanding of the material and technical complexity of cement-based artworks. Ultimately, it supports ongoing conservation efforts by fostering the recognition of the historical and cultural significance of Portuguese cementitious heritage and underscores the need for further research into its material characterization.

3. International development of modern cement technology and industry

3.1. Natural cement: development and industrial production

Although mortars used since ancient Egypt are often referred to as ‘cement’ or as composed by ‘materials with cementing properties’, they differ significantly from modern cementitious mortars in terms of their main components, binding properties, and strength [2,8–10]. Between the Antiquity and the 18th century, numerous examples of mortars made with formulated lime and natural hydraulic lime can be identified. In Ancient Greece, mortars were often composed of highly siliceous volcanic Santorin Earth (a pozzolan), although other mortars produced from limestone with high levels of impurities without pozzolans were also used. In Eastern civilizations, rice husk ash served as a pozzolanic additive because of its high silica content [8]. By the 3rd century B.C., the Romans mastered the production of hydraulic mortars using *pulvis puteolanus*, a pozzolan sourced near Mount Vesuvius. In cases where pozzolanic materials were unavailable, hydraulic mortars were created by combining hydrated lime derived from pure limestone with crushed ceramics (*opus testaceum*) [2,8]. During the Medieval period, mortar compositions varied widely, ranging from non-hydraulic to hydraulic. Hydraulic mortars from this period were often made using lime derived from burnt and slaked clay-rich limestone and pozzolanic materials such as crushed ceramics, volcanic ash, and trass [8].

Natural cements are binders produced by calcining limestones that are naturally rich in clay minerals, containing all the necessary oxides (lime, silica, and alumina) in a single source material. Unlike artificial cements, which are made by burning a mixture of crushed limestone with clay or shale [2,9].

Authors such as Henry & Stewart [9] and Trout [10] consider John Smeaton’s investigation into hydraulic lime in the 1750s to be one of the earliest significant advancements in the development of modern cement pastes, both natural and artificial. Smeaton sought to develop a mortar with rapid underwater setting and high resistance to humidity and salts by testing it against trass mortars (two-part lime, one-part trass) [11]. These experiments confirmed the hydraulicity of limestones, establishing for the first time a direct link to the presence of reactive clay materials. Contrary to common understanding, the production of hardened water-resistant mortars did not rely solely on the hardness of the original stone, but rather on the content of siliceous impurities; the

Table 1
International development of artificial hydraulic binders and low temperature natural cements between mid-18th and early 19th centuries.

Year	Engineer	Type of binder	Main components
1750s	John Smeaton	Formulated lime	Clay-rich limestone + Italian pozzolan
1796	James Parker	Natural cement (James Parker's 'Roman cement')	Calcinated ground *septaria* nodules
1796	Lesage	Natural cement (*plâtre-ciment de Boulogne*)	Beach pebbles from Boulogne-sur-mer
1817/18	Canvass White	Natural cement	Argillaceous magnesian limestone

higher the clay proportion, the greater the fitness of the limestone [9,10,12]. Smeaton designed a hydraulic mortar mixture (Table 1) with the ability to set underwater based on clay-rich limestone and Italian pozzolan, which remained listed in government contracts for over a century [2,10].

Driven by Smeaton's findings and the research demands of the Industrial Revolution, mortar technology advanced rapidly. Over the following years, various binder formulations exploring lime/clay ratios were patented [10]. The first commercially successful true natural cement was patented by James Parker in 1796 under the name 'Roman cement' (Table 1) [9,10]. The name reflected its perceived resemblance in appearance to the mortars of ancient Rome [9].

Parker's cement was primarily made from calcinated ground *septaria* nodules, resulting in a cement paste with a distinctive brown color due to its iron oxide content (11–12 %) [9]. It became the leading hydraulic binder in construction and dominated the market until the late 19th century [9,10]. Because of its durability, low shrinkage, strong initial adhesion, rapid setting time, and ease of casting, it was widely used in hydraulic and tidal engineering work, facade ornamentation as an artificial stone, and patch repairs in stonework [10,12]. Its quick setting time allowed for the application of paint shortly after use, providing a unique advantage over other hydraulic binders. Despite being a natural cement, Parker's innovation significantly contributed to the development of modern artificial binders [2,9].

It took nearly half a century for the natural cement industry to expand beyond Britain and begin developing globally [10,11,13]. European countries were importing small quantities of 'Roman cement' before 1850, but by the late 19th century, many had established domestic production using local raw materials [13]. In 1796, Lesage started the production of a hydraulic cement (Table 1) using pebbles from a beach in Boulogne-sur-Mer, known as *plâtre-ciment de Boulogne* [10,11]. In 1817, Canvass White reported a natural cement rock in the state of New York, leading to the production of binders based on argillaceous magnesian limestone at Rosendale in 1818 (Table 1) [10]. In the 1830s, *ciments de Vassy* began to be produced using stones found in Vassy, and, during the second half of the 19th century, several cement factories were founded in Grenoble prompted by the region's geological exploration [11]. By the second half of the 19th century, the Austro-Hungarian Empire had become the largest producer of natural cement in Central Europe, where it remained the dominant hydraulic binder until the end of the century. Astro-Hungarian natural cement was renowned for its high durability and resistance to atmospheric and salt weathering. The unique manufacturing methods and material characteristics of these natural cement mortars, such as their high binder-to-aggregate ratios, fine-grained aggregates, and large residual cement grains, contributed to their durability and mechanical performance [13].

3.2. Artificial cement: from experimentation to industrialization

Between 1805 and 1813, multiple French researchers, motivated by the Napoleonic Empire's endorsement of scholarships and practical studies, experimented on hydraulic cement pastes. Their goal was to adjust the components and mix proportions, either by making artificial pozzolans or by seeking substitutes due to wartime shortages (refer to [10], p. 8, for further discussion on the investigations caried out). These experiments culminated in the development of an artificial hydraulic lime in 1812 by Louis Joseph Vicat (Table 2), with the findings published in 1818 [10,12,14].

Vicat's pioneering work involved experimenting with various grinding processes and firing temperatures to manufacture a binder through the calcination of a mixture of powdered limestone and slaked lime with clay, to which he established the correct proportions for each constituent [2,10]. Although his mixture was implemented internationally, its suitability was publicly questioned in 1829 by Treussart, who advocated for traditional hydraulic limes with pozzolan as more adequate substitutes for naturally hydraulic limes [10].

In 1822, James Frost patented 'British cement', making the first commercially successful attempt to artificially reproduce the properties of *septaria* in Parker's 'Roman cement'. Frost drew inspiration from Vicat's findings but adapted them to local practices, particularly the grinding method [2,10]. Shortly thereafter, Charles William Pasley started a series of investigations into artificial cements, comparing materials, and processes. His work led to the formulation of a specific mixture of five parts chalk to two parts clay, which was published in 1830 (2nd ed. in 1847) and later became a reference in cement technology [10].

Joseph Aspdin applied for the first patent for 'Portland cement' in 1824. Aspdin named its product as such because of its resemblance in color to Portland stone, a widely used building material at the time [10]. The binder, prepared through double calcination of finely ground limestone and clay, lacked specifications on the proportions of constituents, grinding fineness, firing temperature, and firing time [10,12]. Despite this, Joseph Aspdin's mixture, adapted and improved over time, was successfully marketed for many years and was the basis for modern cement production and the manufacturing industry [2,10]. Since kilns could not reach the temperatures needed to cause fusion/vitrification and chemically alter components, in terms of mineralogy and properties, this binder was closer to hydraulic limes than modern Portland cement [2,9]. Thus, it was classified as 'Proto-Portland' cement, the first designated phase of Portland cement development, because only little reaction occurred between calcium oxide and silica in the kiln [9,10].

In 1841, William Aspdin began the manufacture and commercialization of an improved binder that allowed the addition of higher quantities of fine aggregate (sand), now classified as 'Meso-Portland' cement. The binder was composed of a partially vitrified material produced by over-burning a mixture of lime and clay (clinker). This advancement was made possible by improvements in kiln technology (discussed in more detail below), which allowed for higher firing temperatures – i.e., temperatures above sintering [9,10]. Consequently, this resulted in the formation of a cement paste with enhanced strength and durability, primarily composed of belite and small amounts of alite (refer to [15], p. 23, for further discussion on cement components) [9,10].

The development of different artificial cements and their extensive use demanded the construction of industrial installations for

Table 2
International advancements in artificial binders during the 19th century leading to the development of ordinary Portland cement.

Year	Engineer	Type of binder	Main components
1812	Louis Joseph Vicat	Artificial hydraulic lime	Calcinated powdered limestone + clay
1822	James Frost	Artificial Parker's 'Roman cement' ('British cement')	Similar to Vicat's
1824	Joseph Aspdin	'Proto-Portland' cement (artificial hydraulic lime)	Finely ground limestone + clay (double calcination)
1830	Charles William Pasley	Artificial cement (artificial hydraulic lime)	5 parts chalk + 2 parts clay
1841	William Aspdin	'Meso-Portland' cement	Over-burned lime + clay (clinker) Mainly belite content + small amounts of alite
1845	Isaac Johnson	'Meso-Portland' cement	Similar to William Aspdin's

cement production, setting the beginning of the concrete industry [14]. The first cement factory was established in Froost, Britain (1825), but the production of cement at industrial level was only achieved in 1843, in Northfleet, Britain, by William Aspdin [16].

Four years later, while attempting to replicate Aspdin's 'Meso Portland' cement, Isaac Johnson, Aspdin's former assistant who went on to run a rival company, was the first to accurately identify the main principle of artificial cement manufacture. This involved reaching partial vitrification during the firing process of the raw materials (clinker), resulting in an improved product [9,12]. In the following years, the reported rivalry between firms spurred further testing and improvements in production and material performance. Ultimately, Aspdin arranged for the testing of both products' performance, which concluded that Aspdin's 'Portland cement' had 20 % more strength than Johnson's equivalent [10].

Although it was a period of significant technological development and competitive patenting in artificial cements, the shift from hydraulic limes or natural cements to artificial cements was slow. Artificial 'Portland' cement manufacture spread across Europe and America between 1850–1890, but it only began to be extensively applied in masonry work in the 1870s [9,10]. Mass concrete became a popular construction method, evolving from a cost-effective solution for workers' housing to providing middle-class accommodations as architects and builders adopted prefabricated decorative techniques [2]. At the time, the industry was still underdeveloped, and despite its higher strength and durability, artificial 'Portland' cement was considerably more expensive than natural 'Roman' cement, and its production lacked quality control, which led to errors and variations in the proportions of the mixtures [10].

The transition to 'Modern Portland' cement began in the late 19th century and was marked by gradual technological advancements, particularly during the decades following the 1870s, with enhancements in kiln design and production quality control through testing [10].

Kiln design improved considerably from the 1870s onward, allowing the stable and successful commercialization of cement by the 1890s [10]. Initially, cement was produced using static kilns, such as the 'bottle kiln', a dome-shaped structure similar to traditional lime kilns [10,17]. The production process had limited output and required careful preparation and layering of the raw materials to ensure proper airflow and combustion. Each production cycle lasted four to seven days. In 1872, chamber kilns were introduced as adaptations of small 'bottle' kilns. Chamber kilns enabled the construction of compact cement plants at a relatively low capital cost, typically featuring seven kilns. By 1889, the capacity of these kilns surpassed that of the bottle kiln [17]. Hoffmann kilns, invented around 1875, consisted of a series of chambers arranged circularly. Each chamber acted as a static kiln, with firing occurring, allowing for continuous production. Operators could adjust the temperature and burning zone location, but the design often resulted in poor uniformity of burning and a significant proportion of under-burned product [10,17].

During the 1880 and the 1890s, vertical shaft kilns (e.g. Dietzsch and Schneider kilns) were developed to overcome issues such as clinker blockages, common in continuous shaft kilns. These kilns operated continuously, using an energy-efficient process where raw materials were loaded from the top and descended by gravity through a heating zone, forming clinker [17]. The Dietzsch kiln, patented in 1884, incorporated design improvements to enhance airflow and material movement, increasing efficiency and product uniformity [10,17]. In 1898, the Schneider kiln was developed using a simpler single-shaft design. Schneider kilns increased the output, operated automatically via conveyors, and provided a more uniform burn and better temperature control [10,17].

The introduction of rotary kilns in Britain around 1900 marked a significant advancement in cement production. Raw materials could be processed as a slurry in the wet process or as a dry powder in the dry process. Rotary kilns featured a rotating cylinder that allowed for continuous processing, improving efficiency and product consistency. This design enabled precise control over the temperature and burning time, with the rotary motion ensuring uniform heating and mixing. This led to a higher-quality clinker and increased output [10,18].

These technological advancements in kiln design were crucial in meeting the growing demands of the cement industry, representing significant progress towards more efficient and effective cement production methods [10].

As previously noted, improvements in kiln efficiency and output were paralleled by a growing emphasis on chemical analysis and quality control through testing. In the early 1870s, Germany and Prussia began adopting systematic testing to improve product quality. The proportioning of the raw materials was guided by chemical analysis rather than relying on the traditional rules of thumb. Analyses of German cements published in 1879 and 1883 demonstrated their quality and consistency. The calcium oxide content in German cement was generally ~62 %, a level that remained standard until the introduction of the rotary kiln in the 20th century, which allowed for levels to reach 64 % [10]. Advancements in chemical analysis continued through the late 1870s and into the 1880s [10].

The year of 1887 is often mentioned as a key milestone, with significant events contributing to a greater development and scientific understanding of Portland cement, which ultimately lead to the production of a binder with a higher alite content [10]. Among these events are the experiments conducted on the first functional model of the rotary kiln in West Thurrock (Britain), the start of comprehensive testing on French cement at Boulogne, and the publication of Le Chatelier's findings in Paris, who is considered 'the father of cement chemistry' [10].

Le Chatelier was aware of the significance of scientific knowledge regarding the nature of materials for accurately controlling industrial processes. Therefore, he conducted a series of microscopic examinations and chemical analyses on cement, between 1882 and 1887, to identify the different minerals present and their role in determining mortar performance [10]. He discovered that clinker contains four main compounds: tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite (refer to [15], p. 23, for further discussion on cement components). Le Chatelier's findings attributed the hydraulic properties of the clinker to tricalcium silicate (alite) and demonstrated that the setting of the cement paste occurred through a crystallization process from the cement phases (mainly tricalcium silicate and tricalcium aluminate) and gypsum in a supersaturated solution. His publication became a reference in cement chemistry, shaping the science of cement for decades to come [10].

Advances in testing were prompted by the French standard specifications for cement production established in 1885 but were furthered by the scientific progress of 1887, which resulted in the publication of the German standard for Portland cement in that same year. Until the beginning of the 20th century, all subsequent standards adapted both the requirements of the German and Swiss standards of 1887 and the specifications in the French standard of 1885 [10].

In 1890, Édouard Candlot discovered that calcium sulfate acted as a set regulator [10]. Calcium sulfate was widely adopted as a regulator from the 1890s onward, usually by intergrinding gypsum with clinker. However, early in the beginning of the 20th century manufacturers struggled to control setting times. Water added at the grinding stage was another approach, and the variation in methods encouraged significant discrepancies in setting times between manufacturers and products. By the mid 1920s, however, the problem appeared to have subsided [10].

As the improvements in kiln design, the standardization of production testing, and the innovations in binder formulation spread internationally, countries such as Portugal began adopting and adapting these advancements according to local conditions and material resources. Investment in production improvements, such as electrical power, kiln design, or mixture refinement, not only consolidated the cement industry, but also enhanced the binder's properties at the beginning of the 20th century, particularly its strength, stability, durability, and setting time (refer to [10] for further discussion). Gradually, testing became more systematic in factories, and at the turn of the century, rotary kilns began to be installed, improving the overall quality and performance of cement, by reaching higher firing temperatures and producing a more consistent binder [9,10,12]. Laboratory tests performed in Britain and the United States from the 1950s to the 1970s indicated changes in the cement composition, fineness, and strength over this period, particularly between 1926 and 1940. The results showed a higher tricalcium silicate content and improved strength [10].

Despite its high compressive strength, the low tensile strength of concrete required steel reinforcement for spanning distances. By the early 20th century, mild steel (a ductile material easily shaped into reinforcement structures) was widely available and used to resist bending and shear stresses in reinforced concrete. The use of mild steel in reinforcement dominated until the 1950s, when high-yield steel bars (grade 50 carbon steel) were introduced, offering greater strength [2]. Reinforced concrete gained prominence in the 1880s, but lime remained widely used in building construction and finishes until the 1920s, when Portland cement gradually became the preferred material, dominating the engineering and civil construction market [9,10].

Post-World War II construction faced material shortages, leading to a licensing system that prioritized building projects for schools, housing, and industry. The adoption of pre-casting techniques played a crucial role in enhancing both the quality and durability of cementitious mortars to meet these construction needs. Factory-based pre-casting offered greater control over the placement and compaction of concrete in molds compared to in situ methods, contributing to the superior quality of pre-cast concrete. Hydraulic pressing of moist concrete mixes during block and slab production removed excess water, resulting in high-strength, frost-resistant concrete that outperformed the traditional wet-mix casting methods. Additionally, the use of vibration and pressure were essential to achieve durable concrete blocks using drier mixes. By the early 1960s, England had gained recognition for its advanced pre-casting standards [2].

Throughout the 20th century, specialized cements were developed to meet the evolving demands of various construction applications. These included masonry cements and water-repellent cements composed of metallic salts of fatty acids developed in the 1930s, rapid-hardening cements with calcium chloride, sulfate-resisting cements with tricalcium aluminate additive (<5 %), low-heat cements, colored cements, and cement-based paint developed in 1941 for camouflage purposes. Advances such as air-entraining agents enhanced durability, while incorporating secondary cementitious materials reduced environmental impact and enhanced performance [10].

Secondary cementitious materials such as silica fume, metakaolin, and rice husk ash were developed to replace or enhance Portland cement. The growing acceptance of these additions led to a redefinition of Portland cement, allowing for approved composites. By 1999, after decades of effort, European cement standards were harmonized with the publication of BS EN 197.1, which permitted up to 5 % of secondary cementitious materials in Portland cement (CEM 1) [10].

During the 19th and 20th centuries, several cements with alternative chemical compositions emerged, with varying commercial success rates. Magnesium carbonate cements were proposed by the J. Macleod in 1826 and 'Sorel cements' based on magnesium oxychloride were developed by Stanislas Sorel in France in 1867. High alumina or calcium aluminate cements, first marketed as sulfate-resistant cements in France in 1918, were used for rapid setting underwater work, biogenic environments, and high-temperature refractory uses [10].

4. Development of the cement industry in Portugal

4.1. Natural cement production in Portugal

Like other European countries and America, Portugal initially relied on imported cement binders and construction systems before transitioning to domestic production. Despite the wide availability of raw materials suitable for manufacturing hydraulic binders, cement was predominantly imported from England and France (Boulogne and Vassy) during the 19th century [5,11]. Construction techniques were also 'imported' from pioneering countries. François Coignet's construction system, introduced at the Universal Exhibition in Paris in 1855, had a particularly significant influence. One year after its presentation, Carlos Augusto Pinto Ferreira published a report highlighting the potential benefits of Coignet's system in artificial stone cast with movable molds, emphasizing its aesthetic and durable qualities in comparison to traditional lime-based construction methods, and advocating for its adoption in Portugal [19].

In the latter half of the 19th century, as part of this broader international trend, Portugal began exploring the industrial production of natural cement, drawing on its ample geological resources – deposits of limestone, clay, and marl. Natural cement was produced in several locations, including Alcântara, Figueira da Foz, Gândara, and Maceira (Fig. 1), but it failed to dominate the market or achieve economic self-sufficiency [16,20]. The extent of raw materials available in the country supported the emergence of a national lime and cement industry, with production centers established near key geological formations (refer to [5], pp. 245–246, for geological distribution of raw materials) [5,19]. Thus, understanding the evolution of Portugal's cement industry requires an exam-

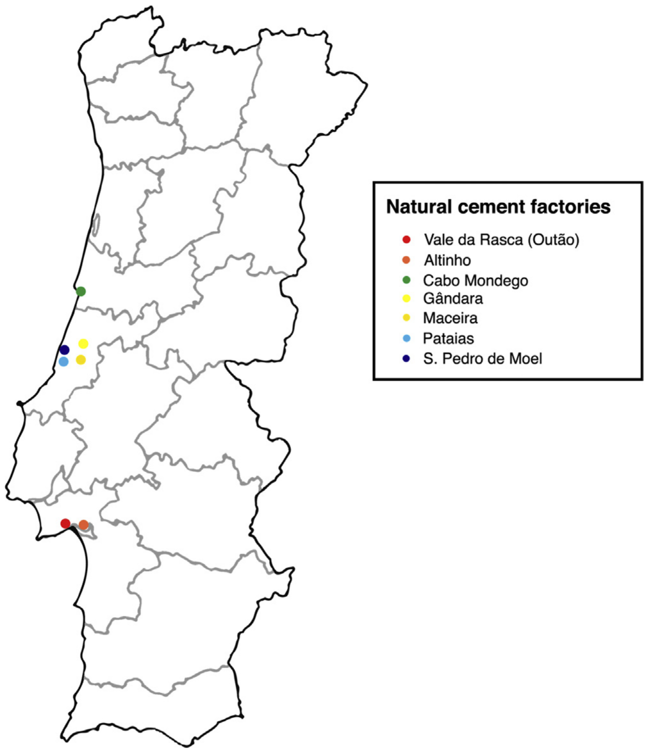

Fig. 1. Location of Portuguese cement plants with natural cement production in the 19th century (diagram by authors).

ination of the various cement companies and factories established over the years.

The first Portuguese cement factory (*Companhia de Cimentos Rasca*) was established in Alcântara in 1866 using clayey limestone from Quinta da Rasca and marl from Vale de Alcântara to produce natural cement. During its operation, the factory was relocated to Altinho, where the production of natural cement failed due to unsuitable raw materials from the Alvito quarry. It was subsequently relocated to Quinta da Rasca to resume production. However, after twelve years, the factory ceased production owing to the poor quality of its mortar, which was deemed inadequate for marine construction [5,16]. In 1896, the Garcia Machado, Bosse & Cie organization was founded, aiming to resume natural cement production using raw materials from Quinta da Rasca [21].

In 1873, industrial production of natural cement near Figueira da Foz began with the establishment of a new factory in the industrial sector of Cabo Mondego, by the corporation *Companhia Mineira e Industrial do Cabo Mondego*, which explored local bituminous coal and marl. By 1884, it was producing natural hydraulic lime from Cretaceous limestones from Salmanha, one of Portugal's highest quality natural cements, and an artificial cement with good market acceptance [5,22].

In 1875, Professor João de Sousa Rodrigues Ribeiro prompted the production of hydraulic lime in Gândara after investigating and exploring the limestone deposits in the area. In 1891, João Henriques Teixeira Guedes founded a factory in the same village (*Fábrica de Cimentos de Maceira*) to manufacture hydraulic lime and natural cement [16,23]. Before establishing the factory, Teixeira Guedes carried out extensive laboratory research on Maceira's calcareous stone deposits and consulted with technicians such as Engineer Édouard Candlot[1] to strictly follow their production methods and produce high-quality cements [22,23]. In 1893, Teixeira Guedes relocated its company to Quinta do Paraíso (Maceira) to meet the need to increase production due to high demand and to use hydraulic energy. In 1900, the entrepreneur published a comparative study between Maceira's cements and French, British, Italian, and Austrian cements that attested to their quality stating that the tensile strength of the Portuguese binders was similar to the others [23].

Despite developments in cement production, imports from France and Britain remained substantial due to technical difficulties such as high extraction costs and low-quality coal [5].

During the Second Industrial Revolution (c.1870–1914), industrial processes and production capacity were improved with the creation of the spark-ignition engine and the promotion of the use of electricity and oil, which prompted a higher demand for civil engineering products and materials. During this period, the Portuguese State became a key client in the national cement industry mainly because of the public building policy [16].

Towards the end of the 19th century, imported artificial Portland cement was introduced in the national market, gradually replacing lower-quality national natural cements. At the turn of the century, national cement production was still three times lower than imports. Different Portuguese companies, entrepreneurs, and engineers started showing interest in the production of artificial cement in Portugal, but the market continued to be dominated by importation until the 20th century [16,24].

The 1880s marked a pivotal moment in the scientific development of cement technology, both internationally and in Portugal. As previously mentioned, during this time significant progress was made across Europe in standardizing production methods, improving kiln design, and promoting chemical analysis to control material performance. In Portugal, a more systematic and scientific approach to the study of cement also emerged during the 1880s, driven by the creation of a discipline on materials' resistance at the Military School and a Mechanics of Materials Department at the *Direção das Obras Portuárias de Lisboa* (Directorate of Lisbon Port Works) [5,19,25,26]. This marked the beginning of a new period for the study and application of cement in Portugal. The establishment of regular and institutionalized chemical, mineralogical, and physical analyses to test and assess binder composition, strength, and behavior marked the beginning of a second phase in the consolidation of the cement and concrete industry in Portugal, alongside the adoption of reinforced concrete [5,19,25,26].

The first director of *Direção das Obras Portuárias de Lisboa*, Engineer José Paixão Castanheira das Neves, also served as the Head Engineer of the first official quality control laboratory for building materials. Castanheira das Neves presented numerous performance reports on the strength of Portuguese building materials, particularly hydraulic lime and natural cement, and later established the first guidelines for the Portuguese Portland cement industry based on his findings. In 1891, he published a study that classified Portuguese natural cement into quick-setting cement (produced in Pataias, Maceira, and São Pedro de Moel) and slow-setting 'Roman cement' (produced in Rasca and Cabo Mondego) (Fig. 1). In the following years, he analyzed samples of both Portuguese cements and the most commonly imported cements sold in Portugal (e.g., British, French, Belgian, and German), covering both natural and artificial Portland cement [5,11,19,25,26].

[1] While being a part of *Société des Ciment Français de Boulogne-sur-Mer*, Édouard Candlot, a French chemist and engineer, carried out numerous laboratory studies on setting accelerants and retardants, developed and perfected new techniques to produce cement that were adopted by various producers [22]. As previously mentioned, the discovery of calcium sulfate as a set regulator was credited to Candlot [10].

Table 3
Development of artificial cement industry in Portugal.

Year	Factory/Company	Event
1840	*Fábrica do Tejo* (António Moreira Rato & Filhos)	Importation of Portland cement and other construction materials
1894	*Fábrica do Tejo* (Alhandra)	Artificial Portland cement production
1906	*Companhia de Cimentos de Portugal*	Acquisition of *Fábrica da Rasca* (Outão) and adaptation for artificial Portland cement production
1912	*Companhia de Cimento Tejo*	Acquisition of *Fábrica do Tejo*
1918	*Companhia Geral de Cal e Cimento*	Acquisition of *Companhia de Cimentos de Portugal*
1921	*Empreza de Cimentos de Porto Santo*	Factory foundation
1923	*Maceira-Liz* (Gândara)	Factory inauguration through the *Empreza de Cimentos de Leiria* (E.C.L.); artificial cement production
1925	*Secil*	Brand foundation
1930s	*Maceira-Liz*	Acquisition of 60 % of *Companhia de Cimentos Tejo*'s capital (Alhandra factory and Alcântara factories)
1930	*SECIL – Sociedade dos Empreendimentos Comerciais e Industriais, Lda.*	Merge of *Secil* and *Companhia Geral de Cal e Cimento*
1944	*Companhia Portuguesa de Cimentos Brancos (S.A.R.L.)*	S.A.R.L. set by SCIAL (factory of cement-based hydraulic mosaic tiles and artificial marbles)
1945	*Companhia de Cimentos de Moçambique*	Foundation by *Maceira-Liz*
1946	*Companhia de Cimentos de Angola*	Foundation by *Maceira-Liz*
1949	*Companhia de Carvões e Cimentos do Cabo Mondego*	Acquisition and foundation by *Maceira-Liz*
1951	*Nova Maceira* (Mozambique)	Factory foundation by *Maceira-Liz*
1952	*Lobito* (Angola)	Factory foundation by *Maceira-Liz*
1954	*Siderurgia Nacional*	Acquisition and foundation by *Maceira-Liz*
1963	*Nacala* (Mozambique)	Factory foundation by *Maceira-Liz*
1973	*Cisul* (Loulé)	Factory foudation by Engineer Mário Gaspar
1974/75	*Cinorte* (Souselas)	Factory foudation by the family Queirós Pereira
1976	*CIMPOR- Cimentos de Portugal, E.P.*	Merge between *Companhia de Cimentos Tejo*, E.C.L. (*Maceira-Liz*), *Cibra, Cisul, Cinorte*, and *Companhia de Carvões e Cimentos do Cabo Mondego*, after their nationalization in 1975
1976–96	*CIMPOR- Cimentos de Portugal, E.P.* and *CIMPOR – Cimentos de Portugal, S.A.*	Expansion in Portugal, Spain, Angola, Turkey, Tunisia, Morocco, Egypt, Cape Verde, Mozambique, South Africa, China, India, and Peru
1991	*CIMPOR – Cimentos de Portugal, S.A.*	Incorporation of *CIMPOR- Cimentos de Portugal, E.P.* as a public limited company
1992	*CMP – Cimentos Maceira e Pataias*	Privatization and merge of *Maceira-Liz* and *Cibra*
1994	*SECIL – Sociedade dos Empreendimentos Comerciais e Industriais, Lda.*	Privatization and purchase of *CMP*

4.2. Artificial cement production and industrial expansion in Portugal

As previously mentioned, despite significant advances in cement science and production processes during the first half of the 19th century, the manufacture of artificial cement spread across Europe and America only between 1850 and 1890. Building on this international trend, Portuguese entrepreneurs and engineers began developing their own artificial cement production (Table 3). The influence of foreign models is evident in both factory design and technological choices, particularly in the posterior adoption of rotary kilns.

Established in 1840, António Moreira Rato & Filhos (*Fábrica do Tejo*) initially operated as an importer and distributor of Portland cement and other construction materials. However, in the early 1890s, under the management of António Teófilo de Araújo Rato, the company conducted a series of economic and chemical studies that lead to its pioneering role in artificial cement production in Portugal [20]. The company purchased and leased land in Alhandra (Vila Franca de Xira), with royal endorsement from King D. Carlos. The construction of the factory began in 1892, and in 1894, the company was granted a ten-year exclusive license for manufacturing artificial cement [16,20,24]. *Fábrica do Tejo* started the production of artificial Portland cement later that year, using a Hoffmann kiln [5,16,20]. Despite its innovation, financial and technical problems forced the suspension of operations and the acquisition of the factory by *Companhia de Cimentos Tejo,* in 1912 [16,20]. The new management attempted to increase production by upgrading raw material preparation and the existing kilns, but these plans were ultimately hindered by armed conflicts [20].

When *Fábrica do Tejo*'s exclusivity ceased, a second cement company was established in Portugal. *Companhia de Cimentos de Portugal* purchased the factory in Outão (Setúbal), previously specialized in natural cement production (*Fábrica da Rasca*) and adapted it for artificial cement, starting its manufacture in 1906 [5,20,21]. The factory already had two vertical kilns installed, and a third kiln was added in 1913 [20]. During World War I, *Companhia de Cimentos de Portugal* became the largest national cement enterprise; however, in 1918, it was compelled to sell the factory to *Companhia Geral de Cal e Cimento* because of the war aftermath. This company, later merged with *Secil* (brand created in 1925) into *SECIL – Sociedade dos Empreendimentos Comerciais e Industriais, Lda.*, in 1931 [16,20,27].

The *Empreza de Cimentos de Porto Santo* was founded in 1921 but ceased production in 1935 [16].

In 1923, the Maceira-Liz factory was officially inaugurated as part of the *Empreza de Cimentos de Leiria* (E.C.L.), which was established in 1919. This initiative was led by Henrique Sommer and José Rocha e Mello, and marked a significant milestone in the development of the Portuguese Portland cement industry [16,24]. Sommer, who took an interest in the cement industry during his time in Britain, recognized that it was economically viable to manufacture an alternative to imported cement upon returning to Portugal and encountering the contrasting reality of low-quality national production. Rocha e Mello came into contact with the lead European cement industry while attending school and an internship in Germany and Switzerland, which gave him knowledge to carry out a report on the Portuguese industry and draw out the project of a technologically advanced cement factory that became the basis for the construction of *Maceira-Liz* [16].

Together, Sommer and Rocha e Mello started building the factory in Gândara (Maceira) in 1919, after geological and chemical studies had shown this area was a location rich in high-quality raw materials (limestone and marl) for cement manufacture [16]. The construction of the cement manufacturing plant was extensive and overly expensive, mainly due to the post-war economic crisis in Portugal and Europe, the lack of infrastructures and supplies in the region, and labor shortage. The management had to recruit qualified technicians from Germany and employees mostly from the north of Portugal. Although the region already had some civil construction industry, it was predominantly agricultural, so it was necessary to build a ceramic factory to produce materials such as bricks and roof tiles needed to construct both the factory and workers housing. In addition, two lime kilns and a railroad branch were installed to support production and transportation [16].

Maceira-Liz became fully operational in 1923, starting the production of high-quality artificial Portland cement almost immediately after its inauguration. As planned, it was highly innovative and productive, prompting the remaining Portuguese cement factories (in Alhandra and Outão) to upgrade their production processes and equipment to remain competitive [16,24]. Mirroring the global trend of cement industry modernization, *Maceira-Liz* introduced the rotary kiln in Portugal and began large-scale production of a binder with superior performance compared to the rest of the national output [16,24].

Despite these advancements, E.C.L. faced significant economic difficulties, mainly due to construction costs, market distrust of domestic cement, and sociocultural and political changes in the country (refer to [16], pp. 16 and 17, for detailed information). Additionally, local residents were still resistant to the factory's presence in the village, citing concerns about its negative impact on their main means of livelihood, the loss of land sold to the company, the destruction of crops, and the distrust of northern laborers [16].To address these difficulties, the management conducted a series of analyses on Liz cement and publicly shared the results, demonstrating its high performance and aiming to accelerate its acceptance as a viable alternative to imports, an achievement that took several years [16,24]. At the same time, management adopted a socially proactive approach, supporting workers through wage raises (higher than those in the agricultural sector), the construction of housing and sociocultural facilities, and the organization of religious celebrations within the company [16,24].

In response to the State's public construction policies in the 1930s, Maceira-Liz experienced a significant increase in the demand for cement production. This prompted the expansion of the factory's operations, leading to the inauguration of two additional manufacturing lines and expansion of the company with the acquisition of 60 % of *Companhia de Cimentos Tejo*'s capital, its factory in Alhandra, and the factories in Alcântara (*Vulcano* and *Colares*). Thus, despite being affected by the economic crisis and the strain in fuel and material supply caused by the Spanish Civil War and World War II, E.C.L. was producing a binder that took a significant market share and was able to compete with imported cement by the mid 1940s [16].

As in other countries, World War II not only impacted industrial production, but also influenced architecture and art. Advances in the research and development of artificial cements favored the use of these mortars (in particular Portland cement) for most projects that required a hydraulic binder, such as tunnels, bridges, and pipelines. Architecture valued simplicity, efficiency, and low-cost solutions, resulting in a shift from buildings with natural cement facade ornaments to artificial cement buildings with smooth surfaces and cleaner aesthetics [5].

In 1944, the director of *SCIAL*, a factory of cement-based hydraulic mosaic tiles and artificial marbles, set the *Companhia Portuguesa de Cimentos Brancos* (S.A.R.L.) [21]. In the same decade, António de Sommer Champalimaud was appointed as managing director of *Maceira-Liz*, entirely shifting the administration policy to a «modernizing, expansionist, concentrationist and aggressive strategy» ([16], p. 18), focusing on business expansion and profit [16,24]. This expansion policy led to the acquisition and creation of businesses in various sectors, such as *Companhia de Carvões e Cimentos do Cabo Mondego* (1949), *Siderurgia Nacional* (1954), several insurance and paper companies, and the majority share of *Banco Pinto e Sotto Mayor* (1960). E.C.L.'s factories increased their production capacity[2] and expanded to Portuguese colonies, through the creation of the *Companhia de Cimentos de Moçambique* (1945) and the *Companhia de Cimentos de Angola* (1946), followed by the construction of cement factories in Mozambique (*Nova Maceira* in 1951, and *Nacala* in 1963) and Angola (*Lobito* in 1952). As a result, Champalimaud became a prominent industrialist in Portugal by the end of *Estado Novo*, controlling two-thirds of the national industry and three-quarters of its total revenues, which ensured that he stayed in management until the acquittal of E.C.L. [16].

In the early 1970s, *Cisul* and *Cinorte* were set up in Loulé (*Cisul*) by Engineer Mário Gaspar, the owner of *Somapre,* and in Souselas (*Cinorte*) by the family Queirós Pereira. The former began production in 1973 and the latter in 1974/75 with two kilns [21].

After the Carnation Revolution (*Revolução dos Cravos*) in 1975, *Companhia de Cimentos Tejo*, E.C.L. (*Maceira-Liz*), *Cibra, Cisul, Cinorte*, and *Companhia de Carvões e Cimentos do Cabo Mondego* were nationalized and, in 1976, merged into *CIMPOR- Cimentos de Portugal, E.P.* [16,21]. Over the next two decades, *CIMPOR* expanded domestically (Azores included) and internationally, establishing operations in twelve countries: Spain, Angola, Turkey, Tunisia, Morocco, Egypt, Cape Verde, Mozambique, South Africa, China, India, and Peru [28]. In 1991, *CIMPOR* was incorporated as a public limited company and rebranded as *CIMPOR – Cimentos de Portugal, S.A.* [28].

In the 1990s, the Portuguese State set a privatization plan for the cement sector, resulting in the creation of *CMP – Cimentos Maceira e Pataias* in 1992 (with *Maceira-Liz* and *Cibra,* thus ceasing to be a part of *CIMPOR*), the privatization of *SECIL* and the purchase of *CMP* by *SECIL* in 1994 [16,21,28]. Currently, *SECIL* produces various civil construction products, including concrete, pre-cast, hydraulic lime, and other mortars, and has diversified into the transport and energy sectors [16].

5. Cementitious mortars for artistic purposes in the 19th and 20th centuries

5.1. International artistic applications of cement mortars

In the 20th century, engineers, architects of the Modern Movement, and sculptors began to recognize and explore the aesthetic possibilities of cement-based mortars and concrete. Until then, hydraulic lime and cement were used to cast 'stone' blocks for functional applications and were occasionally used as artificial stone for the casting of architectural decorative elements [2,29]. As previously mentioned, throughout the 19th century, Parker's 'Roman cement', and other natural cements, such as Atkinson's or Mulgrave Cement and other manufactured in France, were highly valued for creating facade ornaments due to their properties [29–31]. The main drawback of these cements was their undesired color, which was often addressed by applying color washes (with limited durability) or finishing layers of light-colored cement.

In the 1820s, William Lockwood conducted extensive research on various limestone sources to produce a 'stone-colored cement' that did not require color washing. In 1822, he launched the full-scale production and commercialization of 'Portland Stone cement', named for its resemblance in color to Portland stone [9]. His product was a mixture of sand, other aggregates, and eminently hydraulic lime from Sawsea or Barrow (depending on the required quality) [10,29,32,33]. In a letter to *The Builder* magazine (1845),

[2] Three new production lines are built in *Maceira-Liz* in 1957, 1968 and 1970, and in the 1980s the last two are upgraded along with the factory in Alhandra [16].

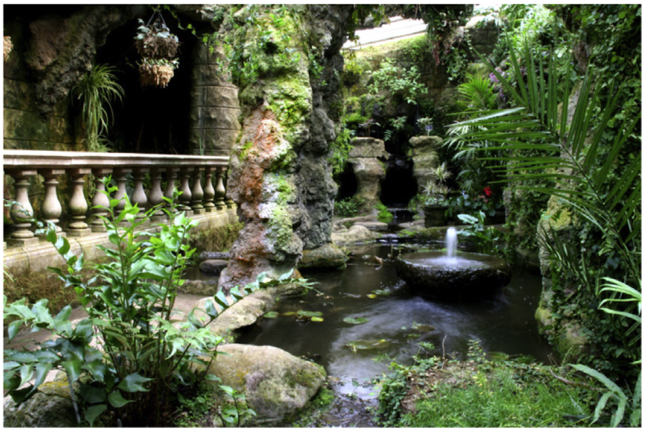

Fig. 2. Grotto in Dewstow Gardens composed of *pulhamite.* (From Dewstow new [Photograph], by Hazel, 2008, Flickr. https://flic.kr/p/5suU5E. CC BY-SA 2.0).

James Pulham, the son of an associate of Lockwood, mentioned that the durability and finish of 'Portland Stone cement' allowed for its use for both exterior and interior ornamental purposes in flooring, stucco, molding in building facades, statuary, and garden décor [29,31].

During the mid-19th century, artificial rockwork became popular, with cement-based artificial stones such as *pulhamite* (Fig. 2) being used for garden and landscape ornaments, grottoes, and ferneries [2,29,30,32]. The term *pulhamite* was commonly used to refer two distinct mortars produced by the Pulham's family firm. The first, also known as 'Pulham's Stone cement' was a mixture similar to Lockwood's 'Portland Stone cement' of natural cement or eminently hydraulic lime with aggregates. It was used, from the late 1830s to the late 1870s, as a render material in artificial rockwork with a masonry core of cheap, locally available filling materials (overburnt bricks, stone, and slag). The surface of the rockwork was worked while wet and different aggregates (crushed stone and shells, pebbles, or brick burrs) and inorganic pigments (ochres, iron oxides, charcoal, chalk or lime) were used to mimic the texture and natural color variations in stones. The second, also known as 'Pulham's terracotta', was a stone-colored terracotta developed in the 1840s for pre-cast garden and architectural ornaments, which was used until the 1880s [32].

Conflicting perspectives exist on when cement and concrete were first used for sculpture.

Moreira Mena [34] identifies the rowing boat created by the engineer Joseph-Louis Lambot as the first known 'sculpture' in reinforced concrete. Lambot presented his creation at the *Exposition Universelle* in Paris and used it to patent his ferrocement ('*ferciment*') system in 1855, becoming the inventor of reinforced concrete [14,30,35]. Ward [30] and Bailey [36] recognize the use of concrete in sculpture only beginning in the 1920s, when it was becoming a common building material, specifically after the introduction of reinforced concrete. This inspired artists, like Henry Moore, to experiment with concrete, hoping to be commissioned to produce sculptures that would connect with the new concrete buildings [30,37]. However, Collins [37] mentions the exploration of concrete as a sculptural material in Europe before World War I.

Cement and concrete were a new, freely available and affordable art media, that allowed the incorporation of pigments or other materials and was suitable for various working methods such as casting in molds, shaping while not fully hardened, or carving after hardening [30,34,37]. Sculptors favored this material for creating geometric, abstract, or semi-figurative compositions inspired by the prevailing styles of the time [30,38]. Sculptures were generally hollow and reinforced with a mild-steel mesh to improve durability [30,34,37].

Between 1911 and 1918, German artist Wilhelm Lehmbruck experimented with cement to create portrait heads and figures with a mixture of cement binder, stone dust and water (known as 'cast stone') poured into molds [37]. Hungarian artist Peter Peri first started using concrete to mold colored figures and abstract geometric reliefs, which he exhibited in the *Der Sturm Galerie* in Berlin (1922), and later continued making small concrete figures and reliefs using a mixture of Portland cement and sand trowelled onto a metal mesh, after his move to London in 1933 [37].

The exploration of concrete as an artistic medium is also mentioned in Britain with the concrete sculpture of a mother-and-child by Loris Rey and with the multiple reinforced concrete figures created by Henry Moore between 1925 and 1933, through plaster molding and carving before hardening [30,37]

French sculptor Carlo Sarrabezolles is also mentioned for introducing the technique of direct carving in cement mortars in 1926. Alongside Georges Lucien Vacossin, Sarrabezolles constructed the tomb of photographer Félix Martin-Sabon in Montmartre Cemetery, which is remarkable for having the entire weight of the sculpture supported by only four points: the paws of the lions [34].

A collaborative project between Picasso and Norwegian sculptor Carl Nesjar, one of the artists to pioneer the use of cement in sculpture, resulted in a series of works exploring the artistic possibilities of a recent technique known as *betograve* or *bétongravé* [34,38,39]. Developed in Norway within the context of architectural concrete, *betograve* involved molds packed with compacted gravel filled with concrete, which were then sandblasted after hardening to reveal the texture and pattern of the aggregates [34,39]. This process allowed for a wide range of surface finishes, from large textured areas to fine engraved lines, which Picasso and Nesjar explored in *Tête de Femme* (Woman's Head, 1958) and *Sylvette* (1970, Fig. 3) [39].

In the 1950s, the construction boom in western Europe and America, marked by the development of new suburbs, towns, airports, and industrial complexes, was associated with a modernist movement that sought to integrate architecture with sculpture (refer to [38] and [40] for further information) [30]. The work of the modernist architect Le Corbusier in the *Unité d'Habitation* series of apartment buildings (e.g., Marseille, 1945–52 or Berlin, 1957, Fig. 4) exemplifies this interrelation, where the wall is decorated with non-colored stylized human figures that «integrate with the concrete skin of the building in an original way» ([30], p. 122).

This tendency to integrate architecture with sculpture, combined with the advantageous properties of cement-based mortars for outdoor locations, contributed to the development of public sculpture in concrete [30]. In the modern urban spaces, concrete was used not only in utilitarian art, such as facade decoration, funerary work, garden and landscape ornaments, but also in large-scale free-standing pieces valued for their aesthetics. These works were either integrated into buildings or designed as independent, site-specific creations intrinsically connected to their surroundings and the community [30,40]. They were generally cast on-site, rarely colored, and the surfaces were left untreated or smoothed over [30]. *Torres de Satélite* (Satellite Towers, 1958) constructed by German-Mexican sculptor Mathias Goeritz and *The Signal* (1961, Fig. 5) created by Henri-Georges Adam are both great examples of the artists' intent to integrate visual artwork into architecture and its surroundings [30].

During the 1960s, sculptures were constructed with concrete slabs prefabricated into different shapes, generally in combination with wood or steel (e.g. *Declaration* by British sculptor Phillip King, 1961). However, the use of cement and concrete by sculptors decreased as the decade progressed, with metal and plastics becoming preferred [30].

Fig. 3. *Sylvette* (1970) by Picasso, in Rotterdam. (From Rotterdam - Sylvette [Photograph], by Fred Romero, 2015, Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Rotterdam_-_Sylvette.jpg. CC BY 2.0).

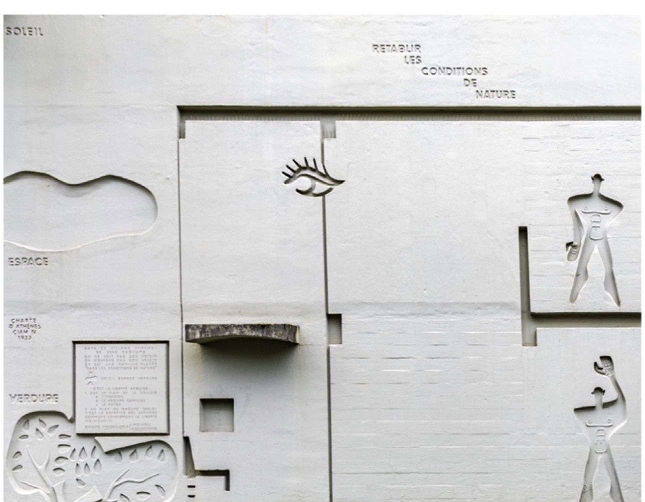

Fig. 4. Detail of the facade of Le Corbusier's *Unité d'Habitation* (1957) in Berlin. (From Corbusierhaus, Berlin – Fassade [Photograph], by Matthias Süßen, 2021, Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Corbusierhaus,_Berlin-msu-2021-2370-.jpg. CC BY-SA 4.0).

Fig. 5. *The Signal* (1961) by Henri-Georges Adam in *Musée d'art moderne André Malraux — MuMa Le Havre*. (From Le musée d'art moderne André Malraux (Le Havre) [Photograph], by Jean-Pierre Dalbéra, 2021, Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Le_mus%C3%A9e_d%27art_moderne_Andr%C3%A9_Malraux_(Le_Havre)_(51487304038).jpg. CC BY 2.0).

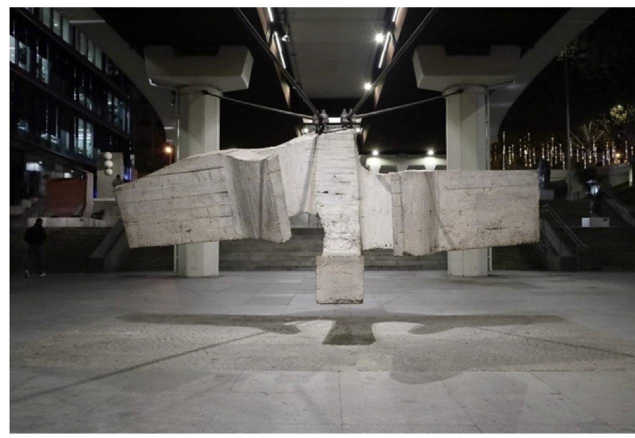

Fig. 6. *La Sirena Varada* (1972) by Eduardo Chillida in *El Museo de Escultura al Aire Libre de la Castellana*. (From Lugar de encuentros III - Museo de Escultura al Aire Libre de La Castellana - Madrid [Photograph], by Javier Perez Montes, 2024, Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Lugar_de_encuentros_III_-_Museo_de_Escultura_al_Aire_Libre_de_La_Castellana_-_Madrid_03.jpg. CC BY-SA 4.0).

The use of concrete rose again in the 1970s, either as a sculptural material or support for potentially shifting elements in kinetic sculptures [30]. *La Sirena Varada* (The Beached Mermaid, Fig. 6), created by Spanish sculptor Eduardo Chillida in 1972, is an exceptional example of the use of concrete during this time [34]. The sculpture, formerly known as *Lugar de* Encuentros (Meeting Place) is constructed by a concrete piece suspended by four steel cables created expressly for its placement under a bridge in *El Museo de Escultura al Aire Libre de la Castellana* [34].

In the 1980s, concrete was used either in monolithic outdoor pieces, or in «subtler, more nuanced ways» ([30], p. 122). At the time, concrete was preferred over polyester resins when casted, as it exhibited a more predictable behavior, higher durability and resistance, and less tendency to damage than molded fiberglass. It was often finished with paint or mixed with other art media. Eduardo Chillida's work in *Elogio del Horizonte* (Praise of the Horizon, 1989, Fig. 7) and *White Sand, Red Millet, Many Flowers* (1982) by Anish Kapoor are great examples of both uses [30].

5.2. Portuguese artistic applications of cement mortars

The international trends discussed above had a strong impact on the Portuguese context, where artistic uses of cement emerged slightly later but evolved in parallel with local inno-

Fig. 7. *Elogio del Horizonte* (1989) by Eduardo Chillida in Santa Catalina, Gijón. (From Elogio del horizonte. Gijón [Photograph], by David Álvarez López, 2014, Flickr. https://flic.kr/p/pfwC35. CC BY 2.0).

Fig. 8. Detail of the main facade of *Teatro Nacional de S. João* (1910–20) in Porto. (Photograph by authors).

vations and socio-political conditions. As artificial and reinforced cements gained popularity for both structural and aesthetic application internationally, Portuguese artists and architects increasingly explored their creative potential. European advancements in cementitious sculpture and ornaments directly shaped emerging artistic practices in Portugal.

The use of cement-based mortars in Portugal began in the latter half of the 19th century and continued into the early 20th century. Similar to trends observed internationally, hydraulic lime and cement were used in architectural decorative elements, statuary, and garden features. Natural cement was frequently employed in exterior ornaments because of its rapid setting and high weathering resistance. As in other countries, artificial Portland cement progressively replaced natural cement and hydraulic lime [41].

Casa Barbot (Vila Nova de Gaia, 1904), an *Art Nouveau* building and surrounding garden built by Bernardo Pinto Abrunhosa, has long been considered a notable example of the use of natural cement for artistic purposes. However, a recent study by Maljaee, Santos Silva and Velosa [41] revealed the opposite. The decorative elements in the garden (cave and gazebo) were constructed from multiple layers of a mixture of materials, with Portland cement as the primary binder, hydraulic lime, air lime, blast furnace slag, charcoal, and limestone filler [41].

The use of cement-based mortars in Portuguese sculpture began in the 1910s. The reliefs on the facade of *Teatro Nacional de S. João* (S. João National Theater, 1914–18) and the statue *Monumento aos Mortos da Grande Guerra* (Monument to the Dead of the Great War, 1914–18) are identified as some of the earliest examples [34].

Fig. 9. *Monumento aos Mortos da Grande Guerra* (1914-18) by Ruy Gameiro. (From Ruy Gameiro Monumento aos Mortos pela Pátria Abrantes [Photograph], by Manuelvbotelho, 2014, Wikimedia commons. https://commons.wikimedia.org/wiki/File:Img_8470_Ruy_Gameiro_Monumento_aos_Mortos_pela_P%C3%A1tria_Abrantes.jpg. CC BY-SA 3.0).

Teatro Nacional de São João (Fig. 8) was designed and rebuilt between 1910 and 1920 on the same site as the previous theater, reusing stone from the original building after its destruction. It is a remarkable example of the use of an innovative material for its time and is now classified as a National Monument [42,43].

Portuguese architect José Marques da Silva employed hydraulic binders, particularly cement, for the external ornaments, which include floral arrangements, geometric patterns, figurative high-reliefs, masks, festoons, and motifs related to performing arts. His choice of material and techniques was heavily influenced by his connection with French engineer Auguste Perret, a leading figure in the development of reinforced concrete architecture [42].

Sculptors Henrique Araújo Moreira, Diogo de Macedo, José Fernandes de Sousa Caldas and Joaquim Gonçalves da Silva are associated with the execution of the decorative motifs. Diogo de Macedo is believed to be the author of *Bondade, Dor, Amor,* and *Ódio* (Kind-

Fig. 10. *Cristo Rei* (1959) by Francisco Franco in Lisbon. (From Cristo Rei, Lisboa, Portugal, 2012-05-12 [Photograph], by Diego Delso, 2012, Wikimedia commons. https://commons.wikimedia.org/wiki/File:Cristo_Rei,_Lisboa,_Portugal,_2012-05-12,_DD_02.JPG. CC BY-SA 3.0).

Fig. 11. *Monumento ao General Humberto Delgado* (1975) by José Aurélio. (From Monumento ao General Humberto Delgado - Cela Velha – Portugal [Photograph], by Vítor Oliveira, 2021, Wikimedia commons. https://commons.wikimedia.org/wiki/File:Monumento_ao_General_Humberto_Delgado_-_Cela_Velha_-_Portugal_(51385248649).jpg. CC BY-SA 2.0).

ness, Pain, Love and Hatred), the four statues at the top of the main façade, though the authorship of *Amor* remains unconfirmed. Joaquim Gonçalves da Silva was responsible for the two masks on the west facade and other decorative elements on both the east and west sides of the building [42].

All ornaments were constructed using reinforced cement-based mortars with steel bars and metal mesh, a technique that reflects the pioneering work of Joseph Monier, who developed reinforced concrete systems in the mid-19th century [42]. A study conducted on the mortars determined that they were composed of natural cement [26,42,43]. Visual differences among the decorative elements were confirmed to be related to the type and quantity of aggregate used [42]. Most ornaments, particularly those on the east and west facades, are composed of siliceous aggregates, giving them a granite-like appearance with yellow-colored sand [42,43]. The high-reliefs on the main facade and the decorative frieze on the south facade were constructed using a finer mortar with a smoother limestone-like finish, given by the presence of white or beige-colored aggregates (possibly stone or marble dust) [42].

As previously mentioned, one of the earliest examples of cementitious public art in Portugal is the *Monumento aos Mortos da Grande Guerra* (Monument to the Dead of the Great War, 1914–18) by Ruy Roque Gameiro (Fig. 9). This monumental statue honors all the soldiers who lost their lives during the war, featuring a stylized female figure of 'Motherland', alongside a fallen hero and a soldier armed and ready for battle. Following this public sculpture, Ruy Gameiro experimented with the binder on different small-size sculptures [34].

The use of cement in public art was reexplored in 1940 by the sculptor Maximiano Alves, with two monumental concrete fountains. However, because of their colossal size and the topography of the surrounding ground they suffered structural failure. Both were stored, and in 1998, the head of one of the fountain's figures was placed within a red cubic-edged metal structure that is located next to the bridge over the Trancão River [34].

In 1951, the ceramic sculptor Júlio Pomar created a sculpture with patina of the portrait of poet Armindo Rodrigues [44].

One of the most paradigmatic sculptures of the 20th century in Portugal is *Cristo Rei* (Christ the King, 1959, Almada, Fig. 10), which was inspired by *Cristo Redentor* (Christ the Redeemer, Rio de Janeiro, Brazil). Sculptor Francisco Franco, along with a team of architects and engineers, devised a plan for the foundations and construction of the sculpture's structure, similar to *Cristo Redentor*. The work was carried out by the company *Obras Públicas e Cimento Armado* (OPCA), which built the main block from formwork and integrated the scaffolding as part of the structure. The remaining form was hand-sculpted by Francisco Franco and was finished by the sculptor Leopoldo de Almeida [34].

By the late 20th century, Portuguese sculptors had begun developing a more personal and formally experimental language with cement, blending influences from modernist and local traditions.

Following the Carnation Revolution (*Revolução dos Cravos*), in 1975, sculptor José Aurélio reflected the paradigm shift in Portuguese sculpture with the *Monumento ao General Humberto Delgado* (Monument to General Humberto Delgado, Fig. 11) [34,40]. This work exemplifies the anti-monumental movement of the time, breaking away from traditional notions of monumentality and es-

Fig. 12. Sculpture by Pedro Cabrita-Reis (1996) in *Fundação Calouste Gulbenkian.* (From Monument to the first President of the Board of Directors of the Calouste Gulbenkian Foundation -José de Azeredo Perdigão-(1997) - Pedro Cabrita Reis (1956) [Photograph], by Pedro Ribeiro Simões, 2019, Wikimedia commons. https://commons.wikimedia.org/wiki/File:Monument_to_the_first_President_of_the_Board_of_Directors_of_the_Calouste_Gulbenkian_Foundation_-Jos%C3%A9_de_Azeredo_Perdig%C3%A3o-_(1997)_-_Pedro_Cabrita_Reis_(1956)_(49185080666).jpg. CC BY 2.0).

chewed statuary for essential, abstract symbolism (refer to [40] for further discussion). While maintaining a monumental spatial presence, its formal language relies on material and formal references, aligning it with the anti-monumental dimension. In this sculpture, José Aurélio employed the innovative *betograve* technique also used by Picasso and Carl Nesjar, using painted concrete and brick [34,40].

In the 1990s, a few Portuguese sculptors stood out for their innovative language: João Duarte with the *Monumento aos Homens do Mar* (Monument to the Men of the Sea) in 1992, and Hélder Batista in 1994 exploring «a simple and objective language in sculpture, using plastic and compositional elements, the essence of forms, space, color, and materials reduced to geometries» ([34], p. 84). In 1996, the sculptor Pedro Cabrita-Reis constructed an architectural structure without restricting walls in the gardens of *Fundação Calouste Gulbenkian* (Fig. 12), which correlated the perception of exterior and interior spaces and emphasized the neutral chromatism of the concrete, inspired by the constructive system developed by Le Corbusier [16].

6. Conclusions

Mortars used throughout history, from ancient Egypt to the 18th century, differ significantly from modern cement mortars in composition and properties, although they often relied on similar materials (e.g., limestone and pozzolan). The foundation for modern hydraulic binders was established in the 18th century by John Smeaton, whose experiments with clay-rich limestone and Italian pozzolan laid the groundwork for advancements, such as James Parker's 'Roman cement' and the subsequent rise of natural cement industries worldwide.

In the early 19th century, innovations in hydraulic binders advanced with Louis Joseph Vicat's development of artificial hydraulic lime. Crucial improvements in the production process, kiln design, and chemical analysis have led to the creation of artificial binders with high quality and enhanced performance throughout the 19th and 20th centuries. These advancements culminated in the creation and standardization of modern Portland cement and its widespread implementation in construction.

In Portugal, progress in the production of building materials has been less thoroughly documented. The specific timelines for the use of natural cement and the transition to artificial cement remain unclear. As in other European countries, the use of cement in Portugal began with importations. The industrial production of natural cement started in 1866 in Alcântara, followed by the creation of additional companies, which marked the beginning of more significant industrial production. Although national production began later and relied initially on imported binders from France and Britain, global advancements in cement technology were quickly integrated. Portuguese engineers and entrepreneurs adopted key industrial processes—such as the use of Hoffmann and rotary kilns—directly inspired by foreign models. This transfer of knowledge and technique spurred the establishment of major factories like Maceira-Liz and marked Portugal's transition from natural to artificial cement at the turn of the 20th century. Despite the start of national production of artificial cement in the late 19th century, imports continued to dominate the Portuguese market well into the 20th century.

These technological influences extended beyond utilitarian construction into the artistic domain. The use of reinforced cementitious mortars in Portuguese public artworks, such as those at the Teatro Nacional de S. João, illustrates how international innovations shaped local artistic expression. However, documentation on such applications remains limited. Further research into the material composition and historical use of cement in Portuguese public art is essential for conservation efforts. By understanding the evolution of cement-based mortars and the cross-cultural exchanges that informed their use, we can better preserve and value this unique aspect of modern heritage.

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