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SUSTAINABLE DEVELOPMENT OF CEMENT MORTARS: A REVIEW OF PALM KERNEL SHELL-BASED ADMIXTURES AND PRE-HYDRATION TECHNIQUE

This review explores sustainable cement mortar production by examining palm kernel shells (PKS) as admixtures and the application of pre-hydration techniques. The environmental impact of traditional cement necessitates alternative materials. PKS, an agricultural waste product, offers a potential solution due to its availability and pozzolanic properties. Pre-hydration, involving controlled water addition before mixing, further improves mortar performance and reduce cement consumption. The results shows that PKS-based admixtures, when combined with pre-hydration technique, improve mortar strength, durability, and sustainability while reducing environmental impact. Future research should aim to optimize the PKS and pre-hydration techniques for various applications, and investigate the ability to use these methods in large-scale construction projects. These developments could lead to a more sustainable construction industry.

Keyword: Palm Kernel shells; Cement; Admixtures; Physical Characteristics; Chemical Characteristics; Pre-Hydration

List of abbreviation

- Palm Kernel Shells (PKS)
- Supplementary Cementitious Materials (SCMs)
- Specific Gravity (SG)
- Saturated Surface Dry (SSD)
- calcium silicate hydrate (C-S-H)

1. Introduction

The major component used in the building industry is cement and the process of cement production harms the environment in many ways [1-3]. Cement manufacturing is responsible for contributing about 8% of the overall global CO_2 emissions which causes greenhouse emissions and climate change [4,5]. To overcome this problem, scholars have looked into the prospects of different cementation binders and materials that will decrease the quantity of CO_2 emissions from cement-based items by utilizing numerous industrial wastes and reprocessed aggregates [6]. Palm kernel shells (PKS) is one of the ideal material that considered as an industrial waste product of the palm oil industry [7,8]. Studies on substituting cement or aggregate in cement mortars with PKS have revealed the possibility of developing environmentally friendly products [9]. Depend on studies using palm oil industry products like PKS clinker would reduce cement production by about 3.3% and carbon emissions by about 52% is due to pozzolanic characteristics in PKS that is supported by given results in the reference [10,11]. Furthermore, pre-hydration of cement has also been investigated as a strategy to optimize the use of cement and improve the sustainability of cement-based materials [12]. Using pre-hydration technique lead to decrease the total consumption of cement in construction projects, which, in turn, will decrease the adverse effects caused by concrete production [12-14]. Studying the Pre-hydration methods and PKS based admixtures of cement mortars create the basis for the development of a new generation of environmentally friendly construction practices. It promote the increased durability and efficiency of the materials used in construction moreover decrease the effects of the construction on the ecosystem. There is a necessity to carry out additional experimental research, set rules of procedure in the industry, and enhance people's familiarity with the concept. Prospects of cement mortars with palm kernel shell-based admixtures and pre-hydration which is significantly decrease the environmental effects of construction with improved mechanical properties at the same time [15,16].

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With growing realization and approaches to declining resources and global crises of environmental degradation especially in the construction industry, these green solutions should be considered for viability [17]. The combined use of sustainable materials like Supplementary cementitious materials (SCMs) and pozzolanic materials with pre-hydration techniques represents a comprehensive strategy for addressing the environmental impact of traditional mortar production. This approach not just enhances mortar quality and performance also reduces the construction industry's overall environmental footprint. As construction practices evolve towards greater sustainability, integrating prehydration offers a promising avenue for improving both the sustainability and resilience of mortar structures. This review paper aims to synthesize the current state of research on the use of PKS based admixtures and pre-hydration techniques in the development of sustainable cement mortars.

2. Palm kernel shell-based admixtures for cement mortars

Recent studies are focused on using agricultural waste in cement mixtures. In this review, the focus will be on studying the impact of using waste from the palm oil industry which is PKS as illustrated in Fig. 1, the processes to extract PKS, as using PKS in concrete mixtures, whether as an alternative to aggregates or cement, reduces the environmental impact resulting from its accumulation in environmental landfills, in return, reduces the demand for raw materials. According to [18], Malaysia was responsible for the production of about 19900 million tons of the world's total palm oil supply, accounting for 26% of global palm oil production. Meanwhile, Indonesia is a dominant palm oil producer in the world and produced 43500 million tons of palm oil in 2020, accounting for 58% of the world's total supply [18].

Several research have been conducted in recent years on the use of palm kernel shell as a partial replacement for cement or aggregate in cement-based products [19]. According to research, using palm kernel shell powder as a partial substitute for cement improves the workability, compressive strength, and flexural strength of concrete [20,21]. The recommended replacement rate is 10-20% by volume, with greater levels potentially affecting the mortar's mechanical qualities.

The hardened performance of concrete mix with PKS are vary depending on the physo-chemical properties of PKS. Physical charecterization which contain specific gravity, thickness and shape, compacted bulk density states, and water absorption are reviewed in TABLE 1. Based on studies [15,22], the colour of PKS ranges from a dark grey to a deep black and its thickness vary significantly from (0.15 mm to 8 mm) based on the type and age of palm tree. The shapes of PKS showed diiferent forms of polygonal shape to angular based on the processing used to extract it from nuts [23]. Various researchers have indicated in the TABLE 1 that the specific gravity (SG) of PKS has never exceeded 2.0, and PKS has an SG values ranged from 1.15-1.62. The highest value for an SG of PKS was given as 1.51 by [24], and According to [25], the lowest SG value of PKS was reported to be 1.15, while [26] and [27] reported a SG value of 1.17. Furthermore, [28-31], reported the same SG value of 1.37. The values corresponding to different studies is less than 2 SG that is correspondance to relationship of pozzolanic activity which is due to pozzolanic reactions during the curing days. The duration of curing days increase the samples strength with pozzolanic reactions enhancement [26].

Bulk density represents the mass of a material relative to the total space it occupies, including the void volume between particles, the particle volume and the internal pore volume [32], Based on the TABLE 1, the values of loose bulk density vary from 568 kg/m^3 [33] to 683 kg/m^3 [34,35], according to [36] the size and shape of PKS significantly influence the packing density, which leads to fluctuations in the bulk density and specific weight. Due to its low bulk density, PKS is classified as a low-weight aggregate. Water absorption refers to the amount of water that needs to be added to the aggregate to achieve a saturated surface dry (SSD) environment. TABLE 1 and show that the water absorption percentage of PKS is between 7.6% and 25.7%.

TABLE 2 shows the chemical compound of PKS based on literature data. The chemical composition of PKS differs relying on factors such as the origin of the material, treatment methods, combustion temperature, boiler operating conditions, and geographic location of the plantation. As shown in TABLE 2,

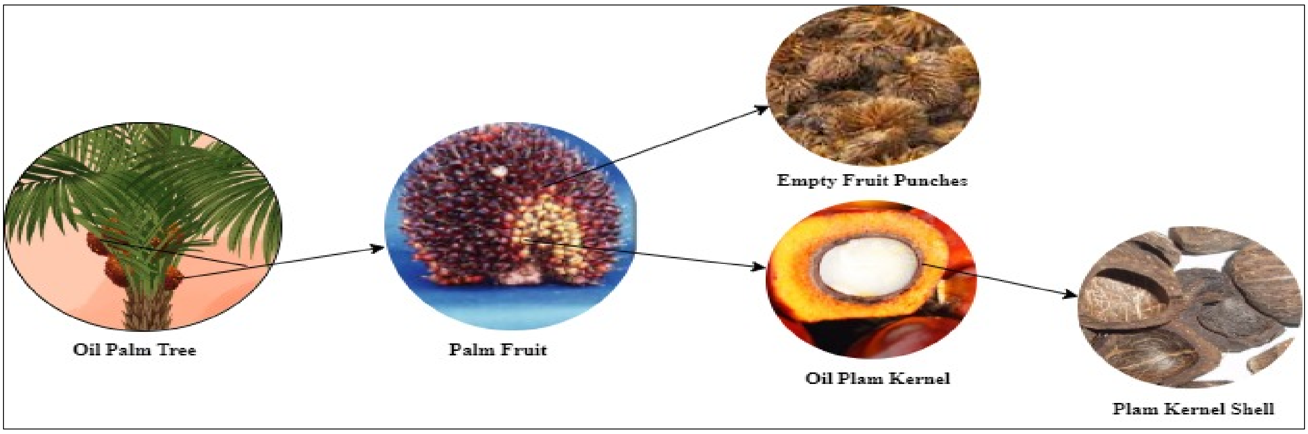

Fig. 1. Process to produce PKS from the oil palm tree

PKS has a high silica content and does not contain any detected toxic elements. Previous research has indicated that the highest reported SiO_2 value for PKS is 55.6% [37]. The use of PKS in cement-based materials not only mitigates the environmental impact of cement production but also helps to address waste management challenges in the palm oil industry [9,38].

TABLE 1

Physical properties of PKS

REF.	Maximum size (mm)	Specific gravity	Bulk Density (kg/m^3)	Water absorption (%)
[39]	10	1.33	—	7.6
[25]	10	1.15	644	25.7
[24]	20	1.51	—	8.7
[33]	20	1.19	—	16.99
[28]	19	1.37	—	—
[40]	8	1.48	—	18.7
[29]	—	1.37	568	12.47
[41]	16	1.31	—	19.93
[30]	16	1.37	635	24
[26]	12.5	1.17	590	23.3
[42]	10	1.22	626	18.7

TABLE 2

Chemical properties of PKS

REF.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O_2	K_2O	SO_3
[43]	49.63	12.12	0.41	7.96	—	8.24	6.21	—
[44]	47.1	15.19	12.2	7.59	0.93	0.94	0.25	—
[45]	31.5	16.5	1.4	10.6	16.9	—	1.75	7.27
[46]	46.2	2.3	3.2	15.1	3.7	1	21.2	—
[37]	55.69	9.43	3.32	11.21	4.85	1.76	9.71	0.67
[46]	46.2	2.3	3.2	15.1	3.7	1	21.2	—
[47]	11.6	0.985	12.9	58	1.76	—	5.33	2.35
[48]	46.23	4.921	31.013	4.786	0.667	1.32	4.254	2.257
[49]	45.13	1.67	0.02	1.03	1.98	—	1.11	—

3. Hydration reaction

The heat produced through the mixing cement processing of cement and water is referred to hydration heat, which indicates an exothermic reaction. Cement paste has a variety of physical properties and is a porous substance with many scales. Approximately half of the volume of hardened hydrated mortar consists of calcium silicate hydrate (C-S-H) [50]. Cement hydration reaction study is complicated but necessary for improving concrete durability and strength [51-53]. As shown in Fig. 2 [54], the cement hydration kinetic reaction is divided into five phases: pre-induction, induction, acceleration, deceleration, and steady-state [55].

It is critical to accelerate the cement hydration rate when using mortar and concrete in certain applications. For example cement hydration rate acceleration is essential in cold weather concreting to ensure timely setting and strength development, preventing issues like freezing before curing [56]. It is also es-

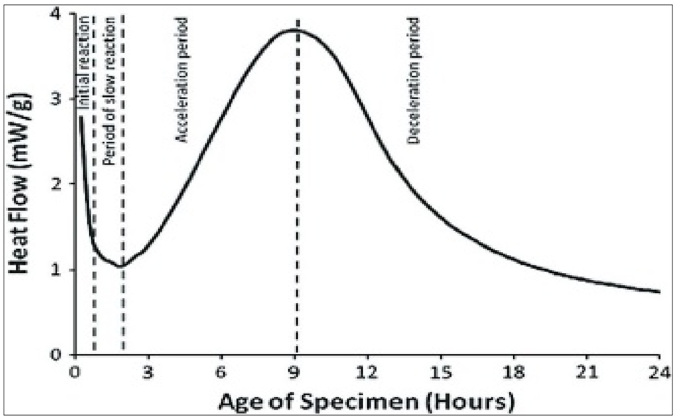

Fig. 2. Cement hydration phases

sential in rapid repair applications, such as roads and runways, here quick setting reduces downtime and efficiently restores functionality [57]. Additionally, there are various approaches to accomplish this aim, such as enhancing cement fineness, escalating the curing temperature and decreasing the water and cement percentages. Furthermore, it turns out that using specifically made admixtures to speed up cement hydration is a workable strategy [58]. These accelerators categorized into two types based on their usage: those intended for sprayed concrete and those created for cast concrete [58]. The first category aids in rapid cement setting within minutes of hydration and encourages early strength growth, while the second facilitates early strength development without affecting the setting time [59]. Furthermore, two new fields in cement research have gained significance as it advances. These include the growing incorporation of new SCMs materials into cement compositions and the increasing adoption of additive manufacturing techniques in the building industry [60]. Note that commonly used SCMs, typically decrease compressive strength [61]. This emphasizes the necessity for creative solutions to manage and maximize the qualities and functionality of cement-based materials, especially in light of changing building practices and environmental concerns [62]. A result of the hydration reaction between cement and water is the evolution of properties in cement-based materials over time [63]. The rate of hydration in Portland cement is significantly impacted by temperature, just like in many other chemical reactions [64]. In order to understand material behavior, it is imperative to look into how temperature and time interact to affect the rate of cement hydration. This includes things like setting, cementing, and changing in different ways over time [65]. These kinetics are usually evaluated by tracking the evolution of hydration heat [66], which has direct and useful applications in calculating temperature variations related to the heat produced during the hydration of cement-based materials [55]. The heating which is produced during reaction and kinetic performance of mortar consisting of steel slag as a cement replacement with varying temperatures were examined by Han et al. [67], for instance. Gołaszewska et al. [68] constructed isothermal calorimeter to investigate changes in early-age intensity of hydration heat of water-cement ratio in cement paste and mortar. Portland cementitious materials with low heat and early strength were studied for hydration by Wang et al. [69], using an isothermal calorimeter. Overall, the strength and durability of concrete are highly dependent on the hydration heat produced during the mixing process. The heat of hydration evolution has been frequently employed in exploring cementitious material hydration dynamics, which is provide information throughout the curing ages of samples, and during many years of research, heat data has been adequately with kinetic reaction parameters for example the level of hydration reaction. To measure the heat which is resulted from hydration reaction three primary methods: the semi-adiabatic approach, the fully adiabatic technique, and the isothermal calorimeter technique [69] .The isothermal calorimeter technique has been widely used to study heat assessment, particularly early-age hydration heat development, and the kinetics of cementitious materials[69]. Accelerating the cement hydration rate is crucial for certain applications, such as increasing the curing temperature, improving cement fineness, and decreasing the water and cement percentages. The construction industry can manage and optimize the properties and functionality of cement-based materials by incorporating additive manufacturing and supplementary cementitious materials into cement compositions.

Using pozzolanic materials, like PKS, has a notable impact on the hydration behavior of cement mortars[70]. PKS ash, which is rich in silica, reacts with the calcium hydroxide formed during cement hydration to produce additional calcium silicate hydrate (C-S-H) [71].This process enhances the density of the mortar matrix and contributes to long-term strength [72]. While this pozzolanic reaction is slower than the hydration of traditional cement, it offers benefits such as increased durability and better resistance to chemical attacks [72,73] Moreover, other pozzolanic materials, such as fly ash and silica fume, improve the structure by reducing permeability and refining pore distribution [74,75]. Incorporating these materials not only improves the mechanical properties and durability of cement mortars but also supports sustainable construction practices by reusing agricultural and industrial waste.

4. Pre-Hydration Techniques

The morphology of cement mortar is a porous structure varying size particles material with different physical characteristics and varying size scales. The vital chemical component in hardened cement paste is C-S-H, which accounts for at least fifty percent of the volume [50]. Accurately imitating the performance of concrete requires constructing a substantial model of cement mortar paste and progressing to the overall performance of mortar composite material [76]. The chemical composition and fineness and kind of cement, the water content, the ratio of additives and admixtures, the mixing technique, and the temperature all significantly influence the qualities of the paste [77]. The hydration of Portland cement produces a range of hydration products, including amorphous or weakly crystalline C-S-H and coarsely crystalline C-H which is typically formed in conjunction with the hydration of C_3S or C_2S [78]. The primary products of the cement-water hydration progression are calcium hydroxide (C-H) crystals, and C-S-H gel, both on the nanosize [79]. However, the (C-H) crystals are an undesirable component of the concrete composite matrix, because it is ultimately degrading the performance of the concrete. Researchers have incorporated nano-scale particles, such as nano-silica, into concrete to counteract the issues caused by calcium hydroxide crystals [5]. This process triggers a pozzolanic reaction that converts the undesirable calcium hydroxide crystals into the more beneficial calcium silicate hydrate gels. Numerous studies have demonstrated that adding pozzolanic materials, including metakaolin, silica fume, and low-calcium fly ash, can enhance the chemical resistance of concrete [80,81]. Although the hydration process of cement can be complex, its properties can be influenced by admixtures and environmental conditions [82]. To enhance the performance of cement mortars, one potential method is the application of pre-hydration, which aims to improve the achievement of desirable characteristics during the hydration process [83]. Cement Pre-hydration defined as a technique that involves partially hydrating the cement prior to mixing with other ingredients [84]. Chemical admixtures in cement mortars can influence the hydration process due to their application. These admixtures affect the cement matrix and influence the development of the hydration reaction over time [85]. Particularly, waterproofing admixtures can redirect water from affecting the fresh concrete, as they render the concrete hydrophobic through various mechanisms, such as reacting with the calcium hydroxide ($CaOH_2$) in the cement system or inherently making it water-resistant. Furthermore, the interaction between some admixtures in a given mix can create additional complications that require resolution before their field application [86]. Pre-hydration approaches which partially hydrates cementitious ingredients before final mixing, stimulates better distribution of hydration products, decreasing early-age cracking. When PKS ash was used, the silica composition combines with calcium hydroxide generated during cement hydration, resulting in the formation of extra C-S-H, which increases strength and durability[87,88]. Similarly, pre-hydration benefits other pozzolanic ingredients, such as fly ash and silica fume, by refining the cement's pore structure and increasing homogeneity [89].

5. Conclusion

In conclusion, the sustainable development of cement mortars using Palm kernel shell-based admixtures and pre-hydration presents an improved way to reduce the environmental impact of construction while enhancing the strength and properties of cement mortars. The building construction industry is a significant consumer of raw materials and a major contributor of CO_2 and other greenhouse gases, necessitating a shift towards more sustainable practices. This review reveals that PKS, a readily available agricultural waste, can effectively replace traditional cement ingredients, helping to curb energy demands in clinker production and waste disposal. Additionally, the pre-hydration technique, which involves pre-hydrating cement particles before mixing with sand, enhances cement utilization and the resulting mortar's strength. Furthermore, the findings of this research indicate that the combined use of pre-hydration technique and PKS in cement mortar is an efficient method to enhance the sustainability and efficiency of cement mortars. Also, PKS is used as a partially replacement with cement in mortar, thereby reducing emissions due to its environmentally friendly nature. Furthermore, PKS enhances long-term strength gain and durability of the mortar due to its pozzolanic properties. Additionally, the use of Admixture increases workability, decreases water requirement, optimizes the hydration process, and improves the mechanical and rheological performance, as well as the density and paste shrinkage cracking.

Recommendation

The use of pre-hydration methods and admixtures based on palm kernel shells in cement mortars appears to be a potential answer in the search for more environmentally friendly building practices. These developments improve the longevity and performance of the materials while also lessening the environmental impact of the building. It is essential to carry out research and development, set industry standards, and increase stakeholder knowledge in order for them to reach their full potential.

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