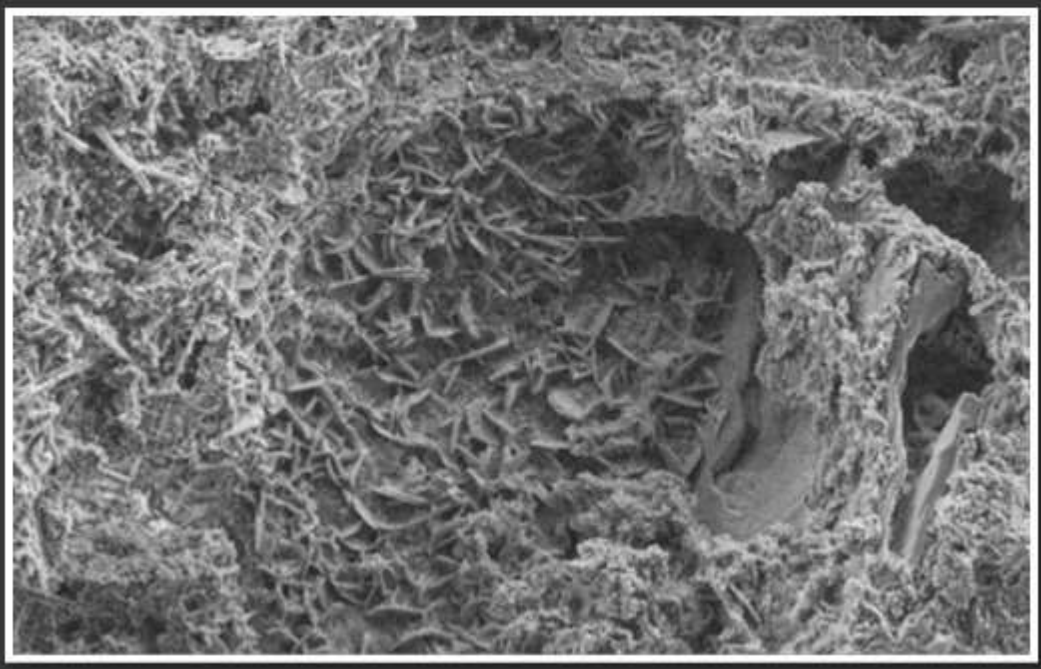
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New Generation Binders for Sustainable Concrete Production

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New Generation Binders for Sustainable Concrete Production

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ÖNSÖZ

Sevgili Okuyucular,

Küresel ölçekte artan nüfus, kentleşme ve sanayileşme faaliyetlerinin, sera gazı emisyonlarının hızla yükselmesine ve iklim değişikliğinin etkilerinin daha belirgin hale gelmesine neden olduğu açıktır. İnşaat sektörü, özellikle de Portland çimentosu üretimi, insan kaynaklı CO_2 emisyonlarının kayda değer bir kısmına sebep olması nedeniyle sürdürülebilirlik tartışmalarının merkezinde yer almaktadır. Çimento klinkeri üretiminin yüksek enerji gereksinimi ve buna bağlı emisyonlar, araştırmacıları daha çevre dostu ve yenilikçi bağlayıcı sistemlerin geliştirilmesine yönlendirmiştir. Literatüre bakıldığında getirilen çözümlerin ana odağının klinker miktarının azaltılması olduğu, bu kapsamda klinker esaslı, magnezyum esaslı ve alkali ile aktive edilmiş bağlayıcıların geliştirildiği görülmektedir.

Bu çalışma, bu bağlamda ön plana çıkan bağlayıcıların betonun taze, mekanik ve durabilite özellikleri üzerine etkilerinin ve çevresel performanslarının anlaşılması, araştırmacılara, mühendislere ve karar vericilere rehberlik etmesi amacıyla hazırlanmıştır. Ayrıca bu alternatif bağlayıcıların özellikle mekanik özellikler üzerindeki birtakım tolere edilebilir olumsuz etkilerinin kullanılacak katkı maddeleri ve/veya optimizasyon yöntemleri ile nasıl üstesinden gelinebileceği de ortaya konulmak istenmektedir.

Konunun daha iyi anlaşılabilmesi adına bağlayıcılar üç ana kategoriye ayrılarak farklı başlıklar altında incelenmiştir. Her bir alt başlık altında ilgili bağlayıcıya ait genel bilgiler verilmiş, reaksiyon mekanizmaları anlatılmıştır. Ardından literatür taraması sonuçları anlamlı bir bütün oluşturacak şekilde detaylıca sunularak bağlayıcıların betonların özellikleri üzerine etkileri, avantajları ve dezavantajları ortaya konulmuştur.

Bu çalışmada çimento ve beton üretiminde sürdürülebilirlik çalışmalarının olmazsa olmazı olan yaşam döngüsü analizlerine de yer verilmiş; başlangıçta yaşam döngüsü analizleri ve farklı yöntemler ile ilgili genel bilgiler verildikten sonra, literatürde her bir bağlayıcı için yapılan yaşam döngüsü analizlerinin sonuçları incelenmiştir.

Kitabın ilgililere faydalı olmasını temenni ederiz.

Şirin KURBETCİ
Mahmut Cenk SAYIL

PREFACE

Dear Readers,

It is evident that increasing population, urbanization and industrialization causes the greenhouse gas emissions to increase rapidly. Construction industry, specifically Portland cement production, contributes to a significant portion of anthropogenic CO_2 emissions, and is in the center of controversies regarding sustainability. Since the production of cement clinker is an energy intensive process, researchers have started to develop other alternative, sustainable binders. Literature reveals that the main principle is to reduce the amount of clinker used, and clinker-based, magnesium-based and alkali-activated binders have been developed for this purpose.

With this work, it is aimed to provide useful insights into the effects of such binders on fresh, hardened and durability properties and environmental performances of concrete, and provide guidance to researchers and practitioners. In addition, it is also desired to demonstrate the fact that some tolerable negative effects of these binders on the mechanical properties could be overcome by using admixtures, additives and/or optimizing production processes or compositions.

In order for the subject to be better understood, binders are divided into three main categories and are discussed under different headings. Under each subheading, general information on the binder of interest are given and the reaction mechanisms are explained. Then, results of the literature review are presented in a manner so that they provide a meaningful flow of information, and the effects of these binders on concrete properties, their advantages and disadvantages are explained.

Life cycle assessment analyses, which are indispensable for sustainability studies in cement and concrete production are also discussed. After general information is given and different methodologies are explained, results of life cycle assessment analysis from the literature, performed for each binder, are discussed.

We wish the book to be beneficial to everyone who are interested.

Şirin KURBETCİ
Mahmut Cenk SAYIL

ÖZET

Son yıllarda, kontrolsüz nüfus artışı ve insan faaliyetleri, sera gazı emisyonlarında önemli artışlara neden olmuştur. Küresel ısınmanın etkilerinin giderek daha somut hale gelmesi ve Portland çimentosu üretiminin insan kaynaklı CO_2 emisyonlarının büyük bir kısmına sebep olması, araştırmacıları alternatif, daha sürdürülebilir bağlayıcılar geliştirmeye sevk etmiştir. Portland çimentosu üretiminden kaynaklı emisyonlar, esas olarak çimento klinkeri üretiminin yoğun enerji tüketimi gerektiren bir süreç olmasından kaynaklanmaktadır. Literatürde, çalışmaların esas olarak klinker bazlı, magnezyum bazlı ve alkali ile aktive edilmiş bağlayıcıların geliştirilmesine odaklandığı görülmektedir. Bu bağlayıcıların her biri, CO_2 emisyonlarını azaltma hedefini, klinkeri alternatif malzemelerle değiştirmek, çimento üretimi için alkali aktivatörlerle birlikte endüstriyel atıkları kullanmak veya bileşen olarak CaO yerine MgO kullanmak gibi farklı ilkelerle gerçekleştirmeye çalışmaktadır. Bu çalışmada, yeni nesil sürdürülebilir bağlayıcılar hakkında genel bilgiler verildikten sonra, bunların betonun taze, mekanik ve durabilite özellikleri ve çevresel performansları üzerindeki etkileri tartışılmaktadır. Literatürde, bu tür bağlayıcıların kullanımının genel olarak dayanımın azalmasına neden olduğu; ancak durabilite özelliklerinde genellikle daha yoğun bir mikro yapının oluşmasından kaynaklı iyileşmeler olduğu bildirilmektedir. Ayrıca, mekanik özellikler üzerindeki olumsuz etkilerin mineral veya kimyasal katkı maddeleri kullanılarak veya bu bağlayıcıların tipik bileşimlerinin optimize edilmesiyle telafi edilebildiği de ifade edilmektedir. Dolayısıyla, bu yeni nesil sürdürülebilir bağlayıcıların bir yandan kabul edilebilir mekanik performans sağlarken bir yandan da CO_2 emisyonlarını önemli ölçüde azaltarak beton üretiminde sürdürülebilirliği mümkün kıldıkları, bunu yaparken atık yönetimi stratejilerine ve doğal kaynakların korunmasına katkı sağladıkları da görülmektedir.

Anahtar Kelimeler – çimento, beton, CO_2 emisyonu, yeni nesil bağlayıcılar, sürdürüebilirlik

ABSTRACT

In recent years, uncontrolled population growth and human activities have resulted in significant increases in greenhouse gas emissions. Given that the effects of global warming have become increasingly tangible and production of Portland cement contributes to a major portion of anthropogenic CO_2 emissions, researchers started to seek alternative, more sustainable binders. Emissions related to Portland cement production mainly arise from the fact that producing cement clinker is an energy intensive process. Literature shows that studies mainly focus on the development of clinker-based, magnesium-based and alkali-activated binders, each of them having different principles to reduce resulting CO_2 emissions, such as replacing clinker with alternative materials, using industrial wastes with alkaline activators to produce cement or using MgO instead of CaO as a constituent. In this study, introductory information on these new generation sustainable binders is given, then their effects on fresh, mechanical and durability properties and environmental performances of the resulting concrete mixtures are discussed. Literature reveals that the use of such binders tends to cause reduced strength in general; however, significantly improved durability properties, generally stemming from the formation of a denser microstructure, are also reported. Furthermore, negative effects on mechanical properties can reportedly be compensated by using admixtures or additives or optimizing the typical compositions. Thus, it is evident that these new generation sustainable binders have potential to reduce CO_2 significantly to promote sustainability in concrete production and contribute to waste management strategies and preservation of natural resources, while maintaining acceptable mechanical performance.

Keywords – cement, concrete, CO_2 emissions, new generation binders, sustainability

1. INTRODUCTION

In recent years, demand for energy consumption has dramatically increased due to factors such as population growth, economic and technological advancements. This has resulted in increased greenhouse gas emissions. Consequently, a great number of people are being negatively affected throughout the entire world (Yeh and Liao, 2017:41; Majewska and Gierałtowska, 2022:322; Umer et al., 2024:102354; Donald et al., 2025: 105048). Although cement and concrete are of vital importance for civilization, their production is the main source of a major part of global CO_2 emissions. The data show that 70% of industrial CO_2 emissions are mainly caused by ten industrialized countries (O'Neill, 2020:958; Zhang et al., 2024b:137852), and primary actions that are responsible for this are electricity, steel, cement and chemical productions (Dahlmann et al., 2015:62; Zhang et al., 2024:137852b). Production of Portland cement contributes to a significant 8% of total anthropogenic CO_2 emissions (Andrew, 2018:2213; Altuntaş et al., 2025:140077). Main reasons for this are the calcination and grinding processes, which are energy intensive. Consequently, although Portland cement has superior mechanical properties, its environmental impacts are high as each ton of Portland cement roughly causes 0.9 ton of CO_2 to be released to the atmosphere (Hasanbeigi et al., 2010:3461; Atasever and Erdoğan, 2024:2407). On the other hand, existing global energy reports anticipate a 12%-23% increase in Portland cement production (GCCA, 2021; Altuntaş et al., 2025:140077). Given all these, it is evident that developing binders with better environmental performance is imperative (Altuntaş et al., 2025:140077). One of the most straightforward approaches adopted by researchers to decrease greenhouse gas emissions related to cement production is using supplementary cementitious materials (SCMs) to partially replace the clinker. Most common pozzolans include silica fume (SF), fly ash (FA) and ground granulated blast furnace slag (GGBFS). However, due to increased demand for cement and concrete, the availability of these materials has become limited (Lothenbach et al., 2011:1244; Hu et al., 2024:e03283). Furthermore, when they are separately used, they cannot replace clinker at high levels due to their possible negative impacts on mechanical properties. Thus, it is of utmost importance to develop alternative binders by utilizing

conventional mineral additives and chemical admixtures combined with recently explored materials.

Literature shows that related research mainly focuses on three groups of new generation sustainable binders: Clinker-based, magnesium-based and alkali-activated ones. In clinker-based binders, as the name suggests, clinker is still used but in reduced amounts. They are typical blended cements where the strategy is reducing energy consumption and carbon emissions by reducing clinker levels. Magnesium-based binders utilize MgO whose processes for the target reactivity require less energy consumption when compared to CaO. Alkali-activated binders gain strength through chemical reactions between alkaline activators and industrial byproducts, or precursors. Aluminosilicates or calcium are often desired in precursors. As it is evident, gaining a better insight into the reaction mechanisms of these binders is of vital importance for practitioners to improve their weaknesses and eliminate their negative impacts on fresh, hardened and durability properties of concrete. There has been a growing body of studies on the use of these binders to replace ordinary Portland cement (OPC) in concrete production, reporting their strong and weak properties. It is necessary to compile the existing findings to provide a meaningful insight into the use of these in green concrete production. Thus, this study reviews and discusses the chemical compositions and reaction mechanisms of these new generation sustainable binders, their effects on concrete properties and contributions to sustainability in concrete production. The subsequent chapters will discuss some of the clinker-based, magnesium-based and alkali-activated binders, respectively. Then, a literature review on life cycle analyses (LCA) performed on cement paste, cement mortar and concrete samples will be presented. Ultimately, conclusions will be drawn.

2. CLINKER-BASED BINDERS

In clinker-based binders, the main aim is replacing cement clinker with mineral additives at replacement levels as high as possible, so that CO_2 emissions related to clinker production are reduced whilst acceptable mechanical performance of the resulting cement and concrete are maintained. Typical examples include limestone calcined clay cement (LC^3), reactive

belite cement (RBC), calcium sulfoaluminate cement (CSAC) and carbonated calcium silicate cement (CCSC).

2.1. Limestone Calcined Clay Cement (LC3)

LC^3 was first proposed in Antoni et al. (2012:1579), utilizing the synergistic effect of calcined clay and limestone to replace clinker at higher levels when compared to traditional blended cements, thus standing out amongst other sustainable construction materials (Jiang et al., 2025b:106210). Literature reports reductions in CO_2 emissions and energy consumption by 41.9% and 26.7%, respectively (Huang et al., 2023:132340; Arbab et al., 2025:140505). Typical composition of LC^3 includes 50% clinker, 30% calcined clay, 15% limestone and 5% gypsum. Metakaolin (MK), which is a highly reactive material, is obtained by calcining kaolinitic clay (Zunino et al., 2022:234; Jiang et al., 2025a:145846). MK is dehydroxylated aluminosilicate (Aiswarya et al.,2013). It reacts with portlandite and sulfates coming from cement, and water, to form phases like C-A-S-H, ettringite and AFm (Zunino et al., 2022:234; Jiang et al., 2025a: 145846). Limestone, on the other hand, reacts with C_3A coming from cement and aluminates coming from calcined clay to form monocarboaluminate (Mc) and hemicarboaluminate (Hc) phases, refining the pore structure and allowing for a denser microstructure (Dhandapani and Santhanam, 2020:105959; Jiang et al., 2025a:145846). Studies in literature report that LC^3 cement concrete has compressive strength on par with OPC concrete (Dhandapani et al., 2018:136), denser microstructure (Scrivener et al., 2018a:49), higher chloride ion resistance (Dhandapani et al., 2018:136; Sree et al., 2021:012075). In addition, since the calcination of kaolinitic clay requires lower temperature (650°C-850°C) than that of clinker production (1450°C-1500°C), environmental impacts of the resulting material are significantly reduced while acceptable mechanical and durability properties are obtained (Ramezanianpour, 2013:47; Scrivener et al., 2018a:49; Fernandez et al., 2011:113; Goudarzi et al., 2024:136302). In addition to its advantages, LC^3 has two main disadvantages: Worsened workability and low early-age strength. Poor workability is attributed to the increased specific surface area of the binder particles arising from the fact that used materials are very fine. This requires a high amount of mixing water. Low early strength has multiple causes: First, a 50% replacement of clinker is very drastic. In addition, MK has low reactivity at early ages (Liu et al., 2024:111422). Furthermore, despite the used 5% gypsum, undersulfation of the system complicates the ettringite and monosulfate formation (Antoni et

al., 2012:1579; Krishnan et al., 2019:64; Hay et al., 2022:104403; Atasever, 2023:1). Typically, polycarboxylate based superplasticizers are employed to overcome poor workability issues. As to the low early strength development, various approaches such as using high temperature curing regimes are adopted.

Table 1 summarizes some key studies focusing on the use of LC^3 in concrete production. As can be seen from the table, there are also studies where LC^3 is used to produce ultra-high performance concrete (UHPC) whose mechanical and durability properties are exceptional, indicating that when designed properly, LC^3 is a very promising binder in terms of reducing environmental impacts of cement industry, preserving natural sources and contributing to waste valorization strategies. In the literature, it is stated that the mechanical properties and durability of concrete using LC^3 cement are generally at least as good as those of concrete using Portland cement, while some studies indicate that in certain cases, slight or significant improvements in these properties have been observed. However, some studies, particularly regarding compressive strength, indicate that it is lower than that of ordinary Portland cement. Nevertheless, since the difference is not significant, LC^3 cement is considered a noteworthy alternative. When compared to OPC composites, LC^3 not only shows comparable mechanical properties (Wang et al., 2021a:106421), it also resists better against chloride and sulfate attacks (Nguyen et al., 2020a:301), prevents alkali-silica reaction (ASR) (Nguyen et al., 2020b:106176) and performs well in terms of water absorption and gas permeability (Dhandapani et al., 2018:136; Dong et al., 2025:113790).

Table 1: Studies on LC^3-Incorporated Concrete

Reference	Concrete Type	Investigated Properties
Dong et al. (2023:105836)	UHPC	Mechanical properties, microstructure
Guo et al. (2023:132026)	UHPC	Mechanical properties, microstructure
Huang et al. (2024b:110767)	UHPC	Mechanical and durability
Venkataraman and Rajkumar (2024:203)	LC^3-GGBFS Concrete	Fresh and hardened properties, microstructure
Leo et al. (2024:137012)	LC^3 Concrete	Mechanical and durability
Liang et al. (2024:139036)	LC^3-ECC*	Mechanical properties, microstructure

*Engineered Cementitious Composite

Dong et al. (2023:105836) observed increments in 28d compressive strength when compared to plain reference UHPC, when 60% of cement was substituted by LC^3. Guo et al. (2023:132026) reported acceptable mechanical performance and reduced porosity when 30% LC^3 was introduced into UHPC mixture designs. Huang et al. (2024b:110767) reported increased chloride ion resistance for the mixtures where LC^3-incorporated UHPC were produced. Venkataraman and Rajkumar (2024:203) used LC^3 and GGBFS to produce concrete. When LC^3 cement was replaced by GGBFS at 10% replacement level, tolerable decrements in mechanical properties and insignificant worsening of workability were observed. Thus, it was concluded that 10% GGBFS replacement along with LC^3 cement could be utilized to promote sustainability in concrete production.

Workability of LC^3 is typically worsened when compared to OPC due to higher specific surface area of its components. Consequently, the amount of water required to achieve same workability increases, possibly adversely affecting strength.

Although most studies on compressive strength show that 28-day compressive strength is similar to that of OPC when similar clinker is used, some variations are observed in the results for other periods. Reportedly, 3-day compressive strength is lower than OPC (Dhandapani et al., 2018:136; Sharma et al., 2021:106564) and 7-day strength is comparable to that of OPC (Sharma et al., 2021:106564).

Studies reported improvements in pore structure of LC^3 compared to OPC or FA blended cements (Dhandapani and Santhanam, 2017:36; Sharma et al., 2021:106564). This is generally attributed to a better distribution of hydration products, as they precipitate more on higher specific surface area of the materials used. This refined microstructure enables us to design concrete with lower permeability; consequently, durability properties are improved (Sharma et al., 2021:106564).

There have been studies on cement pastes, mortars and concrete samples incorporating a mineral additive which is simply a blend of two major components of LC^3: Limestone and calcined clay. Such additives are often referred to as LC^2. So, it can be stated that LC^3 is simply prepared by replacing OPC by a certain amount of LC^2 additive (Vaasudevaa et al., 2021:124121). Chen et al. (2019:e00267) investigated the mechanical properties, sorptivity and microstructure of LC^2 incorporated and steam cured concrete samples by taking GGBFS and FA concrete as reference. It was seen that LC^2 concrete samples steam cured at 40°C reached the 91% of the compressive strength of reference samples steam cured at 60°C at the end of the first day, indicating

that the use of a combination of limestone and calcined clay enables designers to promote sustainability whilst obtaining a comparable early strength development. In addition, it was observed that, along with steam curing, synergistic effects of limestone and calcined clay improved the reactivity of both metakaolin and OPC, microstructure, and decreased the sorptivity in the long term. Vaasudevaa et al. (2021:124121) studied both cement and concrete samples for two different systems containing a total of 360 kg/m^3 and 400 kg/m^3 binder and a water/binder ratio of 0.45 and 0.50. OPC concrete, 30% FA concrete and 45% LC^2 concrete samples were analyzed. In general, increases in 1-day compressive strength and some tolerable decreases in 7-day and 28-day compressive strength values for both concrete and cement paste samples were observed when steam curing regime was adopted. Consequently, it was stated that the LC^2 additive, when combined with steam curing, would resolve the low early strength issue while providing solutions in terms of durability and sustainability. Dong and Hu (2022:1879) studied steam cured UHPC samples incorporating LC^2 at replacement ratios as high as 60%. It was observed that steam curing accelerated the reactions and caused the calcined clay to consume portlandite way faster.

Ultimately, LC^3 releases less greenhouse gases to the atmosphere than OPC due to the differences between the materials used and the operations required to process these materials. Life cycle analyses (LCA) conducted in the literature always reveal reduced CO_2 emissions when LC^3 is used (Kanagaraj et al., 2024:200197).

2.2. Reactive Belite Cement (RBC)

Reactive belite cement (RBC) or sometimes referred to as reactive belite-rich Portland cement (RBPC) is similar to OPC in terms of clinker mineralogy. The fundamental difference between these two is the ratio of alite to belite (C_3S/C_2S). RBC generally consists of more than 40% belite, while alite content is generally lower than 35%. Literature reveals that production enthalpy and CO_2 emissions of alite are 1.82 GJ/t and 579 kg/t, respectively. On the other hand, for belite, these values are 1.30 GJ/t and 512 kg/t, respectively. Thus, producing cement with higher belite and lower alite contents allows for improved environmental performance (Gartner and Sui, 2018:27).

Ideal calcination temperature for RBC is approximately 1350°C, being 100°C-150°C lower than that of OPC. This allows for 10% less fuel consumption for the production process. On the other hand, it must be noted

that since belite is harder than alite, in order to obtain the same fineness, approximately 5% more energy consumption is required for grinding process (Gartner and Sui, 2018:27).

When compared to OPC, RBC generally has comparable setting times, less mixing water requirements, better compatibility with water-reducers, less heat evolution, lower early-age strength, higher late-age strength and less drying-shrinkage. Fundamentally arising from the fact that less portlandite is formed at the end of hydration reaction, RBC has reportedly better sulfate and chloride resistance. 28-day compressive strength is generally comparable to that of OPC, and late-age strength development is reported to be improved (Sui et al., 1999:488; Gartner and Sui, 2018:27). Another appealing aspect of RBC is low heat of hydration. This is because belite's hydration heat is only half of alite's on the basis of mass (Taylor, 1997:459; Gartner and Sui, 2018:27). This makes RBC favorable for applications such as mass concrete production (Gartner and Sui, 2018:27).

2.3. Calcium Sulfoaluminate Cement (CSAC)

Calcium sulfoaluminate cement (CSAC) is a hydraulic binder, first discovered in China in 1970s (Gao et al., 2022:1642; Meng et al., 2025:140641). It is known as a sustainable alternative, as it reduces carbon emissions and energy consumption by 35% and 15%, respectively, compared to OPC (Seo et al., 2021:103918; Gao et al., 2022:1642; Meng et al., 2025:140641). It has higher aluminate content and is produced by sintering bauxite, limestone and gypsum in a rotary kiln (Phair, 2006:763; Kumar, 2022:797). Principal phases of CSAC are 30% belite, 35%-70% ye'elimite and gypsum (Chatterjee, 2002:186; Kumar, 2022:797).

Main reasons for the carbon emissions associated with OPC production are the decarbonization of limestone and high temperatures required for the formation of alite which is the principal component of OPC to be formed. On the other hand, ye'elimite which is the main component of CSAC contains only half of the CaO that alite contains. Consequently, required temperature and carbon emissions are significantly reduced. Furthermore, ye'elimite reacts fast and compensates for losses in early strength caused by lack of alite. Among other phases, belite contributes to late-age strength development (Kasselouri et al., 1995:1726; Canbek and Erdoğan, 2020:117866).

CSAC exhibits rapid setting and hardening, high early strength, and low expansion. Thus, it is seen as a favorable alternative for infrastructure repair (Gastaldi et al., 2021:106261; Tao et al., 2023:104908; Huo et al.,

2023:107638; Acarturk et al., 2023:105115; Zhou and Shi, 2025:105940). There are studies where CSAC is used to produce UHPC. Meng et al. (2024: e03547) observed 25%-40% reductions in CO_2 emissions and 25%-35% reductions in energy consumption during UHPC production. Wang et al. (2019:767) reported rapid setting and strength development when CSAC-incorporated UHPC was developed, stating that at the end of only 4 hours compressive and tensile strengths were 62 MPa and 4.4 MPa, respectively. Cui et al. (2022:126921) reported that CSAC-UHPC they developed was sulfate resistant (Meng et al., 2025:140641).

2.4. Carbonated Calcium Silicate Cement (CCSC)

Carbonated calcium silicate cement (CCSC) is based on the fact that calcium silicates can also harden through carbonation in addition to hydration (Gartner and Sui, 2018:27). Calcium silicate (Ca_2O_4Si) clinker can be produced with calcium silicate minerals with low lime content, such as wollastonite. Such clinkers require a lime content of around 40%. Since this value is approximately 70% for OPC, such clinkers can reduce carbon emissions significantly (Atakan et al., 2014:60; Kumar, 2022:797). Binders produced from simple calcium silicates such as wollastonite can carbonate very rapidly in relatively pure CO_2 gas at atmospheric pressure, as long as the temperature and relative humidity in the curing chamber are maintained within fairly narrow limits. Therefore, CCSC binders containing wollastonite or other calcium silicates with low hydraulic reactivity can be used to produce precast concrete products if the simple thermal curing chambers used for OPC concretes are converted into carbon dioxide curing chambers with controlled ventilation, temperature, and relative humidity. Although these implementations are not very hard, they require a certain amount of investment cost. In addition, since carbonation is an exothermic process, limited heating is required; however, in order for the water vapor to be removed from the CO_2-rich atmosphere, cooling must be performed, which further increases operational costs (Gartner and Sui, 2018:27).

Calcination temperature for CCSC is ideally 1200℃, being approximately 250℃ lower than that of OPC. Consequently, greenhouse gas emissions are reduced. Produced clinker is carbonated as aforementioned, under controlled conditions. While OPC exhibits the desired compressive strength at the end of 28 days, CCSC can show this strength development at the end of only 24 hours. CCSC requires less water because it captures water vaporized during the curing process (Gartner and Sui, 2018:27; Kumar,

2022:797). Major advantages of CCSC binders are i) reductions in CO_2 emissions by up to 30% due to lower calcium content of clinker, ii) additional CO_2 capture during curing, iii) equal or higher compressive strength when compared to OPC at the end of shorter periods, and iv) retaining most of the mixing water in the concrete through condensation during the curing process, thereby reducing the total amount of water used during the production process (Atakan et al., 2014:60; Gartner and Sui, 2018:27).

Despite all these advantages, CCSC cement applications are limited due to a few important drawbacks. This binder is often used for precast members, and for the curing to be completed properly, dimensions of the members must be within certain limits. Since typical curing process can lower pH of the binder to as low as 9.0, this binder might cause serious corrosion problems for reinforcements. Thus, it is generally used for elements with no reinforcing bars (Scrivener et al., 2018b:2; Gartner and Sui, 2018:27; Kumar, 2022:797).

3. MAGNESIUM-BASED BINDERS

Magnesium-based binders gain their strength through reactions between MgO and $MgCl_2$ solutions or different acids and salts. Three most common binders encountered in the literature are magnesium oxychloride cement (MOC), magnesium oxalate cement (MgOx) and magnesium phosphate cement (MPC).

3.1. Magnesium Oxychloride Cement (MOC)

Magnesium oxychloride cement (MOC) was first discovered in 1867 by Stanislas Sorel and for this it is commercially known as Sorel cement (Ahmad et al., 2024a:135937; Ahmad et al., 2024b:3074). It is a non-hydraulic, environmentally friendly binder that is produced by mixing light burned magnesia (MgO) and a concentrated $MgCl_2$ solution. As aforementioned, production of OPC is energy intensive (Yu et al., 2020; Danish et al., 2021:124295; Ahmad et al., 2024b:3074). However, in order for light burned magnesia to be reactive, required calcination temperature can be as low as 1000°C, which is a relatively low temperature (Li et al., 2020:119381; Ahmad et al., 2024b:3074)

In addition to its environmental benefits, MOC has high mechanical strength (Nie et al., 2022:157871), air-hardening ability, low density, low

thermal conductivity (Xu et al., 2016:1319) and good abrasion resistance (Montle and Mayhan, 1974:243; Ahmad et al., 2024b:3074).

As a result of MOC hydration, crystal phases like phase 2 ($2Mg(OH)_2 \cdot MgCl_2 \cdot 4H_2O$), phase 3 ($3Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$), phase 5 ($5Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$), and phase 9 ($9Mg(OH)_2 \cdot MgCl_2 \cdot 5H_2O$) (Li and Chau, 2007:866; Ahmad et al., 2024b:3074) are formed. Phase 2 and phase 9 stabilize when the curing temperature exceeds 100°C. However, phase 3 and phase 5 remain stable below 100°C. Phase 3 and phase 5 can be described as tubular structures resembling well-crystallized needles. The interlocked and compact microstructure that emerges during the production of these phases makes them the main reaction products responsible for strength development of MOC. Phase 5 shows rapid development, begins to form approximately two hours after mixing the paste, and exhibits good filler properties. This leads to a compact microstructure with reduced porosity. Consequently, phase 5 is the preferred phase in MOC design (Ahmad et al., 2024b:3074).

Despite all its advantages, due to the nature of its hydration products, MOC cement has a major drawback: Very low water resistance. As aforementioned, strength development of MOC mainly stems from the formation of phase 3 and phase 5 crystals. However, these phases are converted into brucite ($Mg(OH)_2$) upon contact with water (Gu et al., 2021:127958; Xie et al., 2024:168773). These phases undergo hydrolysis process, which is the main reason for the poor water resistance of MOC (Jiang and Huang, 2025:1). To overcome this, different approaches have been employed in the literature such as using silica fume (Yu et al., 1999:1038; Guo et al., 2021:127682; Ahmad et al., 2024b:3074), fly ash (Chau et al., 2009:250; Ahmad et al., 2024b:3074), sulfates (Li et al., 2016:233; Huang et al., 2022:857; Ahmad et al., 2024b:3074) and admixtures such as soluble phosphates and phosphoric acid (Deng, 2003:1311; Yu et al., 2023:106399; Ahmad et al., 2024b:3074), with the main aim of ensuring the stability of these phases under their interaction with water (Li and Yu, 2010:721; Guo et al., 2018:1290; Guo et al., 2021:127682; Ahmad et al., 2024b:3074). It is seen that the use of such additives and admixtures promotes the formation of gel-like phase 5, changes the morphology of phase 5 and reduces the formation of brucite, thus increasing water resistance (Guo et al, 2018; Guo et al., 2020:1181; Ahmad et al, 2024b:3074).

3.2. Magnesium Oxalate Cement (MgOx)

Magnesium oxalate cement (MgOx) is an acid-base binder developed through the reaction of soluble oxalic acid salts with dead-burned magnesia (DBM) and is akin to magnesium phosphate cement (MPC) (Haque et al., 2022:130086; Yang et al., 2024:135221; Qin et al., 2024:138198; Zhang et al., 2024a:134738; Bilginer and Erdoğan, 2024:138999). Neutralization reactions allow for rapid setting, high early strength and medium level ultimate strength and sufficient water resistance, along with an environment having a pH of 7-10. The most fundamental reactant is DBM. Acidic components are produced through partial neutralization of oxalic acids with a suitable powder (for instance, sodium hydroxide or a suitable fly ash) (Erdoğan et al., 2022:1), in order to increase the pH and decelerate the acid-base reaction. Reaction of MgOx cement with water involves two phases: In the first phase, acid salt is dissolved in water to form oxalate ions and H^+, making the solution acidic (Bilginer and Erdoğan, 2024:138999):

$$H_2C_2O_4 \rightarrow H^+ + HC_2O_4^- \quad (1)$$

Oxalic acid is a diprotic acid. While at the beginning the pH of the environment is low (approximately 2) (Bilginer and Erdoğan, 2023:e310; Bilginer and Erdoğan, 2024:138999) the solution contains higher concentrations of $HC_2O_4^-$ and a certain amount of HC_2O_4 (Luo et al., 2021:1120; Bilginer and Erdoğan, 2024:138999). In the second phase, periclase in DBM starts to decompose in the acidic solution and reacts with $HC_2O_4^-$ to form magnesium oxalate dihydrate (Bilginer and Erdoğan, 2023:e310; Bilginer and Erdoğan, 2024:138999):

$$MgO + 2H^+ \rightarrow Mg^{2+} + H_2O \quad (2)$$

$$Mg^{2+} + HC_2O_4^- + 2H_2O \rightarrow MgC_2O_4 \cdot 2H_2O + H^+ \quad (3)$$

Increased pH causes oxalic acid to further decompose and formation of oxalate. Concentrations of oxalate and hydrogen oxalate in the solution are approximately equal to each other for pH values of 4-4.5 (Luo et al., 2021:1120; Bilginer and Erdoğan, 2024:138999):

$$HC_2O_4^- \rightarrow H^+ + C_2O_4^{2-} \quad (4)$$

Continuous dissolution of DBM causes amorphous silica and Mg^{2+} ions to be present in the solution (König et al., 2021:360; Bilginer and Erdoğan, 2024). This causes the pH to increase rapidly. Oxalate also reacts with Mg^{2+} to form magnesium oxalate dihydrate (Bilginer and Erdoğan, 2023:e310; Bilginer and Erdoğan, 2024:138999):

$$Mg^{2+} + C_2O_4^{2-} + 2H_2O \rightarrow MgC_2O_4 \cdot 2H_2O \quad (5)$$

CO_2-equivalent/cation molar ratio of magnesium oxalate dihydrate, which is the principal reaction product of MgOx cement is 2. This provides carbon capturing benefits and reduces carbon emissions (Erdoğan et al., 2022:1; Bilginer and Erdoğan, 2024:138999).

Despite its advantages, MgOx has some drawbacks such as short setting time and costs associated with the production of oxalic acids or salts. To resolve high costs issue, the oxalate content of the system must be reduced. However, oxalates are important not only for strength development, but also for balancing the carbon emissions caused by the production of DBM. Consequently, using SCMs could be a solution to this by lowering the need for oxalates and overall costs. Bilginer and Erdoğan (2023:e310) used GGBFS to replace DBM at 50% replacement level, reported improved strength and water resistance. Setting time, however, decreased (Bilginer and Erdoğan, 2024). Bilginer and Erdoğan (2024:138999) reported improved workability when copper slag and silica fume were used to replace DBM partially and at 100% replacement the setting delayed further, 25%-50% replacement increased ultimate strength but replacement levels above these led to reductions in strength. Bilmez and Erdoğan (2025: 04024548) observed that when CSA clinker was used to replace DBM and natural clayey soil was used to produce oxalic acid salt, for 100% replacement of DBM although 28-day compressive strength reached 30 MPa pH was reduced from 9 to 5, setting time and water resistance were decreased. Optimized use of CSA clinker was reported to be 50%.

3.3. Magnesium Phosphate Cement (MPC)

Magnesium phosphate cement (MPC) is a new generation binder that is produced through the acid-base reaction between magnesium oxide and phosphates (Walling and Provis, 2016:4170; Haque and Chen, 2019:885; Gan et al., 2025:107849). When compared to OPC, MPC has way shorter setting time, high early strength, ability to harden at temperatures as low as -20℃ and

good durability. For these reasons, MPC is often preferred as a repair material (Li and Chen, 2013:977). MgO, which is the main component of MPC, captures CO_2 from atmosphere to lead to the formation of a series of carbonates and hydroxyl-carbonates, emerging as a competitive binder which has potential to be carbon neutral (Walling and Provis, 2016:4170; Haque and Chen, 2019:885). MPC has two main types: Magnesium ammonium phosphate cement (MAPC) and magnesium potassium phosphate cement (MKPC). For both types, hydration reactions occur through the interaction of ammonium dihydrogen phosphate and potassium dihydrogen phosphate, resulting in the formation of struvite and K-struvite. Compressive strength of MPC deteriorates upon prolonged contact with water due to the leaching of residual phosphates, dissolution of unreacted magnesium oxide and the instability of hydration products (Wang et al., 2021b:109523; Diaz Caselles et al., 2024:107456; Gan et al., 2025:107849). Various methods have been tried in an attempt to increase the water resistance of MPC, primarily through the use of pozzolanic materials (Qin et al., 2020:117353; Feng et al., 2022:127395; Liu et al., 2023:130456; Gan et al., 2025:107849). Here the logic is increasing water resistance of MPC by reducing the volume of MPC used per unit, thus reducing the content of reactive raw materials and the amount of hydrated products that tend to dissolve in water (Gan et al., 2025:107849).

4. ALKALI-ACTIVATED BINDERS

Alkali-activated cements (AAC) are low-carbon binders, containing higher amounts of aluminosilicates. Amorphous phases in aluminosilicates are activated in alkali environments to form three-dimensional polymeric structures. Such binders generally have better durability when compared to OPC after gaining maturity, in addition to their ecological benefits (Li et al., 2010:1341; Shi et al., 2011:750; Kumar, 2022:797). Various SCMs, alkaline solutions and silicates are used to produce AACs (Li et al., 2010:1341; Kumar, 2022:797). Here additives such as conventional SCMs and limestone are used to replace cement at certain replacement levels. In general, replacement ratio is limited regarding the composition of the cement and the properties of the mixture. For instance, if GGBFS is used at a level higher than 50%, it might deteriorate mechanical properties (Angulo-Ramírez et al., 2017:119). Literature reveals that AACs have high compressive strength (Shi, 1996:1789; Brough and Atkinson, 2002:865), superior sulfate and sea water resistance (Bakharev et al., 2002:211; Puertas et al., 2002:55), good acid corrosion

resistance (Bakharev et al., 2003:1607; Fernández-Jiménez et al., 2007:3055) and chloride ion impermeability (Shi, 2003:77), making them viable alternatives (Lu and Poon, 2018:399). However, these binders have production costs that are 25–30% higher than OPC, limiting their use to building infrastructure. Based on the composition of main constituents, they are mainly categorized as slag-based, pozzolanic, lime-pozzolan-slag based, calcium aluminate blended and Portland blended alkali-activated cements (Shi et al., 2011:750; Kumar, 2022:797). The most sensitive parameter in the development of AAC binders is the curing temperature as it affects the activation energy of the binder matrix. It has been observed that compressive strength develops faster between 40℃-95℃, due to accelerated reaction rate (Khale and Chaudhary, 2007:729; Kumar, 2022:797).

5. LIFE CYCLE ANALYSIS (LCA) OF NEW GENERATION BINDERS

When a presumably greener design is made regarding the production of cement and/or concrete, it must be evaluated whether this design complies with the standards if there are any, or whether to see if it helps reduce CO_2 emissions and energy consumption. Life cycle analysis (LCA) is a useful tool to account for all the greenhouse gas emissions occurring through the processes of material extraction, transportation, processing, construction, service life and demolition of any given system. In other words, it is an approach in order to evaluate the environmental performance of a product or an activity during its service life. Essentially, the main aim is to provide useful insights to the practitioners, allowing them to design more environmentally friendly products (Menoufi, 2011:1).

Throughout the life span of a product, a service or a structure, three main stages can be specified: Manufacturing phase which involves the extraction of raw materials, transportation and processing; service life in which the product or the service is being utilized; and the disposal phase where the product is being demolished or disposed of, indicating the end of its service life. Each of these phases require the use of energy and some essential materials such as water, thus causing environmental harm to environment, public health and natural resources (Jensen, 1998:1; Menoufi, 2011:1).

The focus of the approaches adopted in order to reduce environmental impact has been waste treatment to reduce water, soil and air pollution. However, this approach might not consider the complete environmental harms

of a given product or activity to fully understand its real undesired effects on ecosystems, public health and its damage to limited natural resources. In addition, it does not account for the so called shifting of burdens. This implies that when one changes a certain detail of a process in the life cycle of a product or activity to reduce the related part's environmental impact, she/he might just cause equal or more carbon emissions by adopting that certain approach (European Comission, 2011:1; Menoufi, 2011:1). In the context of cement and concrete, that means that any material used, as an essential ingredient, an additive or admixture, to produce sustainable cement or concrete, or any other approach employed might cause elevated greenhouse gas emissions at another stage whilst reducing environmental impacts at one stage. Thus, solution found might not yield desired ecological benefits, and it could even cause the opposite of what is intended (European Comission, 2011:1; Menoufi, 2011:1). Thus, LCA methodology was developed to be able to fully understand what exactly happens in terms of environmental impacts throughout the entire life of a product or activity and to reduce the shifting of burdens.

Numerous definitions of Life Cycle Assessment (LCA) exist in literature. According to the Society of Environmental Toxicology and Chemistry (SETAC) (SETAC, 2011:1; Menoufi, 2011:1), LCA is an objective methodology used to make an assessment about the environmental impacts associated with a product, process, or activity through identification and quantification of energy and material inputs, as well as emissions and releases to the environment. It also aims to evaluate and apply opportunities for environmental improvement. This assessment considers the complete life cycle of a product, process, or activity, including raw material extraction and processing; manufacturing, transportation, and distribution; use, reuse, and maintenance; as well as recycling and final disposal (Menoufi, 2011:1). ISO 14040 defines LCA as the assessment of environmental impact of a product by preparing a material inventory as inputs and outputs, evaluating emissions associated with these and interpreting the results of the analysis (ISO, 2006:1; Menoufi, 2011:1).

By the term "life cycle", major activities that are significant contributors to greenhouse gas emissions during the defined product's or activity's life cycle must be understood. These include extraction of raw materials, manufacturing processes, the use, the maintenance and end of the defined system's life (Menoufi, 2011:1).

Hence, it can be stated that the aim of LCA is to assess the amount of greenhouse gases to be released to the atmosphere if a product would be produced, or an activity would take place, regarding all the aspects of the

defined system; to find better alternatives to the existing methodology to produce that product in a more sustainable manner, to avoid shifting of burdens and accounting all stages of the life cycle of that product or activity while doing so, from the very beginning to the end. This implies that LCA can help us minimize environmental impacts at one stage, while causing no further increases in greenhouse gas emissions in another stage (Menoufi, 2011:1).

In a nutshell, LCA is a useful tool for estimating greenhouse gas emissions to be released due to the manufacturing process of certain products, or any other kind of human activities, considering the entirety of the life span of that product or activity. Different stages of the life cycle are considered separately; however, since they depend on the previous ones, it can be stated that LCA helps us to find cumulative damage to environment, caused by the actions taken during all the stages. So, it can be said that LCA methodology can be utilized to optimize production processes so as to minimize environmental impacts, enabling practitioners to be able to comply with related standards and come up with sustainable solutions (Menoufi, 2011:1).

There are different system boundaries used in LCA, and one of them is cradle-to-grave, where the analysis is performed from the beginning which is manufacturing process (cradle) to the end of the life cycle (grave) (Jensen, 1998:1; (Menoufi, 2011:1). Another boundary condition is cradle-to-gate, where the gate implies the beginning of the service life of the product. In another approach, cradle-to-cradle, which is a special type of cradle-to-grave, where the grave which designates the end of the life stage is actually a recycling process. In this way, output of one analysis becomes the input of another analysis in another process. This approach proves itself to be useful when waste materials are used to manufacture new products (Jensen, 1998:1; (Menoufi, 2011:1).

Construction industry utilizes LCA methodology to check the suitability of the produced cement and/or concrete to relevant regulatory standards in terms of environmental performance, calculate the theoretical amount of carbon dioxide or total of the greenhouse gases to be released to the atmosphere as a result of the production of a certain type of cement and/or concrete, and find better alternatives to OPC and OPC concrete in terms of environmental performance. It is essentially conducted by multiplying the amount of each raw material used in the production with the specified carbon emission factors, and them summing all the emissions to find the total. Here, analyses can be performed in two ways: Commercial or open source code softwares that use black box in order to model the amount of greenhouse gas emissions according to the specified system and boundary conditions can be

used, or carbon emission factors can be taken directly from either commercial or open access databases and calculations can be made by hand. Some of the most common softwares used with this aim are openLCA (Di Noi et all., 2017:1), SimaPro (PRé Sustainability, 2012:1) and GaBi (Sphera Solutions GmbH, 2023:1); whilst the most preferred databases include The ICE Embodied Carbon Database (Circular Ecology, 2021:1) and EcoInvent (Frischknecht and Rebitzer, 2005:1337). As aforementioned, softwares do generally use black box, but some of them might provide more transparency when compared to others. On the other hand, when carbon emission factors are directly taken from databases or from the relevant literature and calculations are made by hand, this provides a completely transparent process.

Carbon factors in databases are generally compiled from literature studies and practical applications. A typical, reliable way to actually measure greenhouse gas emissions to populate data is using continuous emission monitoring systems. Continuous Emission Monitoring (CEM) is concerned with the measurement of total emissions from stationary sources including power plants, waste incinerators and chemical processing industries. Such facilities are required to monitor the pollutant greenhouse gas emissions on a continuous basis. Consequently, the obtained data can be used to be a source of the databases offering carbon emission factors for LCA (Jahnke, 2022:1).

Once the carbon emission factors are obtained for each raw material, LCA for a cement or concrete product can simply be performed to calculate the total amount of greenhouse gas emissions by summing the multiplications of amount of raw materials with the carbon factor of that material. According to Yang et al. (2015:774), carbon emission of concrete arises from the extraction and processing of raw materials, transportation and production of concrete. Consequently, carbon emissions can be calculated through Equation 6 (Yang et al., 2015:774; Wang et al., 2023:4012):

$$mCO_2 = \sum_{i+1}^{n} (CO_{2i} \times M_i) \quad (6)$$

Where mCO_2 stands for total carbon emission per cubic meter caused by the material of interest ($kgCO_2/m^3$), CO_{2i} is the carbon emission factor of the material of interest ($kgCO_2/kg$) and M_i is the amount of material used (kg/m^3). For instance, carbon emission factors of Portland cement, limestone and metakaolin are specified to be 0.863, 0.008 and 0.33, respectively, in the relevant literature (Miller et al., 2018:115; Xuan and Wang, 2022:105107; Wang et al., 2023:4012). In general, not only carbon emissions are considered; other types of greenhouse gases are also taken into account by converting their

impacts into carbon dioxide. In such cases, it is denoted with CO_{2e} to show that the value represents all the greenhouse gas emissions as carbon dioxide equivalent.

5.1. LCA Studies on LC^3 Binders and LC^3 Concrete

Table 2, taken from Adesina (2020:100004), shows the embodied carbon emission factors of some of the most fundamental materials being used to produce conventional cement and concrete, as well as LC^3 binders and concrete.

Table 2: Carbon Emission Factors of Some Essential Materials for Cement and Concrete Productions (Adesina, 2020:100004)

Raw Material	**Carbon Emission Factor ($kgCO_{2e}/kg$)**	**Reference**
Portland Cement	0.82	Reiner (2007:1)
	0.83	Hammond and Jones (2008:87)
	0.83	Chiaia et al. (2014:386)
River Sand	0.005	Hammond and Jones (2008:87)
	0.0025	Chiaia et al. (2014:386)
Crushed Aggregate	0.0062	Nisbet et al. (2002:1)
Fly Ash	0.0018	Reiner (2007:1)
	0.010	Hammond and Jones (2008:87)
	0.009	Purnell (2013:362)
Slag	0.070	Hammond and Jones (2008:87)
	0.019	Purnell (2013:362)
Metakaolin	0.33	Estimated
Silica Fume	0.014	Hammond and Jones (2008:87)
Water	0.0003	Reiner (2007:1)
	0.0003	Chiaia et al. (2014:386)
Superplasticizer	0.01	Flower and Sanjayan (2007:282)
	0.72	Chiaia et al. (2014:386)
Air Entraining Agents	0.0086	EFNARC (2005:1)

In addition to these, as aforementioned, carbon emission factor of limestone is reported to be around 0.008 (Miller et al., 2018:115; Xuan and Wang, 2022:105107; Wang et al., 2023:4012). As it is evident, in the case of

LC^3, a high replacement of Portland cement whose carbon emission factor is about 0.82-0.83 with materials such as metakaolin and limestone has potential to reduce CO_2 emissions and energy consumption significantly, as metakaolin and limestone have way lower carbon emission factors compared to Portland cement. Obviously, finding random alternative materials with lower carbon emission factors to replace cement and clinker is not a logical approach to promote sustainability in cement and concrete production, because the materials used must yield an end product with sufficient strength and durability properties. In other words, materials used must work well together to promote the strength gaining reactions and the durability properties must be at acceptable levels. In LC^3, metakaolin reacts with portlandite, water and sulfates to promote the formation of C-A-S-H gel, ettringite and AFm phases (Zunino et al., 2022:234; Jiang et al., 2025b:106210). Carbonates from limestone react with C_3A coming from clinker, and other aluminates coming from metakaolin to form monocarboaluminate and hemicarboaluminate phases, which in turn enables refinement of pore structure (Dhandapani and Santhanam, 2020:105959; Jiang et al., 2025b:106210). In a nutshell, calcined kaolinitic clay and limestone have good synergistic effect, promoting strength development and improvement in durability properties. Thus, when materials with lower carbon emissions are used together intelligently, they enable designers to lower associated greenhouse gas emissions, offering environmental benefits. To show these environmental benefits, numerous studies have utilized LCA for the produced LC^3 binders or concretes produced with LC^3, along with studies focusing on conventional cement (Sánchez Berriel et al., 2016:361; Scrivener et al., 2018b; Guo et al., 2022; Ijaz et al., 2022:133492; Yu et al., 2021a:105846; Yu et al., 2021b:123616; Del Serrone and Moretti, 2023:136564; Supriya et al., 2023:137466; Blouch et al., 2023:139065). Table 3 provides an overview of these studies, some of which are compiled from Blouch et al. (2023:139065).

Long et al. (2021:122647) produced a 3D-printed LC^3 cementitious composite by incorporating silica fume, adopting particle packing theory. Relationships between particle packing densities and rheology and printability of the resulting products were investigated. Optimum results in terms of the specific rheological demands of 3D-printing operation were obtained for the mix design where 33.33% calcined clay, 16.67% limestone and 5% silica fume by weight. Furthermore, LCA analyses showed that the embodied carbon emissions and energy were reduced by 45.2% and 50.2%, respectively. Thus, it was shown that producing LC^3 with silica fume and particle packing theory adoption is possible to produce a cementitious composite that meets

the specific rheology demands of 3D-printing technology with way lower environmental impacts when compared to OPC.

Guo et al. (2022:132820) investigated the reductions in CO_2 and energy consumption for the production processes of LC^3-incorporated recycled aggregate concrete. They replaced OPC at 35% and 50% ratios with LC^3. 50% replacement led to insignificant reductions in strength, whilst improving chloride resistance remarkably. For 35% and 50% replacement ratios, reductions in chloride migration coefficients were reported to be 87% and 94%, respectively. It was observed that formation of dense C-A-S-H gels improved the microstructure, carbonates from limestone reacted with aluminates of both cement and calcined clay to form carboaluminate phases, porosity was reduced and electrical resistance was improved. While providing these mechanical and durability benefits, LC^3 helped to reduce environmental impacts as well. Reductions in CO_{2e} emissions and energy consumption were 30.8% and 22.6%, respectively, for 35% replacement ratio. When the replacement ratio was 50%, even greater benefits were provided, with these corresponding values being 42.1% and 30.6%, respectively.

In Yu et al. (2021a:105846), concrete samples containing LCC (Limestone Calcined Clay) additive at replacement ratios that are higher than the typical ratio were produced. LCC/binder ratio varied between 50%-80%. Water/binder ratio varied within the 0.30-0.40 range. It was concluded that producing concrete with way less environmental impacts could be possible through the replacement of the clinker with LCC at levels higher than the usual replacement level, as the compressive strength of the samples varied withing the range of 33-37 MPa at the end of 3 days, 47-51 MPa at 7 days, 56-58 MPa at 28 days and 62-64 MPa at the end of the 90 days of curing. Flexural strength values corresponding to the same curing periods are 4.4-4.8 MPa, 4.8-5.0 MPa, 5.2-5.4 MPa and 5.6-5.8 MPa, respectively. It was noted that the flexural strength values of all LCC-incorporated samples were 2%-10% higher than those of OPC samples belonging to the same compressive strength class. LCA analyses showed that reductions in embodied carbon and energy were to be 36.8%-44.4% and 3.7%-19.35, respectively, demonstrating the possibility of increasing the replacement ratio of the clinker by mineral additives to produce LC^3 with even lower environmental impacts whilst maintaining acceptable mechanical performance.

Table 3: LCA Analyses Performed for LC^3 Binders and LC^3-Incorporated Concrete

Reference	Sample Type	CO_2 Reduction (%)	Reduction in Energy Consumption (%)
Sánchez Berriel et al. (2016:361)	LC^3 Binder	30.0	-
Long et al. (2021:122647)	3D-Printable LC^3 Composite	45.2	50.2
Yu et al. (2021a:105846)	LC^3 Concrete	36.8-44.4	3.7-19.3
Tino Balestra et al. (2023:100792)	LC^3 Binder	32.0-35.0	-
Guo et al. (2022:132820)	LC^3-RAC*	30.8-42.1	22.6-30.6
Guo et al. (2023:132026)	LC^3-RFA**-UHPC	9.0-21	-
Zhou et al. (2023:2701)	LC^3-RFA**-ECC	30.34	13.61
Alghamdi et al. (2024:109881)	LC^3 Binder with Recycled Aggregate	45.0	-
Liang et al. (2024:139036)	LC^3-RFA**-ECC	28.6-47.1	6.6-22.0
Huang et al. (2024a:140380)	LC^3 Concrete	30.5-65.4	18.5-58.9
Altuntaş et al. (2025:140077)	LC^3 Binder	28.3	-
Yu et al. (2025:14122)	LC^3-RAC*	29.9	-

*RAC: Recycled Aggregate Concrete
**Recycled Fine Aggregate

Tino Balestra et al. (2023:100792) produced quaternary blended cement concretes by incorporating different mineral additives into LC^3 such as silica fume, acai stone ash, sugarcane ash and fly ash. The consumption of portlandite through the pozzolanic activity of calcined clay was noted for all mixtures, resulting in 20%-45% reductions in compressive strength. Presence of SCMs increased electrical resistivity by up to 48%. Silica fume yielded the best results in terms of mechanical performance and durability. For the LCA analysis, different projections regarding 20 years and 100 years were made. For all cases, 32%-25% reductions in CO_2 emissions were observed. Moreover, a comparison of silica fume and fly ash incorporated LC^3 to plain LC^3-50 mixture hinted at the differences in CO_2 emissions. This was noted by

the authors, saying that the type of additive would influence the amount of reduction in environmental impacts.

Guo et al. (2023:132026) produced UHPC by using LC^3 and recycled fine aggregate at different ratios. 30% LC^3 and 30% recycled fine aggregate use yielded the best performance as significant ecological benefits were noted whilst obtaining considerable mechanical properties. Factors that were taken into account while calculating the environmental impacts included CO_2, SO_2 and phosphate emissions in addition to ozone layer depletion, freshwater aquatic ecotoxicity, human toxicity, marine aquatic toxicity and terrestric ecotoxicity. Results indicated that when 30% LC^3 and 100% recycled fine aggregate were used together, global warming potential (GWP) decreased from 1220 $kgCO_{2(}eq)/m^3$ to 960 $kgCO_{2(}eq)/m^3$, marking the highest reduction. The mix design that yielded the optimum results, namely $LC^3$30-R30, caused a GWP of 983 $kgCO_{2(}eq)/m^3$.

Zhou et al. (2023:2701) produced sustainable ECC through the use of LC^3 cement and locally available recycled fine aggregate with polyethylene (PE) fibers. Embodied energy and carbon emissions were also determined for unit tensile strength and unit tensile strain. Significant environmental benefits were observed. Reductions in CO_2 emission and energy consumption were reported to be 30.34% and 13.61%, respectively. Similarly, Liang et al. (2024:139036) also produced ECC with LC^3 cement and recycled aggregate. Fly ash was also used, with three different fly ash/LC^3 ratios (1, 1.5 and 2.0) being employed. It was observed that LC^3 substitution increased the hydration heat and the amount of hydration products formed. Increasing fly ash/LC^3 ratio decreased compressive and tensile strength subtly. Improved fiber-matrix interfacial transition zone helped to limit the crack widths, thus providing better crack mitigation performance. LCA results revealed that cement contributed to a significant 85.3% of carbon emissions and 54.4% of embodied energy for fly ash or OPC ECC. On the other hand, LC^3 substitutions reduced carbon emissions and embodied energy by 28.6%-47.1% and 6.6%-22.0%, respectively.

Alghamdi et al. (2024:109881) studied the effects of waste rockwool on the thermal insulation properties of LC^3 cement produced with recycled aggregate. Recycled aggregates were obtained from ferrochrome waste slag. 5% use of rockwool waste reported to cause increases in compressive strengths of mortars made with natural and recycled aggregates by 19% and 21%, respectively. This was attributed to the physical filling effect. After 945℃ exposure, residual strengths of 57.5% and 63.8% were observed for natural and recycled aggregates, respectively. LCA results revealed that for

OPC references, the contributions of rockwool to CO_2 emissions were negligible. In the case of LC^3 based mortars, the use of recycled aggregates resulted in slightly higher emissions compared to LC^3 mortars produced with natural sand. This was attributed to the energy consumed during the recycling process. However, authors also noted that ecological benefits of the use of recycling process, such as reduced CO_2 emissions in terms of landfill disposal, were excluded from the analysis. Consequently, highest ecological benefits were observed for LC^3 based mortar with natural sand, with reductions in CO_2 emissions being approximately 45%.

Huang et al. (2024a:140380) considered a concrete with LC^3 cement, seawater, sea sand and fiber-reinforced polymer bars and performed LCA analyses in order to evaluate the environmental performance and life cycle costs. Both cradle-to-gate and cradle-to-grave boundary conditions were used. The former one was adopted to make an assessment of the concrete produced, while the latter was used to evaluate the performance of a concrete structure that would be built with this concrete. The effects of different parameters such as LC^3 replacement ratio, production process of calcined clay and cement and transportation distances were included in the ecological assessment. With increasing LC^3 replacement, as expected, environmental impacts decreased. GWP and energy consumption were, when compared to OPC concrete, decreased by 32%-41.7% and 23.3%-28%, respectively. Furthermore, these reductions for the reinforced concrete structure that would be built by using the resulting LC^3 cement were observed to be 30.5%-65.4% and 18.5%-58.9%, respectively.

Altuntaş et al. (2025:140077) produced LC^3 with low-grade alternative clays and compared their performance to that of a cement where a higher-grade kaolin clay was used. Low-grade clays had lower content of kaolin and were obtained from mine tailings and construction and demolition waste, including waste hollow bricks. LCA results indicated a 28.3% reduction in GWP. Yu et al. (2025:14122) produced LC^3 incorporated concrete with both fine and coarse recycled aggregate and observed insignificant reductions in 28-days strength when 50% of the cement was replaced by a combination of metakaolin and limestone, and 20% recycled fine aggregate was used by volume. However, increasing the replacement ratio caused further deterioration in mechanical properties. LCA results showed that LC^3 concrete had 29.9% less carbon emissions, when emissions for unit strength were considered.

5.2. LCA Studies on Other Clinker-Based Binders and Concretes

A comprehensive literature review reveals that studies on the development of low-carbon binders that contain cement clinker are rather focused on LC^3 cement, and work on other clinker-based sustainable binders are scarce when compared to LC^3 studies. Consequently, LCA analyses on other clinker-based binders and concrete produced by using them are less in number. Still, it is evident that such binders also offer significant environmental benefits as they enable designers to reduce carbon emissions and energy consumption while providing acceptable mechanical and durability properties.

Decristofaro et al. (2017:19) evaluated the environmental performance of CCSC-incorporated concrete produced with Solidia Technologies and LafargeHolcim collaboration. It is noted that, due to the lower lime content, associated CO_2 emissions would decrease from 540 kg to about 375 kg per ton clinker production since decarbonization of limestone is a major contributor to carbon emissions. In addition, it is stated that the low lime chemistry allows for a temperature for lime-silica reaction that is approximately 200℃ lower than that of OPC clinker, thereby reducing the amount of fossil fuel used per ton from 270 kg to 190 kg. Within the scope of the study, the first worldwide Solidia clinker production was realized, and carbon emissions were measured. 30% reduction in CO_2 emissions was observed. Jain et al. (2019:179) also focused on ecological and durability performance of CCSC-concrete. In terms of freeze-thaw and scaling resistance, efflorescence, sodium sulfate and magnesium solution resistance, CCSC-concrete performed equally or better than OPC references. Similar to findings of Decristofaro et al. (2017:19), due to low lime content, CO_2 caused by limestone's decarbonization was reduced from 540 kg/ton to 375 kg/ton. Reactions between lime and silica took place at temperatures 250℃ lower than that of OPC and CO_2 associated with fossil fuel consumption was again reduced from 270 kg/ton to 190 kg/ton.

Sharma et al. (2023:353) investigated the environmental impacts of CSAC production processes. The data for LCA analysis were gathered from a cement plant in India, two scenarios were considered for the production of CSAC in the same plant and CO_2 emissions and consumed energy were calculated. In CO_2 emissions, 30%-45% reductions were observed whilst no significant reduction occurred in energy consumption, as transportation distance of raw materials critically affected energy consumption. Tanguler-Bayramtan et al. (2024:3673) compared CSAC to OPC, specifically focusing

on carbon emissions and energy consumption. Monte Carlo simulations based on raw material data were performed to conduct environmental impacts, stated by the authors that this statistical approach could be an alternative to a full LCA analysis when comprehensive data are not available. Reductions in energy consumption and CO_2 emissions were reported as 13%-16% and 35%-48%, respectively.

5.3. LCA Studies on Magnesium-Based Binders and Concretes

Kastiukas et al. (2019:6957) performed LCA analyses with cradle-to-grave boundary conditions on MOC samples produced with different $MgO/MgCl_2.6H_2O$ molar ratios and different sources of reactive MgO. Increasing molar ratio resulted in worse environmental performance. This was attributed to the differences in the energy requirements of MgO and $MgCl_2.6H_2O$. It was noted that MOC concrete could be identified as more sustainable when compared to OPC concrete when MgO is obtained through dry process route rather than the wet process route.

Shen et al. (2024:142981) developed a life cycle inventory for MPC based on four different scenarios: Dry route MgO and magnesium dihydrogen phosphate as raw materials, wet route MgO and magnesium dihydrogen phosphate as raw materials, salt lake MgO and magnesium dihydrogen phosphate as raw materials and finally dry route MgO and ammonium dihydrogen phosphate as raw materials. These were denoted as S1, S2, S3 and S4, respectively. It was revealed that S2 had the highest GWP, with its GWP being 3.97%, 74.55%, and 1.41% higher than that of S1, S3 and S4, respectively. Obviously, S2 scenario yielded the best ecological performance, and this was attributed to the fact that energy requirement for the production of salt lake MgO is lower than those of dry and wet route MgO. Environmental impact of salt lake MgO was observed to be 20% less than dry route MgO and 23% less than wet route MgO. It was noted that since MPC is highly suitable for the use as a repair and coating material and can reduce carbon emissions by 12%-98% when compared to other repair materials, findings of the LCA analyses were promising in terms of contributions to the development of sustainable repair and coating materials.

5.4. LCA Studies on Alkali-Activated Binders and Concrete

There are different uncertainties in the environmental performance of alkali-activated and geopolymer binders, although the general consensus is

that their production results in lower carbon emissions. This was attributed to the removal of cement clinker and clinker calcination and use of waste materials. Salas et al. (2018:170) observed better ecological benefits for geopolymer binders, however noting the fact that a great majority of the carbon emissions associated with the production processes comes from factors such as the type and the content of alkaline activator used, longer period of time required for curing and specific curing needs such as oven curing. Bajpai et al. (2020:120147) performed comprehensive LCA analyses for three different geopolymer mixtures and compared their ecological performance to that of OPC concrete. Geopolymer concrete designs with and without silica fume and sodium silicate were considered. GWP values for OPC concrete, geopolymer concrete, geopolymer concrete with silica fume and sodium silicate and geopolymer concrete with silica fume and without sodium silicate were calculated as 597.54 $kgCO_{2e}$, 148 $kgCO_{2e}$, 135 $kgCO_{2e}$ and 133 $kgCO_{2e}$, respectively, marking significant reductions in the environmental impacts. However, it is still noted that emissions associated with the production of alkaline activators are noteworthy (Nodehi et al., 2024:135816).

Ramagiri et al. (2022:119) investigated the mechanical performance of alkali-activated fly ash and slag incorporated concrete before and after high temperature exposure. Eight mixture designs were realized, each of them having a different fly ash/slag ratio and activator modulus. OPC concrete had 1.5 times higher GWP potential when compared to alkali-activated concrete (AAC), and this was attributed to the production processes of OPC concrete. Although in general AAC was more sustainable, on the impacts categories basis, for ecotoxicity, eutrophication and ozone layer depletion, AAC performed worse. This was explained by the discharge of toxic effluents which are generated at the end of the production processes of alkaline activators into the nearby water bodies or land.

6. CONCLUSIONS

In today's world, it is of vital importance to take measures in order to cut greenhouse gas emissions in any industry, to prevent the negative consequences of global warming and associated environmental issues. Production of Portland cement contributes to CO_2 emissions significantly. This has made the development of new generation, alternative binders with lower CO_2 emissions a necessity. Researchers are actively seeking to develop more and more environmentally friendly binders to ensure the sustainability

of concrete production. In the light of these findings, clinker based, magnesium based and alkali-activated types of new binders have been developed. This study reviews the reaction mechanisms, fresh, hardened and durability properties and environmental impacts of these binders and their use in concrete production. Clinker-based binders utilize mineral additives and their synergistic effects to replace cement clinker at higher levels when compared to conventional blended cement to further reduce CO_2 emissions; or the composition of the clinker and/or the additives are changed so that the required energy consumption to produce the cement is reduced. For instance, LC^3 utilizes synergistic effects of calcined clay and limestone to replace the cement clinker at levels as high as 50%. RBC mainly contains belite, which requires less energy for production when compared to alite. CSAC requires lower calcination temperature due to its ye'elimite content in its clinker. CCSC is a binder cured through carbonation, capturing CO_2. Although due to reduced clinker levels strength is generally seen to be decreasing, filler effects of the used fine mineral additives and additional hydration products formed through the pozzolanic reactions reportedly refine the microstructure, leading to improved durability properties. Furthermore, when engineered properly, these clinker-based binders can have mechanical strength on par with OPC, or in some particular cases even higher strength can be achieved. MgO, which is used to produce magnesium-based new generation sustainable binders, require less energy consumption during the production processes, enabling practitioners to reduce associated greenhouse gas emissions. These have superior mechanical properties and durability in general; however especially MOC and MPC reportedly have poor water resistance. Researchers, on the other hand, have successfully overcome this issue by employing various approaches such as using SCMs or organic acids. Alkali-activated cements utilize high amounts of industrial waste, contributing to waste management strategies, preserving natural resources and reducing CO_2 emissions.

LCA results show that greenhouse gas emissions associated with production and the use of these mentioned new generation sustainable binders and different types of concrete made by using these binders can be reduced drastically, stemming from significant reductions in required energy consumptions. Still, in general it is reported that the contributions of pollutants generated at the end of alkaline activators processes are noteworthy, although alkali-activated materials are, overall, way more environmentally friendly when compared to OPC.

Although a great majority of the weak sides of each of these binders have successfully been improved as implied by literature, there is still room

for improvement as some of the key drawbacks of these binders still require solutions. These drawbacks are not only restricted to the properties related to the performance of binders and concrete; they are also related to productions costs. Thus, future studies must focus on improving the disadvantages of these binders in a more economical and sustainable manner and optimizing costs and production processes to ensure the use of these binders on industrial scale.

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