Chemical soil stabilization - conventional and alkali activated materials (review)

Estabilización química de suelos - Materiales convencionales y activados alcalinamente (review)

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Resumen

El creciente interés por el desarrollo de alternativas frente al uso masivo de cementantes tradicionales en aplicaciones geotécnicas, tales como cemento y cal, se debe en gran medida a los retos ambientales y costos asociados en este tipo de aplicaciones. Los cementantes activados alcalinamente surgen como una de las alternativas de mayor sostenibilidad, particularmente por su bajo consumo energético y en teoría la baja huella de carbono en su fabricación; además, tienen la posibilidad de utilizar residuos y subproductos industriales como materiales precursores en su fabricación. Este artículo presenta un estado del arte de los diversos materiales empleados convencionalmente en la estabilización química de suelos y realiza una revisión de los artículos publicados en relación con la implementación de cementantes activados alcalinamente, su viabilidad técnica, los impactos ambientales asociados y los retos que se deben superar para lograr posicionarlos como una alternativa sostenible para procesos geotécnicos.

Palabras clave: estabilización de suelos; materiales activados alcalinamente; cemento; residuos industriales.

Abstract

The growing interest in the development of alternatives to the massive use of traditional binders in geotechnical applications, such as cement and lime, is largely due to the environmental challenges and associated costs in these types of applications. Alkali activated binders emerge as one of the most sustainable alternatives, particularly due to their low energy consumption and, in theory, the low carbon footprint in their manufacture. In addition, they have the possibility of using industrial waste and by-products as precursor materials in their manufacture. This article presents a state of the art of the various materials conventionally used in the chemical stabilization of soils and reviews the articles published in relation to the implementation of alkali-activated binders, their technical feasibility, the associated environmental impacts, and the challenges that must be overcome to position them as a sustainable alternative for geotechnical processes.

Keywords: soil stabilization; alkali-activated materials; geopolymers; cement; industrial waste.

1. Introduction

The definition of "soil" can be interpreted in different ways according to interests or applications. For engineering, soil is an earthy substrate or deposit of unconsolidated mineral particles, a system that is formed by multiple phases: solid, liquid, and gaseous, on which various engineering works are carried out (Nortcliff *et al*., 2012). Soil is considered the oldest, most complex construction material used by engineers, being the physicochemical and mechanical properties, such as compressibility, resistance, permeability, volumetric stability, and durability, of great importance in engineering, since practically all civil structures are founded on or within the earth's surface. In addition, soil is not only a support element for civil constructions, but also provides innumerable raw materials for the manufacture of masonry elements and the construction of structures.

Soil, as a bearing element, plays a determining role in the foundations, the stability of the structures depends to a great extent on its properties. Loads are transmitted through the foundation, this causes stresses and deformations to be generated, which will depend on the magnitude of the applied load and the properties of the supporting soil. Under these stress conditions, the integrity of the supporting soil is mainly affected by the unanticipated action of water (Liu *et al*., 2011), frosts (Jing *et al*., 2019) and excessive unforeseen settlements, among others. The loss of resistance of the supporting soil leads to severe damage to the structures. In the United States alone, the costs of damage to structures caused by expansive soils reach the figure of 1 trillion dollars a year; in the UK about £ 150 million a year, and generally they amount to billions around the world (Firoozi; Guney Olgun; Firoozi; Baghini, 2017; Puppala; Pedarla, 2017; Zhao; Ge; Petry; Sun, 2014). In many of the civil works engineering projects, the native soil does not meet the design requirements and therefore it is necessary to carry out modification, stabilization, or replacement processes to provide the work with improved construction material.

Soil stabilization can increase the bearing capacity of native soil, improve shear resistance, increase resistance to softening by the action of water, provide volumetric stability since water permeability is minimized, decrease plasticity, and increase the unit weight of treated soils (Hall; Najim; Keikhaei, 2012). The simplest soil stabilization processes that have been implemented are soil compaction and soil drainage. However, in some cases, these two techniques are not enough to achieve a good stabilization of the land, so improved particle size soil gradation is one of the most widely used soil stabilization processes, and can be achieved by adding binders (Makusa, 2013). The application of binders is known as chemical stabilization of soils, this methodology uses universal cementing materials such as Portland cement and lime, although also in specific applications salts such as sodium chloride (NaCl) or waterproofing agents such as asphalt products have been implemented (Hall *et al*., 2012).

Portland cement is one of the most widely used materials in the construction sector in different applications, including, as mentioned above, soil stabilization. Because the production of this has been closely related to global warming associated with the high temperatures used in the production process, the excessive consumption of energy and natural resources (Damtoft *et al*., 2008), alternative materials have been developed that can reduce the carbon footprint and also preserve the binding properties of Portland cement. From there, alkaline activated materials or also called geopolymers have arisen, which are produced by the chemical interaction of an aluminosilicate type material with an activating alkaline solution (Provis; Bernal, 2014; Shi; Fernández-Jiménez; Palomo, 2011). The main materials used as a source of aluminosilicates are fly ash, steel slags, and metakaolin. Recent studies have used other materials such as demolition waste, brick waste, and glass waste, among others (Rivera; Cuarán-Cuarán; Vanegas-Bonilla; Mejia de Gutierrez, 2018; Robayo-Salazar; Rivera; Mejía de Gutiérrez, 2017; Robayo; Mulford; Munera; Mejía de Gutiérrez, 2016). Unlike Portland cement, the production of alkaline activated materials does not consume large amounts of energy, since it is carried out at low temperatures, offering a more environmentally friendly alternative. Since 1930, the scientific community has increased its interest in studying the properties of this type of materials, finding that they generally present high mechanical performances, high resistance to chemical attack, as well as high temperatures, among other properties (Wu *et al*., 2019). The use of this type of material as a cementing material for the application in the chemical stabilization of soils is a relatively new concept.

2. Methodology

The methodology followed in the present study includes a review of the scientific database (Scopus, Elsevier), using as keywords "soil stabilization alkali-activated / geopolymer" and "soil stabilization Portland cement". The review, carried out for the last nine years (2010-2019), shows that the number of publications related to soil stabilization using alkali-activated cement does not exceed 70 documents. According to Figure 1 (data taken from Scopus), the first publications date from 2012, and its study has been increasing little by little over time. It should be noted that of the publications as of October 2019, only 72 % correspond to articles, the remaining percentages are book chapters or presentations at the international conference level. By April 2020, it has already been increased by 11 more items. In general, most articles are published in journals of the Science Direct (Elsevier) and Springer databases. In Figure 1 it is observed that the scientific production related to chemical stabilization with Portland cement is approximately six times higher than of alkali-activated materials. However, although this technology is relatively recent, the excellent mechanical performances obtained in the different research studies at a global level, using different types of soils (fine and granular), have led to consider it potentially viable in chemical soil stabilization.

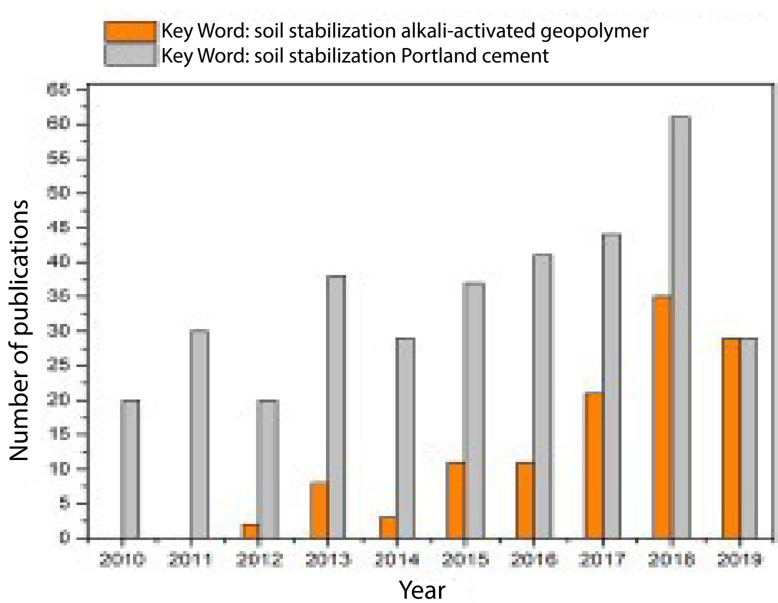

Figure 1. Publications of the last 9 years (January 2010-October 2019) in the field of soil stabilization with alkali-activated materials vs. Portland cement. (Scopus database)
Source: own elaboration.

This review presents a brief description of the materials traditionally used in soil chemical stabilization such as Portland cement, lime, fly ash (FA), blast furnace steel slags (BFSS), and salts, followed by the presentation of some of the most relevant results of soil stabilization using alkaline activated cementing materials. Additionally, the possible advantages and disadvantages of the use of this alternative material, its opportunities and challenges associated with its application are presented.

2.1. Soil stabilization methods

A soil is considered stable when it has sufficient resistance to not undergo large deformations or excessive wear in service due to the action of the variable climatic conditions that may arise, and it must also retain these properties over time. Natural soil can sometimes have the right granulometric composition, plasticity, and moisture content so that, when compacted alone, it has the mechanical characteristics that make it usable as a foundation for a road or path. However, if an adequate balance is not achieved between the inter-particle friction and their adhesion, the expected stability will not be achieved. Therefore, in general, soil stabilization is a process of improving the quality of the natural soil to obtain stable physical, chemical, and mechanical characteristics in relation to the environmental service conditions. With these stabilization processes, one or more properties of the soil can be altered: control of expansion, increase resistance, reduce plasticity, decrease permeability, prevent erosion, among other properties. For instance, it is possible to improve the strength of soils and convert them into materials suitable for construction, capable of withstanding the effects of traffic and the environment with excellent durability. The soil stabilization methods can be classified into mechanical, physical, chemical, and biological.

Mechanical stabilization consists in compacting the soil statically or dynamically to increase its density, mechanical strength, decrease its porosity and permeability. It can also include previously the mixture of soils of different gradation to obtain the appropriate specification. The engineering objectives of such a procedure are mainly a) to increase bearing capacity, b) to decrease settlement of structures, c) to control undesirable volumetric changes, d) to reduce water permeability, and e) to increase slope stability (Das, 2013). The compaction of a soil depends on the compaction energy, by the type and gradation of the soil, and the degree of compaction depends on the moisture content and the dry unit weight. The degree of compaction is then measured in terms of the unit weight of the dry soil.

Physical stabilization consists of modifying the properties of soils by intervening in them to provide them with new structural characteristics. Physical procedures include the use of materials known as geosynthetics, such as geotextiles, generally made of synthetic fibers such as polyester or polypropylene; geogrids, three-dimensional structures but with the characteristic of being mono or bi-oriented and made of high-density polyethylene; geomembranes, impermeable polymeric sheets made of polyvinyl chloride (PVC), or high or low density polyethylene (HDPE/LDPE); the geocomposite, designed specifically for soil stabilization where both reinforcement and separation of a granular base and a very thin subsoil is required, is produced by attaching a non-woven geotextile to a geogrid, which allows a high interaction with the reinforced soil; and geocells, which are three-dimensional cellular confinement systems made of polyethylene or polypropylene panels, very resistant for the confinement of loads (Liu *et al*., 2011).

Chemical stabilization consists in adding to the soil other materials, or chemicals, that modify its properties, either by a physicochemical reaction or by creating a matrix that binds the soil particles together (Bahar; Benazzoug; Kenai, 2004; Billong; Melo; Louvet; Njopwouo, 2009). Some authors (Bahar *et al*., 2004; Billong *et al*., 2009) recommend the combination of two methods, the one of stabilization by mechanical methods of compaction and vibration and stabilization by chemical methods, to obtain greater resistance and durability.

A final technique is biological stabilization, which basically consists of the use of biological enzymes which, when incorporated into the soil, increase the degree of agglutination and compaction of the soil particles, as a consequence of a cation exchange in the soil structure which leads to an accelerated cementation process.

In the following sections, the traditional and alternative methods of chemical soil stabilization are detailed, pointing out in each case their advantages and disadvantages.

2.1.1. Chemical stabilization of soils - traditional methods

Chemical stabilization can be used in all types of soils for the improvement of their geotechnical properties, changing the initial physicochemical properties of the native soil to mitigate some problems such as volumetric instability or to increase some of its properties such as strength and durability of the treated soils. This type of stabilization includes the use of a wide range of materials, among which cement and lime have been the most conventional. However, other products such as salts (sodium chloride, calcium chloride) and industrial residues or by-products (blast furnace slag, fly ash) have also been considered in the stabilization of soils for road construction (Syed-Zuber *et al*., 2013). In addition, the combination of several properly selected raw materials can allow the synergy of their properties to provide better soil stabilization behavior.

It should be noted that the selection of the type and percentage of the stabilizer is primarily a function of the soil type or classification and of course, secondarily, of the improvement expectation required for the particular case. Other important factors are cost and environmental conditions. Thus, when it is only intended to modify some of its properties, such as workability, plasticity, or particle distribution, it is possible that low proportions of the additive are required; however, when it is desired to interact with properties such as strength and durability to increase service life, the amount of additive can be higher. Although there may be more than one stabilizer suitable for a given soil type, there are some guidelines for selecting the specific stabilizer based on soil grain size, plasticity, and texture.

In general, the criteria for deciding on a type of chemical stabilization are generally based on the Atterberg limits, which are used to characterize the behavior of fine soils. A soil can present four states of consistency depending on its moisture content: dry, semi-solid, plastic, and liquid. The plastic limit (PL) corresponds to the transition from semi-solid state to plastic state; and the liquid limit (LL) corresponds to the transition from the plastic state to the liquid state. The plasticity index (PI) is calculated as the difference between the moisture content in LL and LP. Some standards consider that LL cannot exceed values between 30-40 % and IP between 10-12%, respectively for subbase and base materials, and around 40 and 20 % for subgrade materials. Other characteristics that determine the type of stabilization are related to the density in the dry state and the value of the California Bearing Ratio (CBR) of the soil. These characteristics, in general, define the quality of the soil and their knowledge is as important as the choice of the stabilization materials. The ASTM D4609 norm, which evaluates the potential of products used to improve the engineering properties of soils, states in section 8.1.4 that "any product that achieves a 345 kPa increase in compressive strength of the soil and, in addition, ensures that when immersed in water the specimens do not significantly lose strength, can be considered suitable for stabilization". However, it is common that, once the chemical stabilization has been carried out, mechanical methods are applied to compact the soil.

2.1.2. Stabilization with Portland Cement

Portland cement (from English, ordinary Portland cement, OPC) is the most widely used binder worldwide because it has the ability to stabilize a wide variety of soils, although it is much more effective in sandy and clay soils with between medium and low plasticity indices (Pandey; Rabbani, 2017). The material generated by mixing soil with different percentages of OPC is called soil-cement. This material is used in many types of civil infrastructure applications such as bases or sub-bases to build roads, embankments, dikes, and for foundation stabilization, among others. It has been implemented for more than 80 years, and its development occurred simultaneously in the United States and England, where in 1917 they successfully applied mixtures of clay soil with cement to create roads. Despite this, it was not widely used at that time due to the traffic type. In the United States, the earliest recorded projects using soil-cement in road construction were in South Dakota, Iowa, Ohio, California, and Texas. From 1935 onwards, the Portland Cement Association (PCA) developed a series of investigations that led to the first moisture-density, wetting-drying, and freeze-thaw tests of various soil-cement mixtures and from this work, in the mid-1940s, the first ASTM and AASHTO standards for this type of material were developed (Portland Cement Association, 1992).

The mechanisms by which the soil is stabilized by cement are hydration, cation exchange, flocculation and agglomeration, carbonation, and pozzolanic reactions. The most important of these is the hydration of the cement, as it generates calcium silicate hydrate (from English calcium silicate hydrate, C-S-H) compounds that cement the soil particles, creating stability against changes in humidity in the environment. The cation exchange is the second most important mechanism when cohesive soils are stabilized, the Ca^{++} cations in the cement fill the voids in the soil structure or are exchanged for some cations in the soil, reducing the net surface charge, generating a lower attraction of water molecules by the material (Pandey; Rabbani, 2017). Khemissa and Mahamedi (2014) when treating expansive soils with Portland cement corroborated that the plasticity index and the liquid limit of the treated soils decreased appreciably (in the order of 50 %), thus reducing their swelling potential and making them less sensitive to water with the consequent improvement in the compaction processes of the soil-cement mixtures. Flocculation can change the plastic texture of some soils to a fine and granular texture (Prusinski; Bhattacharja, 2007), while carbonation contributes to the strength of the stabilized material and pozzolanic reactions contribute to the generation of additional cementing material (C-S-H) over time increasing the stabilization by the cementation of particles.

Depending on the proportion of the components in the mixture between soil and cement, various kinds of soil-cement are generated: compacted soil-cement, plastic soil-cement, and soil modified with cement. The most widely used type of mixture is the compacted soil-cement commonly called soil-cement, as it contains a proportion of OPC between 4-25 % by weight of dry soil and is compacted to achieve greater resistance. Soils that show the best results when stabilized with OPC are well-graded granular materials with a sufficient amount of fine material to produce a kind of floating aggregates in the matrix. According to the PCA, the maximum size of the particles of the material to be stabilized must be 5.1 cm, the Plasticity Index (PI) for these materials must be less than 30, while for finer materials the PI must be less than 20 with a Limit Liquid (LL) below 40 (US Department of Transportation, 1992).

Studies by Horpibulsuk *et al*. (2010) related the strength of a clayey soil stabilized with different cement contents for a given amount of water, identifying three zones that were related to the amount of OPC added to the soil. The first one they called the *active zone*, where the strength of the mix increases with cement content between 0-10 %, attributable to the hydration products of the OPC (C-S-H). Between 10 - 30% of cement the increase in resistance is almost zero, this means that there is no significant improvement in resistance, this region was called *inert zone*. With cement contents > 30 % they found that the resistance decreased, and they called it the deterioration zone, this was attributed to an insufficient amount of water to promote the complete hydration of the cement in the mix. Based on the above, they defined a maximum limit of 10 % cement.

Table 1 presents a summary of the different soil/cement mixtures, their main properties, and their respective application in pavements (Quintanilla, 2007).

Table 1.

Classification and properties of different soil/ cement mixtures

Classification	Materials	Amount of cement (% w)	Properties	Uses
Cement soil	Fine or granular soils and cement	3-7	> 4MPa Compression	Subbases
Cement modified soil	Fine or plastic soils with excessive moisture and cement	Maximum 2 %	Increases CBR and decreases plasticity	Subgrade or esplanades
Cement stabilized soil	Soils with high granular fraction and cement	Minimum 2 %	Increases rigidity and mechanical resistance	Subgrade or esplanades
Plastic cement soil	Soil, cement, and additives	-	3-8.5 MPa Compression	Bases for pavements
Cement-treated granular base	Aggregates and cement	3-13 %	3-6 MPa Compression 7.000-14.000MPa Elasticity modulus	Base cover for pavements
High-performance single layer pavement	Existing soil on the construction site and cement	11-20 %	5-13 MPa Compression 10.000-20.000 MPa Modulus of elasticity	Base layer or underlayment of pavements

Source: taken and adapted from Quintanilla (2007).

It should be noted that the typical 7-day simple compressive strength ranges required by the ACI 230 code depend on the soil type, thus for ML and CL soils is 17.58 - 35.15 kg/cm^2; for MH and CH soils is 14.06 - 28.12 kg/cm^2, and for the rest of the soil types of the Unified Soil Classification System (USCS) is 21.09 - 42.18 kg/cm^2.

2.1.3. Soil stabilization with lime

Lime is one of the most used materials in soil stabilization. It can be used in different ways depending on the type of application, quicklime, as a desiccant for very humid soils, hydrated lime, and milk of lime for stabilization of fine-grained clay soils. When lime is applied to clay soils, its particles immediately lose their cohesion power, transforming the plastic soil into a more granular material. Records of the use of lime date from as far back as the Mesopotamian civilization through ancient Egypt, the Roman Empire, and ancient Greece (McDowell, 1959). In the modern era, lime was used as a stabilizing agent from around 1924, its use became widespread after World War II as a soil stabilizing chemical for road construction (Bell, 1996). When applying lime to soils, cation exchange is the first mechanism that modifies the engineering properties of the treated soil. Due to the flocculation of its particles, the fixation of Ca++ cations in the soil structure is promoted and this leads to the generation of pozzolanic reactions responsible for stabilizing the soil by modifying its initial properties (Behnood, 2018a; Bell, 1996). When the clay particles are broken, silica and alumina are released and react with the calcium in the lime to form calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), which are analog binders of those formed in the hydration reactions of Portland cement. These hydrated components form a matrix with a lower plasticity index, which contributes to the resistance of the layers of soil stabilized with lime and to their lower permeability. The soil layer is easier to work and compact. In this type of stabilization, lime can be considered as an alkaline activator capable of generating resistant soil, mechanically and chemically from its action with the clayey soil.

Bell (1996) studied the effect of lime on three types of the most common minerals in fine soils, montmorillonite, quartz, and kaolinite. The author reports a significant decrease in plasticity in the montmorillonite mineral, going from 15 % to 3 % when using a 10 % lime content, while in kaolinite the reduction was less. By adding lime, kaolinite and quartz increase their liquid limit while in montmorillonite it was reduced; in the latter, the resistance increases more rapidly. According to Mallela, Quintus and Smith (2004), lime stabilization works best in fine soils with a minimum clay content of 10 % and IP greater than 10. Al-Mukhtar, Khattab, and Alcover, (2012) stabilized with lime a plastic clay known as "FoCa Clay"; after the chemical treatment, the treated soil improved its geotechnical properties by reducing its plasticity and the possibility of swelling and increasing strength, corroborating that immediately after being treated with lime, the soil loses its cohesive properties and transforms into a granular soil with improved geotechnical properties.

Millogo, Morel, Traoré, and Ouedraogo (2012), evaluated the microstructural characteristics of lateritic soils stabilized with lime in different proportions (2, 3, and 8 %); the soils were composed of 26 % kaolinite and 42 % quartz, and their physical characteristics were: LL 22.5 %, LP 12 %, PI 10.5, CBR 43. The authors reported as products of the reaction calcite ($CaCO_3$), portlandite (Ca (OH)2), and poorly crystallized calcium silicate hydrate (C-S-H), the latter formed from the reaction between kaolinite present in the soil and lime incorporated into the mix. The PI indices, and the maximum dry density (from the English maximum dry density, MDD) decrease with the addition of lime while the optimum moisture content (OMC) increases. Regarding the mechanical properties, an increase in the CBR index was observed up to 3 % lime. Therefore, the authors recommend this percentage to modify lateritic gravels and use them as an economic option for bases in road construction (Millogo *et al*., 2012). Ismeik and Shaquor (2020) studied the durability against freeze-thaw cycles of a kaolinite soil stabilized with different percentages of lime; they observed a reduction in the plasticity of the native soil by about 50 %, while the increase in durability and mechanical strength depended on the lime content in the mixture. They reported that 6% lime substantially improved the durability of the freeze-thaw cycles of the compacted mix, concluding that this stabilized soil could be an excellent material to build bases for pavements and even foundations. Generally speaking, the percentage of lime should not exceed 8 %.

2.1.4. Soil stabilization using fly ash

Fly ash (FA) was implemented as a soil stabilization material due to the environmental and economic drawbacks associated with lime and Portland cement, prompting much research into these by-products with the aim of developing new environmentally sustainable binding materials for a variety of engineering applications. Initially, they were used as an additive for products based on cement and concrete; later they began to be implemented as structural fill material in embankments; and finally, as a soil stabilizing material in road construction (Babu; Rao, 1996; Behnood, 2018b; Horiuchi; Kawaguchi; Yasuhara, 2000; Kim; Prezzi; Salgado, 2005; Kumar; Chandra; Vishal, 2006; Senol; Edil; Bin-Shafique; Acosta; Benson, 2006). The fly ash, depending on the kind of coal used in the combustion, is classified into type F ash and type C ash (ASTM C618); type F ashes are composed of oxides of silicon, aluminum, and iron (SiO2,Al2O3, Fe2O3 respectively), which represent a total of 70 % of the material and have a very low calcium oxide (CaO) content (less than 10 %), while type C ash has a CaO content above approximately 30 % and high content of sulfur oxides (SO_3) (Kim *et al*., 2005; Makusa, 2013; Moghal, 2017).

Due to the low cementation power of type F ashes, they are generally mixed with calcium sources such as lime or OPC, since due to their pozzolanic nature they interact with calcium oxides to generate reaction products that cement the particles of the treated soils (Arora; Aydilek, 2005). The cementing power of the ashes can be improved when lime is added together with gypsum, which improves resistance at early ages with moderate amounts of lime. Very significant increases are even observed when the calcium source is added in greater proportions, as demonstrated by Sivapullaiah and Moghal (2010). According to Kim *et al*. (2005), the shear resistance of soils stabilized with fly ash can be attributed to the characteristic internal friction angle of the F-type ashes since the resistance provided is due to the friction between their particles, while with the C-type ashes is more related to a cohesion resistance, thanks to its greater cementing capacity.

The combination of ash and lime can be used successfully to stabilize sandy and silty soils, greatly increasing the rigidity of the stabilized soil (Puppala, 2016). Arora and Aidilek (2005) studied mixtures of F-type ash modified with OPC and lime with which they stabilized a sandy soil for applications as a base layer for road construction; the unconfined compressive strength and the modulus of resilience increased when adding up to 5 % of OPC in the mix. In the freeze-thaw cycle tests, the compressive strength increased in each cycle for the OPC-modified mixes as opposed to the lime-modified mixes. Finally, after treatment, the thickness of the base layer decreased when implementing OPC-modified soil-ash mixtures. Edil, Acosta, and Benson (2006) carried out a study of the effectiveness of type C ashes in stabilizing fine-grained soils, demonstrating that ashes, whether or not they are within the ASTM C618 specification, are equally effective in stabilizing fine-grained soils; in all cases, the soil showed increases in CBR and resilient modulus with any of the ashes used. Similar work was carried out by Joshi, Patel, and Shahu (2019) on stabilizing clay soils for applications as base or sub-base for flexible pavements, in which they agree that as the ash content in the soil mixture increases, the CBR value, resilient modulus, and unconfined compressive strength of the stabilized material increases, which could be used to make even thinner layers allowing for more economically profitable pavement designs.

2.1.5. Soil stabilization using blast furnace steel slags

Granulated blast furnace (GBSF) is a by-product of the steel industry. It is composed mainly of calcium silicates and aluminosilicates and is of particular interest for its latent hydraulic properties that can be developed when combined with Portland cement, lime, or alkaline agents (Das; Prakash; Reddy; Misra, 2007; Gutt; Nixon, 1979). GBSF has been used successfully in the stabilization of expansive soils. Studies by Al-Rawas (2002) showed that GBSF is an effective additive to improve this type of soil by reducing the swelling potential of the soil due to calcium ions interacting with the soil particles to generate flocs and making it less susceptible to volume changes by water action. Similar results were obtained by Cokca, Yazici, and Ozaydin (2009), Hasan, Chegenizadeh, Budihardjo, and Nikraz (2016), Manimaran, Santhosh, and Ravichandran (2018), demonstrating that the alteration of the particle size of the soil when adding GBSF not only decreases the swelling potential but also increases the specific gravity, reduces the plasticity index, increases the CBR and the mechanical resistance. The GBSF in combination with Portland cement generates greater resistance, due to the reaction products of a pozzolanic character; the increase varies depending on parameters such as the percentage of GBSF addition and the curing conditions. When GBSF is combined with lime it provides self-regeneration in case of initial damage to the structure due to overloading, furthermore, the mixture is not affected by the presence of sulfates in the soil (Higgins, 2005), the main reaction products being hydrated calcium aluminates (C-A-H), hydrated calcium silicates (C-S-H) and hydrated aluminum-rich calcium silicates (C-A-S-H) (Sekhar; Nayak; Preetham, 2017; Yi, Zheng; Liu; Al-Tabbaa, 2015). Recently, studies by Bensaifi, Bouteldja, Nouaouria, and Breul (2019) demonstrated that GBFS can be activated with calcined eggshell residues to improve the geotechnical properties of a Marl-type soil used for road construction; the authors report that CBR increases of up to 22 times with respect to the CBR value of the untreated soil.

2.1.6. Soil stabilization using salts

As low-cost alternative materials, salts such as sodium chloride (NaCl) and calcium chloride ($CaCl_2$) have been used. The purpose of its use is to retain moisture and improve the compaction of the material. In addition, they help to reduce the freezing point of water contained in the soil and in very dry areas prevent rapid evaporation of compaction water (Firoozi *et al*., 2017). The plastic properties of clay soils depend on the cation exchange. When clay particles are coated with similar charges, they repel each other; when there are particles with different charges, they attract each other; if the environment is an acidic environment, i.e. excess H+ (pH<7), the particles tend to be positively charged, leading to flocculation of the clay, and in a basic environment a dispersed structure results. Yunus and Zurairahetty (2007) investigated the use of lime mixed with salts (NaCl and $CaCl_2$ in ranges from 2 to 10 %) in the stabilization of a clay soil (57.51 % silt and 20.78 % clay) with an organic material content of 14.41 %, which is known to reduce the effectiveness of lime as a stabilizer. In general, the presence of salts in orders of 10 % increased the resistance of the mixture, with NaCl's performance standing out; in this sense, they claim that these salts act as reaction accelerators in the presence of humic acids.

Sodium chloride is very useful in climates with freezing problems. At high relative humidities, it acts as a water retainer due to its hygroscopic nature, reduces evaporation and prevents dust formation. Also, a better result can be expected if the soil contains fine material that reacts with salt. Limitations for its use include: the environment must have a relative humidity of more than 30 %; the soil particles must pass through 200 mesh and react favorably with the salt; and the absence of organic matter as this inhibits the action of the salt (Garnica; Pérez; Gómez; Yhaaraby, 2002).

2.1.7. Advantages and Disadvantages of Traditional Chemical Soil Stabilization Methods

The advantages of traditional soil stabilization methods are the existence of a wide variety of products on the market developed to improve various types of soils or certain properties in some types of soils. In reference to the most widely used binders, OPC and lime, their main advantage is that they can be used in practically all kinds of soils. As technical advantages, the gain in resistance at early ages and the increase in the durability of the treated soils are pointed out. In road applications, the thickness of the layers of the pavement structures can be reduced, reducing the costs of the work. In general, they are widespread and commercially available products, and their chemical composition has a relatively acceptable variability as their production processes are widely developed and controlled.

As a disadvantage, the negative environmental impact of their production and even their manufacturing cost is pointed out. The OPC production industry alone generates approximately 5 - 8 % of total global CO_2 emissions (Andrew, 2017; Gartner, 2004); according to Kim and Worrel (2002) and Shi *et al*. (2011) for every ton of OPC produced between 0.8 and one ton of CO_2 is emitted into the atmosphere, this is attributed to the decomposition of raw materials and the use of fossil fuels in the manufacturing process. Another drawback associated with the use of calcium-based binding agents is their ineffectiveness in soils with high organic matter content, as the hydration and pozzolanic reactions necessary for the stabilized soil to achieve the appropriate mechanical strength are affected (Tremblay; Duchesne; Locat; Leroueil, 2002). According to Ma, Chen, and Chen (2016) the compressive strength of soils with high organic matter content treated with calcium-based cementitious agents decreases as humic acid increases due to the decomposition of organic matter, this is sometimes compensated with a higher proportion of cement (Chen; Wang, 2006); however, it is a costly practice. Generally, it is not recommended to use cement to stabilize soils with more than 2 % organic matter, nor is it recommended to use cement to stabilize soils with an acidic pH because it can slow down or inhibit hydration processes (Trussell; Spence, 1994).

In response to the disadvantages mentioned above, the scientific community has focused its efforts on the search for new technologies that can be implemented in these types of geotechnical applications and that in some way mitigate primarily the problems related to CO_2 emissions, decrease the exploitation of natural resources, be economically viable and increase the durability in service of stabilized soils.

2.2. Chemical stabilization of soils - alkaline activation

Chemical stabilization of soils using alkaline activation technology is one of the most recent research proposals and emerges as an alternative to traditional binding materials. The literature around this topic is limited, as mentioned previously. Despite this, the investigations carried out have made some significant advances showing promising results, both in terms of the mechanical properties and the durability of the evaluated soils. From an environmental point of view, alkaline activated cements are considered, in theory, a more sustainable alternative compared to traditional cements, due to their lower energy consumption in the production process and the use of precursors derived from some industrial wastes or by-products (fly ash and blast furnace slag, among others) for their production, which mitigates the exploitation of natural resources. The review in the Scopus database analyzed according to the type of precursor used in the alkaline cement used for soil stabilization studies in the last 10 years (2010-2020) shows that the highest number of articles use fly ash (FA) and steel slag (GBSF), as can be seen in Figure 2.

2.2.1. Chemical stabilization of soils with alkaline activated cementitious substances

A new approach to the use of residues in chemical soil stabilization processes was presented by Hughes and Glendinning (2004), who used GBSF mixed with titanium production residues and lime, which when incorporated into the soil gave similar mechanical strengths to those obtained with OPC and increased durability; the stabilized soil was not affected by moisture or freeze-thaw cycles, nor was it susceptible to sulfate attack. The implementation of lime to increase the pH of the medium and to achieve better dissolution of the precursors could be considered as the starting point for the use of alkaline activated cementitious agents in geotechnical applications, although lime is not a strongly alkaline activator like the conventional activator chemicals sodium hydroxide (NaOH) or sodium silicate (Na_2SiO_3).

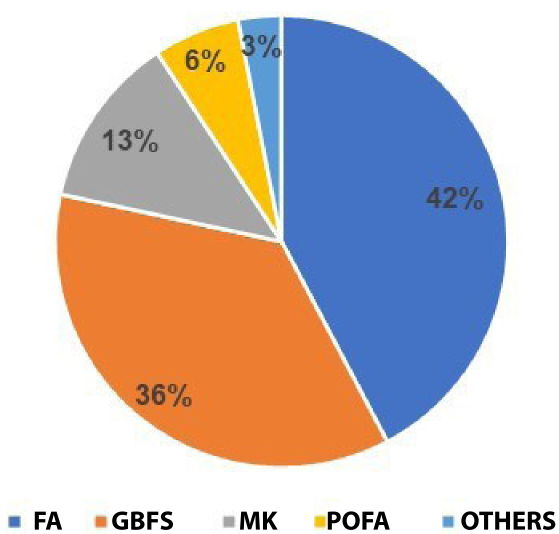

Figure 2. Types of precursors used in soil stabilization investigations with alkaline activated materials 2010-2020 (Scopus database)
Source: own elaboration.

Cristelo, Glendinning, Fernandes, and Pinto (2013) stabilized a soft soil using 20 to 40 % of an alkaline activated cementitious based on FA type F and activated with NaOH at different concentrations (10, 12.5, and 15 M), the results show that the strength of the stabilized soil increases with decreasing activator/ash ratio, reaching 43 MPa after 365 days. Coudert *et al*. (2019) evaluated the stabilization of a soft soil with an alkaline activated cementitious agent based on C-type fly ash added with 20 and 50% metakaolin using sodium silicate as an activator; the results showed that the presence of metakaolin contributed to a fast reaction of the mixture obtaining more compact and less porous structures compared to those produced with 100 % FA. Cristelo, Glendinning, Fernandes, and Teixeira-Pinto (2012); Cristelo, Glendinning and Teixeira-Pinto (2011) when comparing the use of FA type F with FA type C, added in a range of 10-40 % by weight of the soil, report that at early ages the soils stabilized with fly ash type C show greater resistance compared to those stabilized with F type ash. However, at the age of 365 days, soils stabilized with F type ashes reach a higher value and exceed that obtained in the same soils stabilized with lime and cement, which they attribute to the high pozzolanic action of this type of FA.

Cristelo *et al*. (2012) evaluated the effectiveness of the alkaline activator by adding calcium hydroxide, sodium chloride, and a superplasticizer to stabilize a granitic residual soil, the results presented showed that the addition of calcium hydroxide in the mixture accelerated the reactions as in the case of type C fly ash, and as a general conclusion they state that the use of this type of additives in the mixture is not justified, as no significant resistance was observed at advanced ages.

Sargent, Hughes, Rouainia, and White (2013) studied the stabilization of a silty artificial soil, using a cementitious based on blast furnace steel slag activated with an alkaline solution, a mixture of $NaOH:Na_2SiO_3$. Soil treated with 100 % slag presented the highest resistance and rigidity; Furthermore, it showed better performance in freeze-thaw and wetting-drying cycles. Zhang *et al*. (2013) used a mixture of clay soil and metakaolin (3-15 % by weight) activated with sodium hydroxide (NaOH), finding that the mixture is much more stable than the no stabilized soil and even 5 % more stable than soil stabilized with Portland cement. The compressive strength of the soil increases with the proportion of metakaolin, and the brittleness of the soil is reduced, with deformation at failure of specimens ranging from 0.08 % for soils without metakaolin to approximately 3.00 % for soils stabilized with 5 and 8 % metakaolin, desirable properties in the application of flexible pavements. Ghadir and Ranjbar, (2018) used alkaline activated volcanic ash and report the increase in soil strength by 200 % over Portland cement stabilized soil. Abdullah, Shahin, and Sarker (2019) evaluated the effect of an alkaline cementitious cement based on the mixture of FA and GBFS, added to the soil in proportions of up to 30 % with respect to the weight of soil; the authors mention that although the addition of 10 % generates a 28-day strength of 1103 kPa, a value comparable to that obtained with 6 % OPC, in terms of durability it is advisable to use 20 % of the cementitious agent, reaching strengths of 2100 kPa, a value that exceeds that obtained with 9 % OPC. It should be noted that the optimum GBFS content in the cementitious material was 20 %.

The implementation of alkaline activated cementitious materials in the manufacture of compacted and stabilized earth masonry elements has also been studied by different researchers. Silva *et al*. (2015) reported acceptable values of mechanical properties (compression and flexural) of masonry elements produced with compacted soil stabilized with alkaline activated F-type fly ash. Muñoz, Easton, and Dahmen (2015) explored the possibility of using aluminosilicates recovered from quarry waste (waste crushed rock and clayey soils) for the manufacture of stabilized and compacted masonry elements, with promising results. However, due to the nature of the precursors, it was necessary to add feldspar and nano-silica nanoparticles to increase the reactivity of the mixture with the alkaline activator, improving the strength of the specimens by 60-80 % and achieving strengths above 8 MPa at curing temperatures between 50 and 60 C. Palanisamy and Kumar (2018), used sandy soils and manual compaction for the production of compacted soil blocks incorporating C-type fly ash and granulated blast furnace slag alkaline activated with a mixture of sodium hydroxide and sodium silicate; the strengths obtained were higher than those of soil-cement blocks; furthermore, the authors reported an increase in strength of 20 % when using 1 % by volume of coconut fiber waste.

Omar-Sore *et al*. (2018) performed the stabilization of lateritic-type soils to manufacture compacted earth blocks using metakaolin as a precursor and NaOH as an activator. The added proportions of alkaline binder to the soil varied from 5 to 20 % by weight and as reference material they used compacted blocks stabilized with 8 % of OPC; they concluded that the addition of 15 % of metakaolin and a curing temperature of 60 °C gives rise to increases in mechanical resistance and greater stability to water; furthermore, the thermal conductivity was similar to that of non-stabilized soil blocks. The thermal properties of compacted and stabilized earth blocks were also evaluated by Leitão *et al*. (2017), using stabilized blocks with alkaline activated cementitious based on fly ash; The authors reported that, although the performance was less insulating than that of conventional construction materials, the transfer coefficient was 2.94 $W/m^2{}^\circ C$ compared to ceramic bricks (1.74 $W/m^2{}^\circ C$) or concrete bricks (2.70 $W/m^2{}^\circ C$) can be considered suitable for constructions in countries with a temperate or Mediterranean climate. It is emphasized that the main role of compacted earth materials is to provide thermal capacity to store energy and provide thermal inertia against temperature fluctuations, rather than to behave as thermal insulators.

Another type of applications that have involved stabilized soils using alkaline activated binders is in the improvement of bases, sub-bases, subgrades in the design of roads, and even stabilized soils as a rolling layer in tertiary roads. Rios, Cristelo, Viana da Fonseca, and Ferreira (2015); Rios, Cristelo, Viana da Fonseca, and Ferreira (2016), and Rios *et al*. (2019) carried out a series of studies on sandy silt type soils stabilized with an alkaline activated binder based on type F fly ash and silicate and sodium hydroxide as the activator, to evaluate its possible application in the construction of roads in non-tertiary paved roads or as a replacement for soil-cement in road applications such as bases or sub-bases. The results showed that resistance and stiffness increased significantly; The most marked difference between this stabilization system and the conventional one was the speed at which the mixtures gained mechanical resistance, being more progressive and constant for soils stabilized with alkaline activated cements. The behavior of the material at wetting and drying cycles was very similar to that shown by reference soil-cement mixtures. The use of high curing temperatures increases the kinetics of the reaction, which gives rise to greater resistance at shorter ages (Bakharev, 2005; Criado; Fernández-Jiménez; Palomo, 2010; Singh; Subramaniam, 2019). This condition makes this type of application competitive compared to traditional methods in places with a warm climate and that have the availability of optimum quality fly ash to be alkaline activated.

Singhi, Laskar, and Ahmed (2017) evaluated alkaline activated GBSF-FA binary mixtures with a sodium hydroxide solution to stabilize clay-type soils with the objective of improving the subgrade layer for road construction. This study corroborated what was published by previous research regarding the increase in mechanical resistance by stabilized soil. Regarding the durability in the presence of sulfates, the activated soil turned out to be more resistant than the reference soil-cement. In this type of road applications, lateritic soils, characteristic in tropical areas and which present some stabilization problems, with traditional binding materials can be stabilized with these alternative cementitious materials.

Authors such as Phummiphan *et al*. (2017) conducted unconfined compressive strength tests of lateritic soils stabilized with alkaline activated fly ash based cementitious agents, showing that the results were comparable to those required by the Thai national specifications for this type of material, meeting the minimum 7-day strength requirements under saturated conditions for high and low volume road construction; the addition of GBFS accelerated the reaction and produced an increase in the cementitious reaction products, hydrated calcium silicate gels (C-S-H) and hydrated sodium aluminosilicates (N-A-S-H).

In addition to sandy and lateritic soils, the stabilization of highly expansive soils has been investigated using alkaline-activated volcanic ash with potassium hydroxide and calcium hydroxide. Miao *et al*. (2017), showed that with this cement it was possible to reduce the plasticity of the soil from 34.8 to 14.2 % and with respect to the activators used in this research, potassium hydroxide was more effective due to its high alkaline character. The swelling potential of the stabilized soil was also reduced, the 90-day resistance of this stabilized soil was 16.55 MPa. Abdeldjouad *et al*. (2019) analyzed the effect of clay content on soil stabilization with and without palm oil ash (POA) mixed with an alkaline activator based on potassium (KOH) with a concentration of 10M. The results showed that clay minerals play an important role in soil stabilization with alkaline activation; and in general, the highest strengths (150 and 600 kPa at 7 days and between 900 and 2000 kPa at 28 days) were obtained with the alkali-activated binders. In the same sense, Pourakbar *et al*. (2016) reported that 15 % POFA contributes to the contribution of silica and reactive alumina, which induces the soil strength after stabilization to increase to 359 kPa at 7 days; likewise, the authors recommend the use of a 10 M NaOH solution as an activator considering the lower cost compared to KOH.

A recently published article by Miranda *et al*. (2020) presents the results of the construction of 80 m^2 of a stabilized layer, 2.5 m wide, using different cementing materials, three of which are based on the use of alkaline activated fly ash and the remaining two correspond to OPC and lime considered as reference materials. In this study, in addition to the technical tests, which indicate that the mechanical performance of the soil stabilized with activated ash is similar to that stabilized with traditional cementing agents; financial and environmental analyses were carried out. The authors report that the application methodologies, equipment, and procedures can be the same traditional ones, but recommend reducing the proportions of alkaline activators or their replacement by solid and environmentally sustainable activators to achieve lower costs and environmental impact.

2.2.2. Advantages and disadvantages of chemical soil stabilization using alkali-activated cements

The most significant advantage of the use of alkaline-activated binders in soil stabilization processes lies mainly in the use of by-products or residues from industrial processes, such as fly ash, steel slags, demolition residues, glass residues, and, in theory, any material composed of aluminosilicates, which contributes to reducing the exploitation of natural resources and CO_2 emissions, at the same time that this type of waste is valued, that is, the environmental impact is minimized. McLellan *et al*. (2011) carried out a study of the life cycle and the cost of alkaline-activated binding materials vs OPC, finding that under the conditions studied, alkaline-activated cement products reduced the emission of greenhouse gases with respect to OPC by between 44-64 %, but the associated costs almost doubled compared to OPC products; these results coincide with the studies carried out by Cristelo *et al*. (2015).

Among the disadvantages of using alkaline activated binding agents in soil stabilization applications, apart from the possible manufacturing costs, we can mention the use of sodium silicate as an activator, which affects the environmental indicators since it is the component that contributes to the CO_2 emissions, due to the high temperatures required in its production process, and in turn increases the toxicity factors (Habert; D'Espinose De Lacaillerie; Roussel, 2011) both in humans and in water sources and in soils. With the aim of minimizing or eliminating the use of silicate, several investigations have been carried out by the scientific community in which some residues have been evaluated for use as alkaline activators or reactive silica generators in the mixture with the precursors. Torres-Carrasco and Puertas (2014) carried out a study of the solubility process of various types of glass waste in alkaline solutions with the aim of generating sodium silicate solutions to be used as an activator in the preparation of binders and concrete. The authors concluded that, to achieve a good solubility of the residues, a process with temperatures above 80 °C must be implemented, in addition, the glass residues must have particle sizes less than 45 μm to guarantee a solubility of approximately 60 %. Torres-Carrasco and Puertas (2015), carried out the mechanical and microstructural characterization of an alkaline activated binder based on fly ash, using a mixture of NaOH with glass residues as alkaline activator, and concluded that this type of glass residues can be an excellent substitute for commercial sodium silicate to activate fly ash. Fernández-Jiménez, Cristelo, Miranda, and Palomo (2017), and Cristelo *et al*. (2019), studied the sustainability of using industrial wastes as precursors and activators to synthesize fly ash-based cements; the authors used glass waste, aluminum anodizing waste and aluminum mold cleaning solution residues to replace sodium silicate and NaOH in the mixture; the strength results were very similar to those obtained using activated cements with conventional activator solutions. The use of agro-industrial wastes such as rice husk ash and residues from kaolin production was evaluated by Passuello *et al*. (2017); a life cycle analysis conducted by the authors showed that, compared to commercial sodium silicate, rice husk ash reduced six of the nine impact categories by approximately 60 %.

Although alkaline activated binding materials have been under development for several years, this is a technology that has much to be explored as there are several studies that demonstrate their excellent binding properties in various applications and in particular the potential use of these binding materials for soil stabilization and geotechnical applications. In general, the efforts of researchers should focus on the search for binding materials that are economically, technically, and environmentally viable. The optimization of the mixtures between precursors and activators, the use of activators that reduce the impacts in their manufacture and the availability of finding good quality precursors or available residues, are some of the challenges that must be overcome if one wants to think about this type of binders as an effective replacement to the use of a calcium-based binder. Another major challenge of the application of this type of binder is the preparation on-site, since mainly aqueous alkaline solutions are used, which are generally corrosive, viscous, and difficult to handle in large applications.

In recent studies, the so-called "one-part geopolymers" have been reported, these materials only need to add water to be used in service (Luukkonen *et al*., 2018) since their main components are solid and are activated, in the same way as cement, by incorporating water into the mix. However, these types of materials are still under development. It is important to mention that research is still needed on the properties of durability in soil stabilization with this type of alternative binders and in turn, the standardization of the product is required in the field of application.

3. Conclusions and lines of future research

Based on the review of the articles published in databases, the following conclusions can be drawn, as well as identifying future fields of research and challenges that must be reviewed to achieve the implementation of alkaline activation technology in the stabilization processes of soils:

• Studies on the application of alkaline-activated binding agents in soil stabilization process have been increasing notably over time, particularly due to the possibility of using some residues or by-products as binding precursors, minimizing the consumption of natural resources, and contributing to lower energy consumption. However, some of the residues studied so far do not have sufficient quality, quantity, and homogeneity for their massive use in all countries, which implies that local viable precursor sources must be identified that, meeting quality criteria, allow the implementation of technology. For example, the use of ceramic or construction and demolition waste and volcanic pozzolans, materials that have proven to be excellent precursors of alkaline binders for other types of uses, should be investigated and whose availability may be feasible in many regions.

• Likewise, it is worth mentioning the possibility of combining the types of conventional chemical stabilization with the alternative of alkaline activation. If there is synergy between these, their application would contribute to reducing the consumption of cement and lime, which would generate less environmental impacts and probably lower costs. This is therefore a necessary line of future research.

• From the analysis of the results obtained in the different studies, in general, alkaline activation technology is viable as an alternative method in soil stabilization, although there are still a series of challenges that must be overcome for its implementation. Among the challenges to be addressed are the following: the development of alternative activators with lower environmental impacts in their production; long-term durability studies of alkaline-activated soils; and the validation of research results with field tests.

• Additionally, it is important to formulate standards and specifications applicable to these new materials, considering current construction codes and standards, as well as evaluating the financial and environmental costs of the technology, for which it is necessary to incorporate life cycle studies of projects and products.

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