New Materials, Compounds and Applications
Vol.9, No.3, 2025, pp.548-569
https://doi.org/10.62476/nmca.93548

PHYSICO-CHEMICAL IMPACT ON SETTING TIME, NORMAL CONSISTENCY AND WATER SORPTIVITY FROM PARTIAL OPC REPLACEMENT WITH STONE-CUTTING DUST, LIMESTONE AND NATURAL POZZOLANA IN SUSTAINABLE BLENDED CEMENTS

Nancy Mweni Paul[1*], Jackson Wachira Muthengia[1], Genson Murithi[1], Esther Wanja Nthiga[2], Joanne Ogunah[1]

[1]Department of Physical Sciences, University of Embu, Embu, Kenya
[2]Department of Chemistry, Dedan Kimathi University of Technology, Nyeri, Kenya

Abstract. This study evaluates the physico-chemical performance of Ordinary Portland Cement (OPC) when partially replaced with stone-cutting dust (SCD), limestone (LS) and natural pozzolana (NP), both individually and in ternary combinations. Blends were formulated with SCD and NP at 10-40% and LS at 5-20%, including optimized ternary mixtures. Tests focused on normal consistency, setting time and water sorptivity. Results showed that all supplementary cementitious materials (SCMs) increased normal consistency, from 28.0% in OPC to 35.0% at 40% substitution. Setting time was significantly extended in SCM-rich blends, with initial and final setting times reaching up to 250-260 minutes, compared to 100 and 180 minutes for OPC. This delay, especially in NP and SCD-rich mixtures, reflects reduced reactivity and higher water requirements. Water sorptivity improved in optimized ternary blends, with Mix H (10% SCD + 10% LS + 15% NP) showing the lowest sorptivity coefficient of 0.1666 $g/cm^2/hr^{0.5}$, compared to 0.1908 for OPC. These findings demonstrate that carefully balanced combinations of NP, LS and SCD enhance workability, provide longer setting windows and reduce water ingress, leading to improved durability. The results support the use of locally available materials in Kenya as sustainable and cost-effective alternatives for blended cement production.

Keywords: *Ordinary Portland Cement, supplementary cementitious materials (SCMs), normal consistency, setting time, water sorptivity.*

Corresponding Author: *Nancy Mweni Paul, Department of Physical Sciences, University of Embu, Embu, Kenya, e-mail: 1622@student.embuni.ac.ke, nancymuheni@gmail.com*

Received: *4 July 2025;* ***Accepted:*** *19 August 2025;* ***Published:*** *4 December 2025.*

1. Introduction

The increasing global demand for sustainable construction practices has amplified the need to reduce the environmental footprint of Ordinary Portland Cement (OPC) (Oliveira *et al*., 2023). Cement production is responsible for an estimated 8% of global CO_2 emissions, primarily due to the calcination process and the intensive energy use in clinker production (Environment *et al*., 2018). As a result, researchers have focused attention on the partial replacement of OPC with supplementary cementitious materials (SCMs), aiming to mitigate environmental impacts while maintaining or improving the performance of cementitious composites (Knight *et al*., 2023). This study explores the effects of using three locally available materials in Kenya: natural pozzolana (NP), limestone (LS) and stone-cutting dust (SCD) to partially substitute OPC and improve its physico-chemical properties.

Natural pozzolana is a siliceous material of volcanic origin, widely recognized for its pozzolanic reactivity (Santana *et al*., 2022). It reacts with calcium hydroxide, a by-product of OPC hydration, to form additional calcium silicate hydrate (C-S-H), the primary binding phase in cement (Maddalena, 2018). This reaction refines the microstructure, reduces porosity and improves long-term strength and durability (Luo *et al*., 2024). In contrast, limestone, primarily composed of calcium carbonate, functions as a physical filler and nucleation site for hydration products (Wang *et al*., 2018). Although non-pozzolanic, limestone enhances particle packing, early strength and workability, particularly when used in lower replacement ratios (up to 20%) (Ioanna Dedousi, 2021). Stone-cutting dust, a by-product of dimension stone processing, contains finely ground particles that can contribute to microstructural refinement through filler effects and limited pozzolanic activity (Chen, 2023). In Kenya, the abundance of these materials makes them ideal candidates for sustainable cement replacement strategies (Marangu *et al*., 2024).

In this study, OPC was partially replaced with NP and SCD at 10-40% by weight and LS at 5-20%, both individually and in ternary combinations. The physico-chemical parameters evaluated were normal consistency, setting time (initial and final) and water sorptivity. These properties were chosen due to their direct impact on workability, hydration kinetics and long-term performance. Experimental results revealed that substituting OPC with SCMs increased normal consistency from 28.0% (pure OPC) to 35.0% for blends with 40% NP and SCD. This increase is attributed to the higher water demand of pozzolanic and filler materials due to their fine particle size and porous structures (Khan *et al*., 2017).

Setting time is another critical indicator of the hydration process (Hewlett & Liska, 2019). OPC exhibited an initial setting time (IST) of 100 minutes and a final setting time (FST) of 180 minutes. In contrast, SCM blends exhibited significantly extended setting times. A 40% substitution with SCD resulted in IST and FST values of 255 and 260 minutes, respectively. Similar delays were observed in NP-rich blends, which registered IST values of up to 250 minutes. This extension is due to the dilution of OPC’s reactive clinker phases, particularly tricalcium silicate (C_3S) and tricalcium aluminate (C_3A), by the inclusion of less reactive SCMs, coupled with the increased water requirement for paste workability (Haha *et al*., 2023). The extended setting time provides improved handling properties and longer workability windows, which can be advantageous in hot climates where rapid setting is undesirable (Zahir *et al*., 2023).

Water sorptivity, a key measure of capillary water absorption and thus durability, was also influenced by SCM replacement. OPC showed a sorptivity coefficient of 0.1908 $g/cm^2/hr^{0.5}$, while Portland Pozzolana Cement (PPC) recorded a lower value of 0.1731 $g/cm^2/hr^{0.5}$ due to the pozzolanic action of its constituents. Among ternary blends, Mix H (10% SCD + 10% LS + 15% NP) demonstrated the lowest sorptivity coefficient of 0.1666 $g/cm^2/hr^{0.5}$, indicating a refined pore structure and better resistance to moisture ingress. These results align with findings from other studies that report improved pore refinement and decreased permeability with optimized SCM combinations (Huang *et al*., 2022).

This study’s findings confirm that well-formulated ternary blends of NP, LS and SCD can significantly improve both fresh and hardened cement properties. The observed synergy between pozzolanic and filler materials suggests that blends can be tailored to enhance durability, reduce environmental impact and lower production costs critical goals in modern construction (Navarrete *et al*., 2023). Importantly, this approach promotes the use of local waste materials like stone-cutting dust, contributing to circular economy principles and reducing the burden of quarry waste disposal in regions such as Kajiado County, Kenya.

2. Materials and Methods

2.1. Research Design

This study used an experimental quantitative approach to examine the impacts of partially replacing Ordinary Portland Cement (OPC) by blended materials, stone-cutting dust, natural pozzolana and limestone on the physicochemical characteristics of cement. The experiment included systematically varying the proportions of the replacement materials and determining the effects of these on setting time, normal consistency and water sorptivity under laboratory conditions.

All the tests were conducted according to the given procedures and the data obtained was analyzed statistically to identify performance differences among the blended materials and commercial cement products (OPC and PPC). Analysis of variance (ANOVA) and independent sample t-tests were performed to determine whether differences among the blends were statistically significant at a 95% confidence level ($p < 0.05$). This approach facilitated valid comparison and interpretation of the effects of varying blends on cement performance.

2.2. Sampling Method and Sampling Sites

This study employed a purposive sampling method, where materials were intentionally chosen because they are pertinent to the research objectives and available from trusted sources. Portland Pozzolana Cement (PPC 32.5N) and Ordinary Portland Cement (OPC 42.5 N) were purchased from appointed distributors within Athi River town, Kenya. ISO standard sand complying with EN 196-1: 2016 was obtained from Savannah Cement Ltd, Kitengela, Kenya.

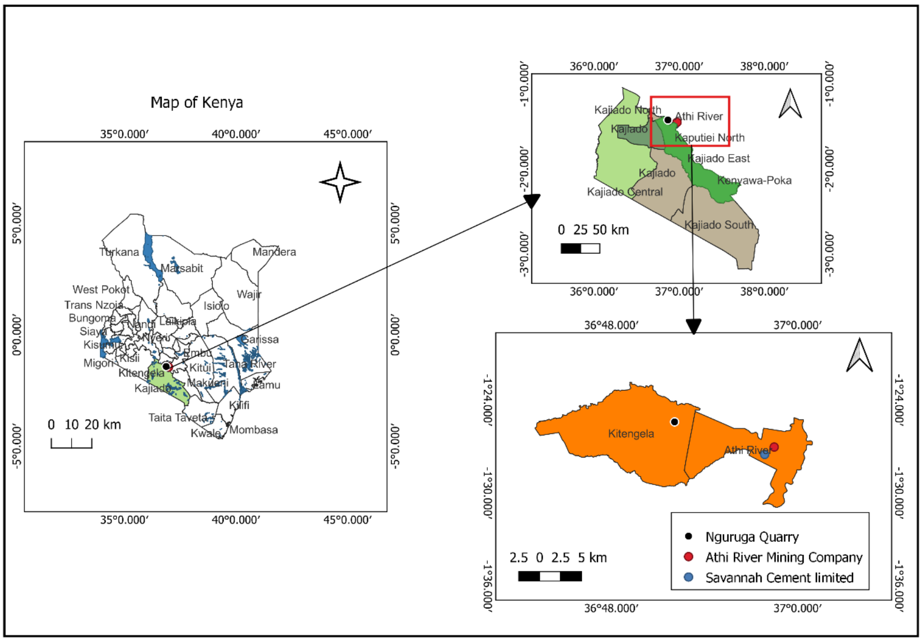

Figure 1. Sampling Sites

Natural Pozzolana was acquired from local volcanic minerals in Nguruga, Kajiado County, Kenya. Limestone was sourced from Athi River Mining Company, Nairobi, Kenya. Stone-cutting dust was sourced from Nguruga, Kajiado county, Kenya, which lies between latitudes 1030’ and 2 000’ S. and longitudes 360 30’ and 370 30’ E and at an altitude of 1710 m higher than sea level. Distilled water was used in all activities in this study whenever water was used.

2.3. Chemicals and Reagents

All of the reagents and chemicals utilized in this study were of analytical quality to ensure accuracy and consistency in the test results. Distilled water was utilized throughout the experiments for mixing, curing and cleaning purposes to avoid interference from dissolved salts or impurities.

2.4. Sample Preparation

The test materials, natural pozzolana, limestone and stone-cutting dust, were first air-dried to eliminate moisture and then ground using a laboratory ball mill to accomplish fine and consistent particle sizes suitable for cement blending. Sieve analysis was performed to confirm that the distribution of particle size fell within the required range and to ensure consistency across all samples.

Each material was blended with Ordinary Portland Cement (OPC) in specified proportions by weight, as outlined in the experimental design. The blending process was done manually and further homogenized using a laboratory rotary mixer to guarantee a uniform allocation of materials in the cement matrix. No chemical admixtures were added during mixing to maintain the integrity of the study's natural-material focus. Before testing, the prepared blended samples were kept in containers that were airtight to prevent contamination and absorption of moisture.

2.4.1. Optimization of the ratios

The optimization of replacement ratios in this study was informed by previous research that demonstrated the performance benefits of using supplementary cementitious materials in partial substitution of Ordinary Portland Cement (OPC). Ground samples of stone-cutting dust and natural pozzolana were individually blended into OPC at replacement levels of 10%, 20%, 25%, 30%, 35% and 40%, in line with studies like those by Ngui et al. (2022) and Affan et al. (2024) which reported that pozzolanic and siliceous materials improve long-term strength and reduce porosity when used within these ranges. For consistency in labelling, each blended sample was named based on its replacement level, for example, 10% NP for 10% natural pozzolana. Limestone was also partially substituted at 5%, 10%, 15% and 20%, following the recommendations of Bentz et al. (2017) and Srinivas et al. (2022), who noted improved early strength and packing density at lower limestone dosages.

Additionally, ternary blends of natural pozzolana, limestone and stone-cutting dust were prepared and substituted into OPC at 25%, 30%, 35% and 40%. These blend ratios were guided by findings from Cheah et al. (2025) and Amin et al. (2017) who proved that combining reactive and inert materials in carefully balanced proportions can yield synergistic effects in strength, durability and workability. The selected proportions aimed to explore a wide performance spectrum while ensuring that the combined replacement levels remained within acceptable limits for structural applications.

2.4.2. Preparation of Mortar Prisms

According to the guidelines in KS EAS 148:1-2017, test cements were prepared using moulds of dimensions 40 mm x 40 mm x 160 mm. The water to cement ratio was 1:2 for the control samples and all cement categories whereas the ratio of cement to sand ratio was 1:3. The control samples comprised of commercial OPC and commercial PPC. 450g of cement were weighed and added to 225 g distilled water in the automatic programmed mixer's mixing bowl.

The bowl with its contents was then subsequently strapped onto the programmable automated mixer and permitted to start mixing at a low speed. After 30 seconds, 1350 g of standard sand produced in accordance with ISO 679:1989, EN 196 - 1 (2016) was gradually added into the bowl for the following 30 seconds. After that, the machine was programmed to run at maximum speed for the following 30 seconds and then to pause for 90 seconds. Using a plastic scoop, the mortar on the bowl's surface was scraped off during the first 15 seconds of the pause and the entire mortar was scraped to one side of the bowl. After that, the mixer was run at maximum speed for an additional sixty seconds.

The generated mortar was then transferred in 40 mm × 40 mm × 160 mm steel moulds to make three mortar prisms at a go. The mortar was being filled into these steel moulds in two occasions, at first, they were half filled and compacted for 1 minute with aid of a jolting machine after which the moulds were fully filled and compacted again by a jolting machine for another 1 minute. The mortar that was on the mold's surface after it had struck off during compacting was removed by wiping it off.

The mould was then removed from the jolting machine and placed inside the humidity cabinet set at (20 ± 2) ℃ temperature and humidity above 95 % for 24 hours after which it was removed and demoulded. The prisms were then cured in distilled water maintained at (25 ± 10) ℃ temperature with the 40×40 mm side as the base for 3,7,28 and 56 days. This procedure was repeated for all the cement categories and the control samples.

2.5. Determination of Physico-Chemical Properties

2.5.1. Normal Consistency and Setting Time of the fresh cementitious pastes

Setting times and normal consistency for PPC, OPC and blended cement samples were identified using a Vicat equipment in accordance with KS EAS 148-3:2017. An analytical balance was used to weigh 400.0 g of cement sample, which was then moved into a mixing bowl to create a crater in order to determine a standard consistency value. A trial volume of water was poured into the crater using a burette.

For 240 seconds, the cement and water were mixed uniformly in an automatic mixer (model number: JB/T10391-2008). A setting time Vicat's Mold, which had been put on a lightly oiled plane metallic base plate, was then immediately filled with the resulting fresh cement paste without being overly compacted. To make the paste's upper surface level with the top of the mold, it was smoothened off.

The plunger was then lowered to rest on the base plate to be utilized and the pointer was adjusted to read zero on the scale, allowing the Vicat apparatus to be calibrated with the plunger attached prior to the test. To prevent initial velocity or forced acceleration of the moving components, the plunger was elevated to a standby position for two seconds. The plunger was then let to enter the center of the paste vertically after the moving pieces were promptly withdrawn. Four seconds after zero time, the plunger was released. Once penetration had stopped, the scale was read.

Together with the paste's water content, the scale reading which showed the separation between the plunger's bottom phase and the base plate was noted and converted to a percentage by cement mass. As soon as penetration was achieved, the plunger was cleaned. Pastes with varying water concentrations were used to repeat the test until one was discovered to create a 6 mm gap between the plunger and base plate. This procedure was used for every kind of cement.

Normal consistency and setting time were done in the same way. Only the application of the needle for the setting time differed from the usual uniformity. On a Vicat mold that was filled with paste of the established standard consistency, the Vicat needles for both initial and final setting times were applied in compliance with the guidelines.

2.5.2. Water Sorptivity Test

This test was conducted using the method outlined in ASTM C 1585-04. After 28 days of curing, test mortar prisms were dried for 24 hours in an oven set to 105 °C. The test prisms were then submerged in water of 5mm level height above the base of test mortar prisms with the 40 mm × 40 mm facing downwards at a regular interval of 0.25 hours, 0.5 hours, 1 hour, 1.5 hours, 3 hours, 5 hours, 8 hours, 24 hours, 72 hours, 96 hours, 120 hours, 144 hours and 168 hours. Each mortar prism was taken out after every interval and fresh weight determined after drying the submerged surface with a clean towel. This process was repeated across all the test mortars up to 168th hour. The sorptivity coefficient (k) was obtained graphically using Equation 1 by plotting Q/A against $\sqrt{t}$.

$$\frac{Q}{A} = Kt^{\frac{1}{2}} \quad (1)$$

Q represents amount of water absorbed in grams, A is the cross-area of the mortar in contact with water in cm^2 and t is the amount of time of exposure in hours.

2.6. Microstructural Characterization (Limitation)

Microstructural analysis using techniques such as Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) was not conducted in this study due to resource constraints. However, these techniques are commonly used to validate pore refinement and hydration phase development in blended cements. Previous studies (Hewlett & Liska, 2019; Huang *et al*., 2022) have shown that the inclusion of pozzolanic and filler materials leads to microstructural densification, reduced porosity and improved hydration. Future work should incorporate SEM and XRD characterization to directly confirm the microstructural changes suggested by the observed improvements in normal consistency, setting time and sorptivity.

3. Results and Discussion

3.1. Normal Consistency of the fresh cementitious pastes

Table 1 provides the regular consistency values for Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC) and blended cement specimens where OPC was partially replaced by stone-cutting dust (SD), Limestone (L) and natural pozzolana (NP) at various percentages. The values are presented as mean ± standard deviation (%).

Table 1. Normal Consistency (NC) for all categories of test samples

Sample	Normal Consistency % (Mean ± SD)	Sample	Normal Consistency % (Mean ± SD)
OPC	28.0± 0.50	PPC	34. 0± 0.125
5% L	28.0 ± 0.5	(10%SD+5%L+10%NP) A	30.0 ± 0.50
10% L	29.0 ± 0.5	(15%SD+5%L+5%NP) B	31.0 ± 0.50
15% L	30.0 ± 0.5	(5%SD+5%L+15%NP) C	30.0 ± 0.875
20% L	31.0 ± 0.5	(5%SD+10%L+15%NP) D	32.0 ± 0.50
10% SD	30.0± 0.5	(10%SD+10%L+10%NP) E	31.0 ± 0.875
20% SD	31.0 ± 0.5	(15%SD+10%L+5%NP) F	32.0 ± 0.875
25% SD	32.0 ± 0.5	(5%SD+10%L+20%NP) G	33.0 ± 0.50
30% SD	33.0 ± 0.5	(10%SD+10%L+15%NP) H	33.0 ± 0.00
35% SD	34.0 ± 0.5	(15%SD+10%L +10%NP) I	33.0 ± 0.875
40% SD	35.0 ± 0.5	(20%SD +10%L+5%NP) J	34.0 ± 0.00
10% NP	30.0 ± 0.50	(5%SD+15%L+20%NP) K	35.0 ± 0.50
20% NP	31.0 ± 0.50	(10%SD+15%L+15%NP) L	34.0 ± 0.50
25% NP	31.0± 0.875	(15%SD+15%L+10%NP) M	34.0 ± 0.875
30% NP	32.0 ± 0.50	(20%SD+15%L+5%NP) N	35.0 ± 0.00
35% NP	32.0 ± 0.875		
40% NP	33.0 ± 0.50		

Based on the findings in Table 1, OPC paste presented a low normal consistency compared to PPC paste. The porous nature of natural pozzolana present in PPC was the cause of high water demand (Ulusu *et al*., 2023). The NP particles' micro-pores enhance water uptake, thus increasing normal consistency in PPC mixtures. Several authors have made similar observations (Gowda & Muktha, 2016; Sahoo *et al*., 2016; Mutitu *et al*., 2019).

Substituting OPC with limestone resulted in to increase in normal consistency (Table 1). As the substitution dosage increased, the normal consistency (NC) values increased further. At 5% there was no difference in normal consistency as compared to OPC. However, at 10% to 20% substitution, there was a difference in normal consistency as compared to OPC. In contrast, when compared to PPC, the normal consistency values were lower. Limestone acts as a filler at lower substitution levels (5%), leading to similar properties as pure OPC (Panesar & Zhang, 2020). Bentz et al. (2017) reported a similar observation and attributed this effect to limestone acting as a nucleating agent that accelerates the hydration process, leading to improved workability.

Substituting OPC with stone-cutting dust resulted in to increase in normal consistency. The higher the substitution, the higher the increase in normal consistency (Table 1). The finer particles in stone-cutting dust enhance the packing density of the cement matrix, leading to a more cohesive mixture, which contributes to higher normal consistency (Raj & Somasundaram, 2021). The same observation can also be attributed to pozzolanic properties in stone-cutting dust that facilitate chemical reactions which lead to the formation of calcium silicate hydrates (C-S-H), improving workability of the mixture (Shyam Prakash & Rao, 2016).

Normal consistency increased when OPC was substituted with natural pozzolana (NP) of volcanic tuff origin. The higher the substitution, the higher the increase in normal consistency (Table 1). As the substitution dose increased, there was increase in normal consistency values apart from 20% to 25% and at 30% to 35% where the difference was not significant. The increase in normal consistency can be attributed to irregular shape and higher microporous qualities of natural pozzolana. Similar findings were reported by Mohsen et al. (2023).

Substituting OPC with a mixture of stone-cutting dust (SD), limestone (L) and natural pozzolana (NP) while optimizing the ratios, the mixtures in Table 1 which contained higher proportions of stone-cutting dust and natural pozzolana, demonstrated higher normal consistency values. This suggests that these combinations effectively balance the contributions of stone-cutting dust, limestone and natural pozzolana to enhance workability. In contrast, mixtures with lower natural pozzolana and stone-cutting dust content yielded lower NC values. Notably, all mixtures exhibited Normal consistency values higher than that of OPC. The finer particles in stone-cutting dust enhance the packing density of the cement matrix, thereby improving workability and increasing water demand for achieving normal consistency. Also, the higher content of natural pozzolana generally correlates with higher normal consistency due to its porous nature. Similar observations have been reported by various researchers who attributed these findings to the microporous structure of natural pozzolana which affects normal consistency and limestone's role as a nucleating agent that accelerates hydration processes, potentially leading to enhanced workability (Mohsen *et al*., 2023; Suliman *et al*., 2020). ANOVA results indicated statistically significant differences ($p < 0.05$) in normal consistency across the blends compared to OPC and PPC, confirming that the observed increases were not due to random variation.

3.2. Setting time of the fresh cementitious pastes

Table 2 summarizes the initial setting time (IST) and final setting time (FST) values for Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC) and several blended cements incorporating stone-cutting dust (SD), limestone (L) and natural pozzolana (NP). The table indicates that OPC replacement by these supplementary materials tends to result in increased IST and FST, especially at higher levels of replacement. OPC and low-percentage L blends have the shortest setting times, whereas high SD and NP blends and ternary mixtures show very prolonged setting.

OPC cementitious paste exhibited shorter initial and final setting time than PPC. The high content of tri-calcium silicate (C_3S) and tri-calcium aluminate (C_3A) phases in OPC was attributed to the effect of shorter setting times. C_3S and C_3A phase reacts fast and exothermically, upon contact with water. The increased reaction temperature speeds up both hardening and setting of OPC by raising the temperature range in which fast setting happens (Xie *et al*., 2022). The pozzolanic materials in PPC partially replaces C3S and C3A responsible for shorter setting time as well as lowering setting temperatures. It has also been discovered that temperature reduction in PPC retard the PPC's setting time. Additionally, high water demand in pozzolanic cement reduces the cement paste's cohesiveness, which lengthens the setting time (Soriano *et al*., 2013; Feng *et al*., 2019).

Blending OPC with limestone resulted to an increase in initial and final setting time. An increase in setting time as the substitution level increased was observed (Table 2). There was no significance difference in initial and final setting times as compared to OPC at 5%. As an inert filler, limestone can enhance particle packing and provide hydration products with sites to nucleate (Bentz *et al*., 2017). This effect may slightly accelerate hydration at lower replacement levels (5%), resulting to similar properties as OPC. However, the setting times differed from OPC at 10% to 20% substitution. As the limestone content increases beyond 5%, the inert nature of limestone becomes more distinct, resulting to longer setting times due to dilution effect and decreased reactivity (Poudyal *et al*., 2021).

Table 2. Setting Times for all categories of test samples

Sample	IST	FST
OPC	100	180
5% L	100	180
10% L	115	195
15% L	120	198
20% L	130	200
10% SD	115	210
20% SD	140	225
25% SD	170	230
30% SD	195	245
35% SD	198	258
40% SD	255	260
10% NP	115	210
20% NP	140	225
25% NP	145	228
30% NP	190	240
35% NP	192	245
40% NP	250	255
PPC	180	240
(10%SD+5%L+10%NP) A	140	225
(15%SD+5%L+5%NP) B	150	230
(5%SD+5%L+15%NP) C	145	228
(5%SD+10%L+15%NP) D	190	240
(10%SD+10%L+10%NP) E	185	238
(15%SD+10%L+5%NP) F	191	242
(5%SD+10%L+20%NP) G	192	245
(10%SD+10%L+15%NP) H	192	242
(15%SD+10%L +10%NP) I	193	245
(20%SD +10%L+5%NP) J	194	245
(5%SD+15%L+20%NP) K	210	252
(10%SD+15%L+15%NP) L	200	250
(15%SD+15%L+10%NP) M	250	255
(20%SD+15%L+5%NP) N	252	258

Substituting OPC with stone-cutting dust exhibited an increase in initial and final setting times with increasing stone-cutting dust replacement. Stone-cutting dust can improve particle packing at lower replacement levels (10%), which can lead to a slight acceleration in hydration kinetics resulting in relatively stable setting times. Nevertheless, as the replacement level increases beyond 10%, the reactive components of OPC (C3S and C3A) are being replaced, indicating a progressive slowing of hydration which results to longer initial and final setting times (Saxena *et al.*, 2016). Similar findings were attributed to dilution effects elsewhere (Krishna & Azaruddin, 2018).

Substituting OPC with natural pozzolana (NP) exhibited a similar trend to stone-cutting dust. An increase in setting time as the substitution level increased was observed (Table 2). The irregular structure and higher microporous properties of natural pozzolana require more water to maintain workability, which can further slowdown hydration kinetics and lead to longer setting times, especially at higher replacement levels. Conversely, lower percentages may enhance workability (Bayiha *et al*., 2023; Waghmare *et al*., 2021).

Substituting OPC with a mixture of stone-cutting dust (SD), limestone (L) and natural pozzolana (NP) while optimizing the ratios resulted in a distinct trend where higher proportions of stone-cutting dust and natural pozzolana resulted longer initial and final setting durations. High natural pozzolana compositions in mixtures result in longer setting times since hydration requires more water to activate the porous microstructure. The increase in water demand prolongs the setting period. An increase in stone-cutting dust content within the mixture diminishes the available OPC reactive components which in turn delays hydration processes (Mohsen *et al.*, 2023; Fode *et al.*, 2024; Kupwade-Patil *et al.*, 2018). Statistical analysis showed that setting time differences between OPC and high-level SCM blends were significant ($p < 0.05$). However, at lower replacement levels (≤10% LS), the variation was not statistically significant, supporting the conclusion that limestone at low dosages behaves similarly to OPC.

3.3. Water Sorptivity

Water sorptivity was determined as described in section 2.5.2 and the sorptivity coefficient was determined using equation 2.1. The results are discussed in the following subsections.

3.3.1. The controls

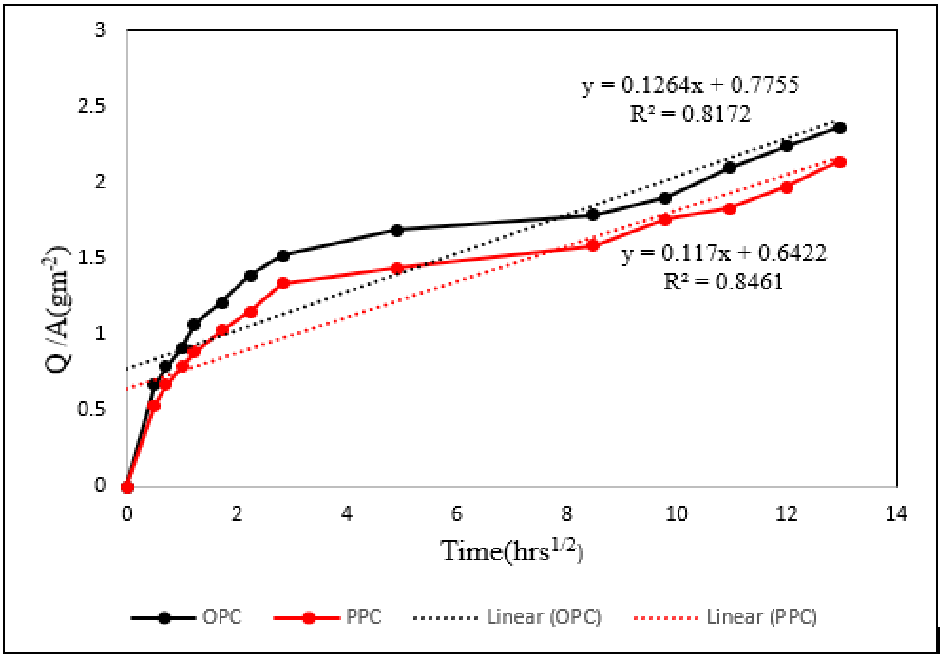

Figure 2. Comparison of sorptivity between OPC and PPC, showing cumulative water uptake (Q/A, g/cm^2) versus √time (hr$^{1/2}$)

The sorptivity plot for OPC and PPC demonstrates the distinct difference in water absorption behavior among these two cements. The plot presented here is the cumulative water uptake (Q/A) against the square root of time and is the conventional way to assess capillary action in cementitious materials. Both OPC and PPC exhibit a general sorptivity characteristic, early marked rise and subsequent gradual plateauing in absorption. Yet throughout the period under investigation, the OPC curve comes above the PPC curve to reflect greater water absorption.

Quantitatively, the OPC sorptivity coefficient is 0.1264 gm/cm^2/hr$^{0.5}$ and that of PPC is slightly lower at 0.117 gm/cm^2/hr$^{0.5}$. While numerically small, this difference is significant on the durability front. A lower sorptivity coefficient indicates that PPC absorbs water more slowly and this implies that PPC has a denser microstructure with fewer capillary pores that are interconnected. This is what is to be expected from PPC based on existing literature. The pozzolanic material in PPC, like fly ash or natural pozzolana, reacts with lime to form extra amounts of calcium silicate hydrate (C-S-H), which seals the pores and makes the pore structure finer.

This improvement lowers the rate with which water can pass through the matrix. Thus, the resistance to moisture penetration and overall durability is increased. Buildings constructed using PPC are thus more durable to degradation by wetting and drying cycles, freeze-thawing conditions and chemical attack. Established sources like Monteiro et al. (2019) validate these findings such that the pozzolanic reaction lowers permeability and enhances the long-term performance of concrete. Hossain et al. (2021) and also validate that applying pozzolanic cements results in lower sorptivity and better resistance to aggressive environmental conditions.

3.3.2. Natural pozzolana

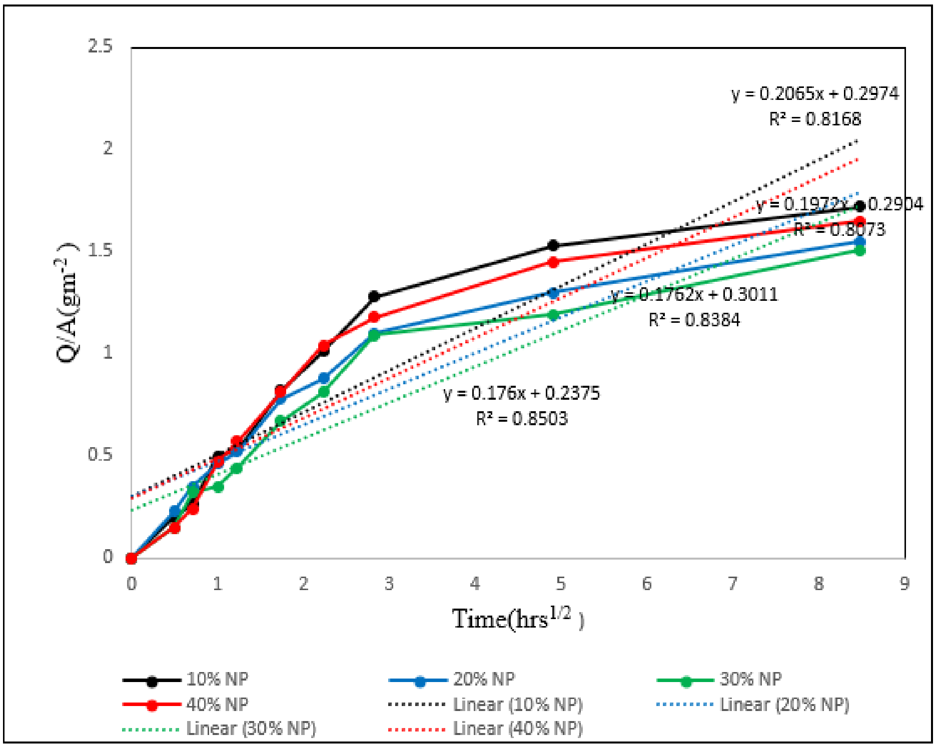

Figure 3. Sorptivity curves for OPC blended with 10-40% NP, showing cumulative water uptake (Q/A, g/cm^2) versus √time (hr$^{1/2}$)

The sorptivity graph for 10%, 20%, 30% and 40% natural pozzolana blends succinctly indicate the influence of pozzolana content on capillary water absorption with time. The cumulative uptake of water (Q/A) versus square root of time reveals that with any increase of NP content from 10% to 30%, capillary absorption of water decreases, reflecting refinement of pores. The 10% NP mixture reported the greatest sorptivity coefficient of 0.2065 gm/cm^2/hr^0. Whereas 20% and 30% NP mixture both recorded very low coefficients of 0.1762 and 0.176, respectively. This indicates that the addition of pozzolana up to these percentages had the effective effect of reducing capillary suction since the pozzolanic reaction absorbs calcium hydroxide and combines with it to produce more calcium silicate hydrate (C-S-H), which fills pores and lowers permeability.

Surprisingly, sorptivity went up again for 40% NP, with a coefficient value of 0.1972 $gm/cm^2/hr^{0.5}$, which indicates that excess pozzolana could contribute to a dilution of reactive content of OPC, hence decreasing early C-S-H development and leaving un-reacted pozzolanic particles that do not contribute to pore blocking. The graph also confirms the trend, with the 10% NP line always higher than that of the others and that of the 20% and 30% blends with the most flat slopes denoting slower and lesser water uptake.

3.3.3. Limestone

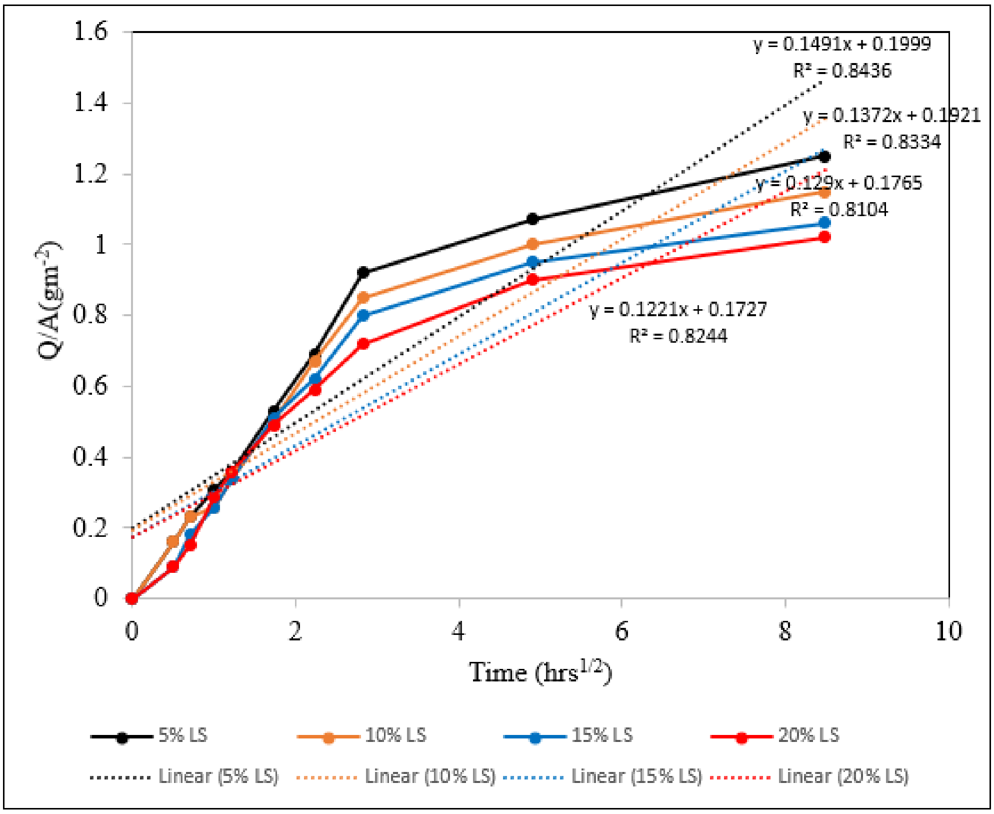

Figure 4. Water sorptivity of OPC blended with 5-20% LS, showing cumulative water uptake (Q/A, g/cm^2) versus √time ($hr^{1/2}$)

OPC blended with limestone has a noticeable trend of declining water absorption as the content of the latter increases. The sorptivity coefficient for the 5% LS mixture is 0.1491 $gm/cm^2/hr^{0.5}$, which gradually declines to 0.1372 for 10%, 0.129 for 15% and 0.1221 for 20% of the replacement. This trend has been observed from the cumulative water uptake graph, with the 5% LS plot always higher than the rest and the 20% LS mixture registering the lowest absorption throughout the duration of the test.

This decrease in sorptivity results from the filler effect of finely ground limestone that enhances the packing of the particles and limits the interconnection between pores. Even though the limestone is not pozzolanic, the physical contribution serves to densify the microstructure, thus minimizing the capillary suction channels through which the water penetrates the cement matrix. The continuous drop of sorptivity with increasing replacement percentages suggests improved durability and moisture resistance, especially with 15%-20% replacement. The evidence confirms that the addition of limestone, particularly up to 20%, effectively reduces the permeability without hampering the performance of cement, consistent with the vision of yielding a more durable and environmentally friendly binder.

3.3.4. Stone-Cutting dust

The sorptivity performance for OPC partially replaced by Stone-Cutting Dust (SCD) was assessed based on the cumulative water absorption in terms of time.

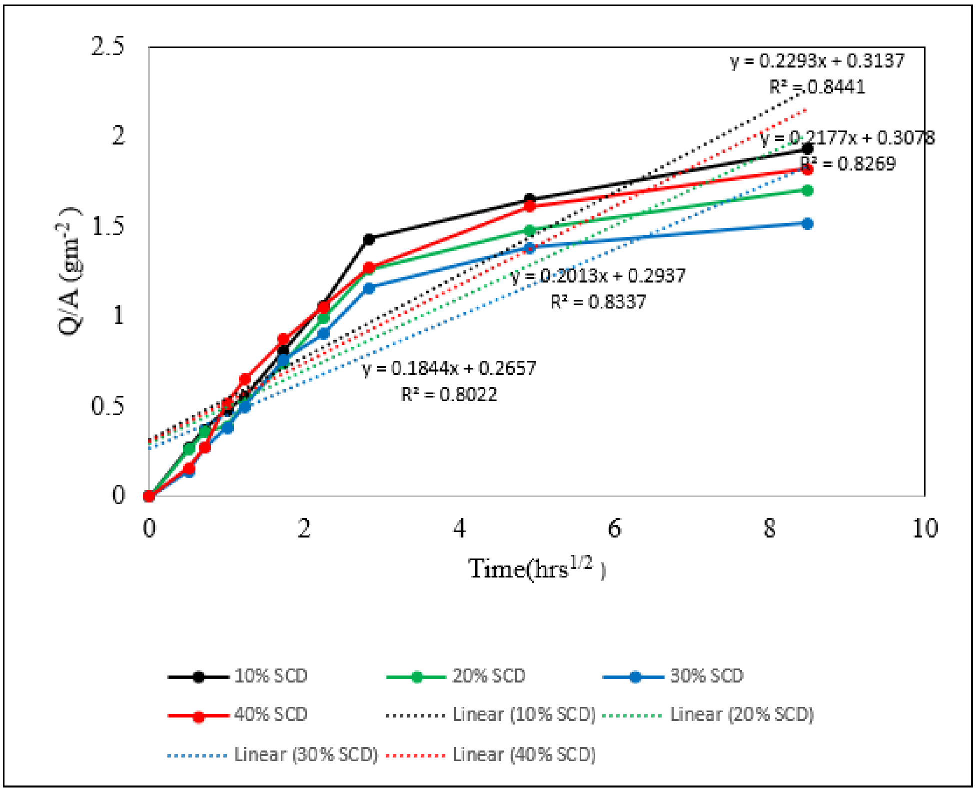

Figure 5. Water sorptivity of OPC blended with 10-40% SCD, showing cumulative water uptake (Q/A, g/cm^2) versus √time (hr$^{1/2}$)

As demonstrated in Figure 5, the results follow a non-linear pattern in regard to the SCD replacement level. The sorptivity coefficients, obtained by the slope of the linear section of the water uptake vs. √time profiles, are presented as: 0.2293 gm/cm^2/hr$^{0.5}$ for 10% SCD, 0.2177 for 40%, 0.2013 for 20% and the lowest value of 0.1844 for 30% SCD. The order 10% > 40% > 20% > 30% suggests that the greatest reduction in water absorption was achieved by using 30% replacement.

The decrease in sorptivity, more pronounced in 20% and 30% SCD content levels, is caused by the filler nature of the SCD particulates that enhance the cementitious matrix filling density and decrease the inter-connexion between the pores. Despite being an inert, non-pozzolanic material, SCD has a very fine particulate nature that enhances the refining of the pore system as well as restricts the capillary suction channels to decrease the water ingress.

Yet a slight rise in sorptivity for the 40% substitution indicates that a high level of substitution might weaken the cementitious binder and undermine the densification and the cohesion of the matrix. It represents a threshold after which the physical advantage of SCD would be counteracted by a decrease in the active cement content.

In general, the findings indicate that 20-30% SCD replacement levels have the best balance between material performance and permeability reduction. These results confirm the application of SCD as a cost-efficient and sustainable filler in cement-based composite durability improvement without the need for relying on pozzolanic.

3.3.5. Water sorptivity behavior for blended ternary mixtures of Stone-Cutting Dust (SD), Limestone (L) and Natural Pozzolana (NP)

The water sorptivity behavior of various ternary blended mixtures incorporating Stone-Cutting Dust (SD), Limestone (L) and Natural Pozzolana (NP) was assessed over a 9-hour testing period. The sorptivity values were plotted as cumulative water uptake (Q/A, g/m^2) against the square root of time (hrs$^{1/2}$).

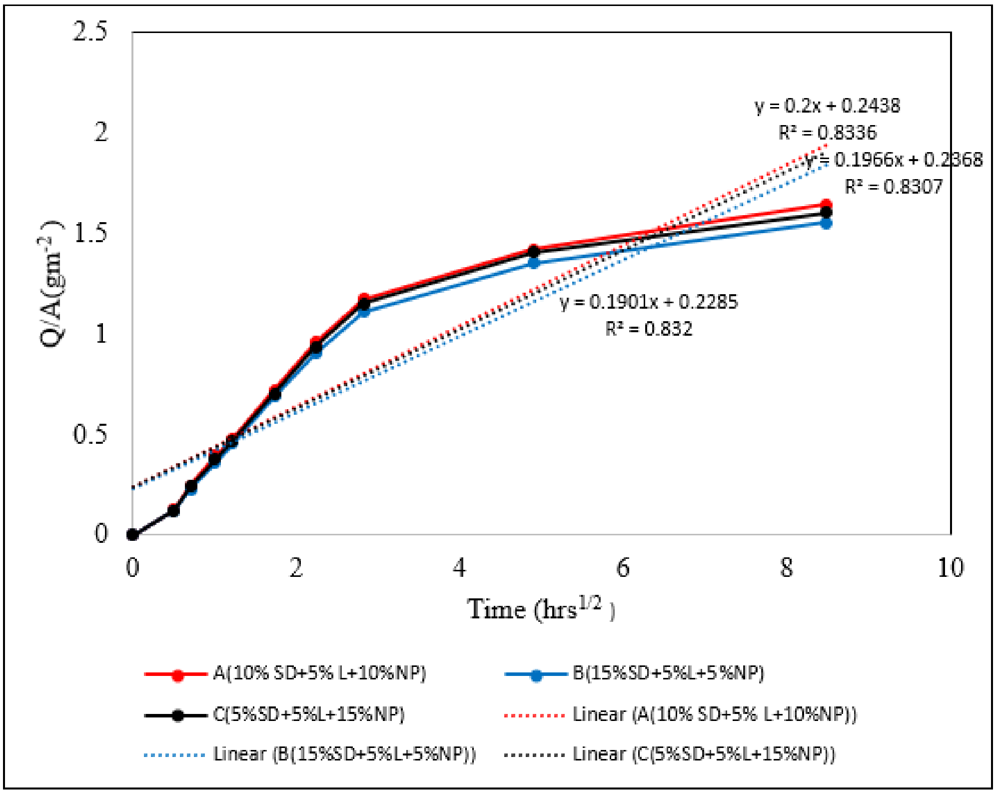

Figure 6. Sorptivity of A, B and C. Cumulative water uptake (Q/A, g/cm^2) versus √time (hr$^{1/2}$)

The cumulative water absorption characteristics of OPC ternary blends in different proportion combinations of Stone-Cutting Dust (SD), Limestone (L) and Natural Pozzolan (NP) are as shown in Figure 6. Sorptivity coefficients, quantified using the slope of the linear section of the absorption vs. √time curves, are as follows: 0.2 gm/cm^2/hr$^{0.5}$ for Mix A (10% SD + 5% L + 10% NP), 0.1901 for Mix B (15% SD + 5% L + 5% NP) and 0.1966 for Mix C (5% SD + 5% L + 15% NP). In order of absorption performance, the rankings are A > C > B and the highest rate of water uptake belongs to Mix A while the lowest permeability corresponds to Mix B.

This trend indicates a multifaceted interaction between the filler and the pozzolanic reactions of the constituents. Mix A, even though it has a well-balanced composition, exhibits the maximum sorptivity, indicating that the 10% SD content may not lead to adequate refinement of the pore network and the 10% NP cannot fully offset through pozzolanic densification. Mix B, which has more SD content (15%) and lesser NP content (5%), exhibits the lowest sorptivity, which may be due to a more efficient filler-driven refinement of the microstructure despite reduced chemical reactivity.

Mix C, which contains 15% NP and a mere 5% SD, exhibits an intermediate type of behavior. Although the pozzolanic reaction of NP contributes to densification, the reduced content of SD might decrease the physical packing efficiency to enable slightly higher water absorption capacity in comparison to Mix B.

In general, the results indicate that having a balanced filler-to-pozzolan ratio in ternary blends is important. While long-term durability does benefit through the pozzolanic reaction, the early-age physical packing effects due to inert fines such as SD will have a stronger contribution to early-age sorptivity. Therefore, Mix B seems to have the best balance of low permeability and sustainable binder composition.

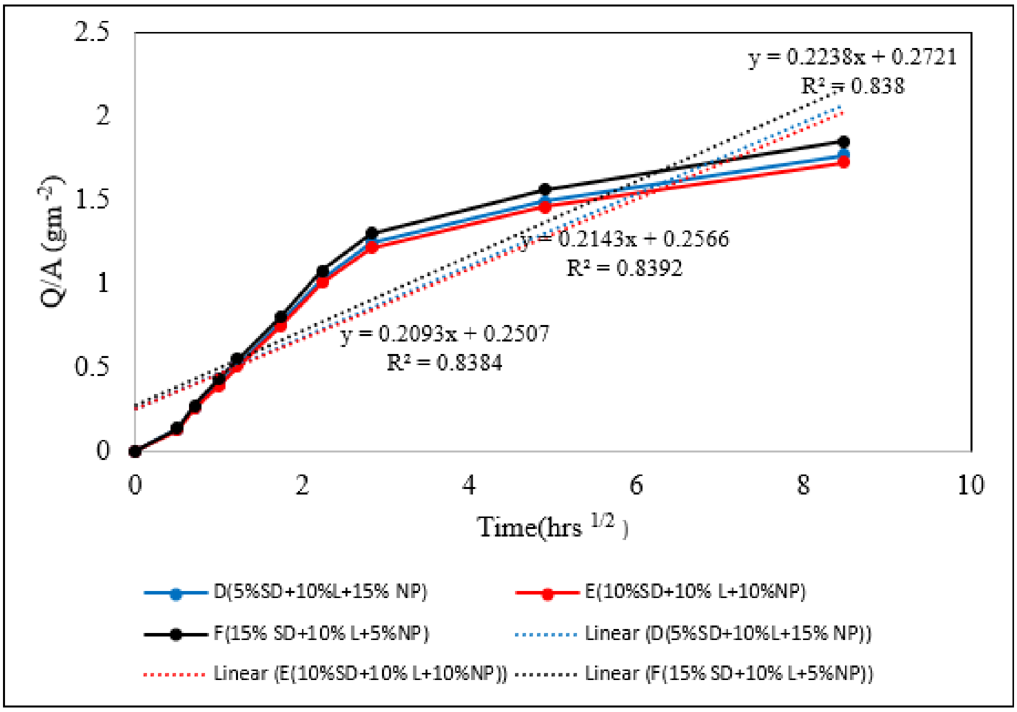

Figure 7. Sorptivity of D, E and F. Cumulative water uptake (Q/A, g/cm^2) versus √time (hr$^{1/2}$)

Figure 7 illustrates the sorptivity curve of cement blends D, E and F, which have all been modified using blends of stone-cutting dust (SD), limestone (L) and natural pozzolana (NP). Sorptivity in the form of the slope of the best linear trendline (Q/A vs. √time) indicates the rate at which water penetrates mortar samples by capillary action.

Of the three mixes, Mix F (15% SD + 10% L + 5% NP) showed the highest sorptivity value of 0.2238 g/cm^2/hr$^{1/2}$. This indicates F possessed the most porous matrix to absorb water more readily. The next was Mix D (5% SD + 10% L + 15% NP), but slightly lower in sorptivity value of 0.2143. The lowest sorptivity of 0.2093 was for Mix E (10% SD + 10% L + 10% NP). These results reveal a distinct trend in which a higher proportion of stone-cutting dust when the natural pozzolana content decreases should have a higher water absorption because of the increase in the capacity for capillary action.

This trend agrees with that reported in the existing literature. Natural pozzolana has a finer particle size, reactivity to pozzolanic reactions and pore-filling capacity, which tend to collectively lower permeability and increase durability in blended cement. Reports by Ramezanianpour et al. (2010), are in line with the fact that a higher pozzolan proportion leads to lower sorptivity due to secondary calcium silicate hydrate (C-S-H) production and a denser microstructure. Stone-cutting dust, while having some reactive silica content, has poor pozzolanic potential unless highly processed and tends to increase open porosity when in excess, as in Mix F.

Thus, the comparison between D, E and F illustrates that a balanced replacement involving a larger proportion of NP (as in Mix D) produces stronger resistance to the entry of capillary water in contrast to higher SD contents (as in Mix F). This verifies the significance of the optimization of the pozzolanic content and the study of the performance of each additive in cementitious systems.

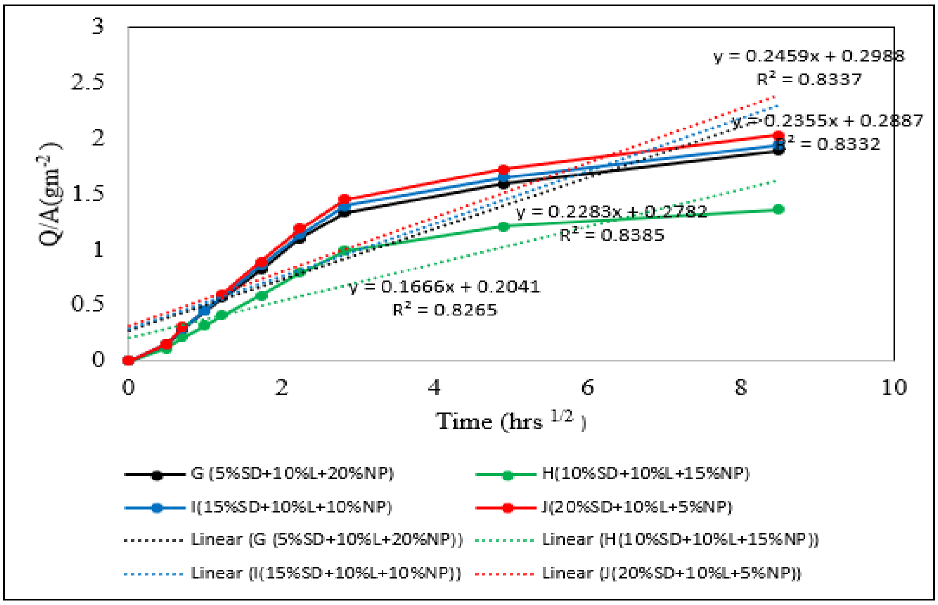

Figure 8. Sorptivity of mixes G, H, I and J with 10% LS. Mix H (10% SCD + 10% LS + 15% NP) recorded the lowest coefficient (0.1666 $g/cm^2/hr^{1/2}$), indicating improved pore refinement

Figure 8 represents the water absorption characteristics of cement blends G, H, I and J. These blends have a constant 10% limestone content while varying in content of stone-cutting dust (SD) and natural pozzolana (NP). Sorptivity or the rate of water absorption after a given duration of exposure to water was the largest for Mix J (20% SD + 10% L + 5% NP) and was equal to 0.2459 $g/cm^2/hr^{1/2}$. Such a high rate of absorption indicates the porous nature of the gel structure having a high volume of channels within the capillary system due to the poor availability of pozzolanic material and the high SD content.

Mix I (15% SD + 10% L + 10% NP) has a slightly lower sorptivity value of 0.2355, whereas Mix G (5% SD + 10% L + 20% NP) has a moderate sorptivity value of 0.2283. It is observed that Mix H (10% SD + 10% L + 15% NP) has the lowest sorptivity value of 0.1666 indicating the lowest water penetration and a denser cement paste.

The trend indicates that raising the proportion of SD while reducing the content of NP augments sorptivity due to enhanced porosity and diminished pozzolanic reaction. In contrast, the increase in NP content leads to the formation of more calcium silicate hydrate (C-S-H), which fills the pores and minimizes capillarity. This finds support in the work by Ramezanianpour et al. (2010) which established that pozzolanic content in general and particularly in optimal proportion minimizes permeability and increases the durability of blended cements. Accordingly, the data verifies that well-balanced application of NP, as in the case of Mix H, greatly enhances the resistance to water in comparison to the mixes having a higher proportion of SD.

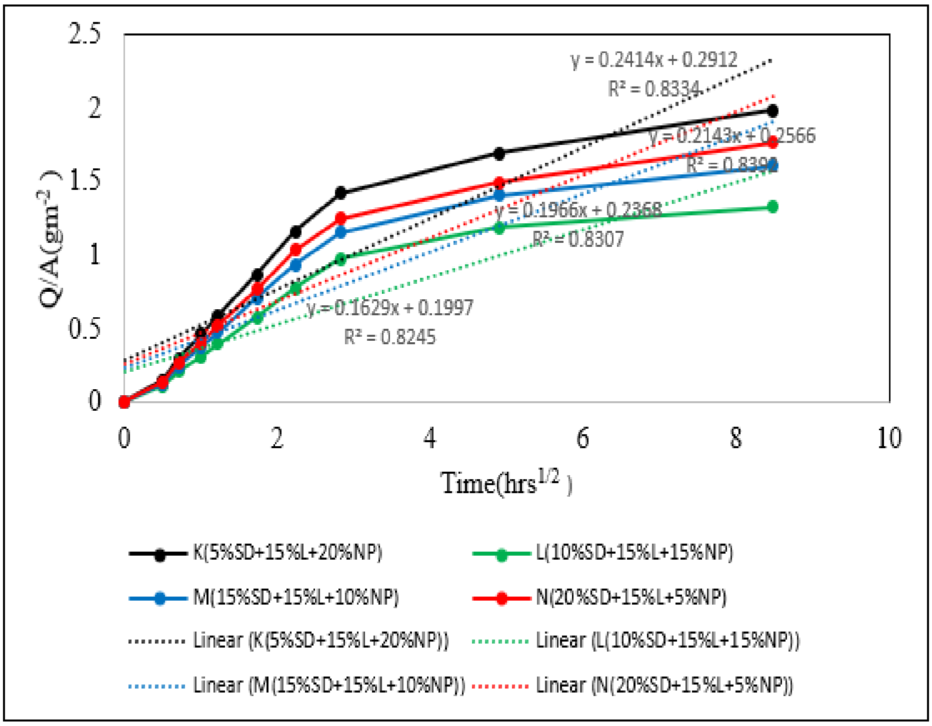

Figure 9. Sorptivity of Mixes K, L, M, N, showing cumulative water uptake (Q/A, g/cm^2) versus √time (hr$^{1/2}$)

Figure 9 presents a comparison between the sorptivity of mixes K, L, M and N, which have 15% limestone and differ in the proportion of stone-cutting dust and natural pozzolana. Mix K (5% SD + 15% L + 20% NP) has the highest sorptivity of 0.2414 g/cm^2/hr$^{1/2}$ in this group despite having a higher amount of pozzolan. This may indicate that the proportion of materials used in this mix does not blend well or that there is poor compatibility, resulting in loose or unreacted particles that facilitate the penetration of water.

Mix N (20% SD + 15% L + 5% NP) has a sorptivity of 0.2143, whereas Mix M (15% SD + 15% L + 10% NP) has 0.1966. Mix L (10% SD + 15% L + 15% NP), which has the lowest sorptivity of 0.1629, implies a more defined and closer pore structure. This trend suggests that although high NP content generally reduces sorptivity, the performance also relies on the ability to work well across the other elements. The high sorptivity in Mix K result from material incompatibility or inefficient particle arrangement in that blend ratio. However, the overall trend still reveals that Mix L, having a balanced ratio of both SD and NP, recorded the best water absorption performance. This is echoed in the literature, which outlines that best performance in ternary blends comes not only when pozzolan is maximized but also when there is proportional synergy among all materials (Villar-Cociña *et al*., 2021). The differences in sorptivity coefficients among ternary blends were also validated through ANOVA, which confirmed that Mix H (10% SCD + 10% LS + 15% NP) exhibited significantly lower sorptivity ($p < 0.05$) compared to OPC and other blends.

Beyond the physico-chemical improvements observed, partial replacement of OPC with NP, LS and SCD also offers environmental benefits. Cement production accounts for nearly 8% of global CO_2 emissions, mainly due to clinker calcination and energy consumption during production (Environment *et al*., 2018). Literature-based Life Cycle Assessments (LCA) indicate that replacing 30% of OPC with supplementary cementitious materials can reduce CO_2 emissions by 20-30% and lower energy demand by up to 25% (Oliveira *et al*., 2023; Knight *et al*., 2023). Thus, the ternary blends studied here, particularly Mix H, not only enhance durability but also contribute to sustainable construction practices in regions such as Kenya where these raw materials are abundant.

3.4. Microstructural Considerations (Limitation)

Although SEM and XRD analyses were not performed in this study, the observed reductions in water sorptivity and extended setting times are consistent with microstructural refinements reported in the literature. Hewlett and Liska (2019) and Huang et al. (2022) demonstrated that pozzolanic reactions and filler effects reduce pore connectivity and densify cement matrices. The improved performance of ternary blends, especially Mix H, therefore likely arises from similar pore structure refinement. Nonetheless, direct microstructural validation should be addressed in future investigations to strengthen these conclusions.

4. Conclusion

This study has demonstrated the feasibility and benefits of partially replacing Ordinary Portland Cement (OPC) with stone-cutting dust (SCD), limestone (LS) and natural pozzolana (NP) to improve the physico-chemical properties of cementitious materials. Results showed that incorporating these supplementary cementitious materials (SCMs), either individually or in ternary blends, significantly influenced normal consistency, setting time and water sorptivity, key indicators of workability, hydration behavior and long-term durability. Normal consistency increased across all blends due to the finer particle size and porous nature of SCD and NP, which elevate water demand. Setting times were extended in most cases, particularly with higher NP and SCD content, a desirable feature in hot climates where rapid setting is a concern. Water sorptivity decreased notably in ternary blends, especially in Mix H (10% SCD + 10% LS + 15% NP), indicating enhanced pore structure refinement and reduced permeability. Importantly, the use of these locally available materials not only improves technical performance but also contributes to sustainability by reducing OPC usage, lowering carbon emissions and promoting circular economy practices through the reuse of industrial waste such as stone-cutting dust. This approach is particularly relevant for regions like Kenya, where access to NP and SCD is widespread. Overall, this research supports the development of alternative, sustainable cement products using optimized SCM combinations. Further studies should explore long-term durability, structural performance in real-world applications and the economic implications of scaling up these blends for commercial use. In addition to performance improvements, the partial substitution of OPC with NP, LS and SCD has the potential to lower CO_2 emissions by an estimated 20-30%, reinforcing the environmental value of adopting blended cements in sustainable construction.

References

Affan, H., El Haddaji, B., Ajouguim, S. & Khadraoui, F. (2024). A review - durability, mechanical and hygrothermal behavior of building materials incorporating biomass. *Eng*, *5*(2), 992-1027. https://doi.org/10.3390/eng5020055

Amin, M.N., Khan, K., Saleem, M.U., Khurram, N. & Niazi, M.U.K. (2017). Aging and curing temperature effects on compressive strength of mortar containing lime stone quarry dust and industrial granite sludge. *Materials*, *10*(6), 642. https://doi.org/10.3390/ma10060642

Bayiha, B.N., Bahel, B., Kenmogne, F., Yemetio, U.N., Yamb, E. & Billong, N. (2023). Comparative study of the effects of a natural pozzolan and an artificial pozzolan on the hydraulic properties of Portland cement mortar. *Global Journal of Engineering and Technology Advances*, *14*(01), 107-119. https://doi.org/10.30574/gjeta.2023.14.1.0021

Bentz, D.P., Ferraris, C.F., Jones, S.Z., Lootens, D. & Zunino, F. (2017). Limestone and silica powder replacements for cement: Early-age performance. *Cement and Concrete Composites*, 78, 43-56. https://doi.org/10.1016/j.cemconcomp.2017.01.001

Cheah, C.B., Gong, Y.X. & Liew, J.J. (2025). Utilising quarry fines and GGBS as cement substitutes in mortar for enhanced performance. *Results in Engineering*, 26, 105502. https://doi.org/10.1016/j.rineng.2025.105502

Chen, Z. (2023). Environmental alternatives for stone slurry circularity: From waste to resource. Thesis, Master of Science in Building and Architectural Engineering, School of Architecture, Urban Planning and Construction Engineering.

Environment, U.N., Scrivener, K.L., John, V.M. & Gartner, E.M. (2018). Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry. *Cement and concrete Research*, 114, 2-26. https://doi.org/10.1016/j.cemconres.2018.03.015

Feng, Y., Yang, Q., Chen, Q., Kero, J., Andersson, A., Ahmed, H., ... & Samuelsson, C. (2019). Characterization and evaluation of the pozzolanic activity of granulated copper slag modified with CaO. *Journal of Cleaner Production*, 232, 1112-1120. https://doi.org/10.1016/j.jclepro.2019.06.062

Fode, T.A., Jande, Y.A.C. & Kivevele, T. (2024). Effect of natural pozzolana on physical and mechanical properties of concrete. *Advances in Civil Engineering*, *2024*(1), 3356641. https://doi.org/10.1155/2024/3356641

Gowda, B.S.K., Muktha, K. (2016). Comparative study on OPC and PPC composites with foundry sand as partial replacement for fine aggregate - an experimental approach. In *Proceedings of the Conference: Advanced Trends in Civil Engineering and Sustainable Development*, 258. https://doi.org/10.13140/RG.2.1.1227.9448

Haha, M.B., Termkhajornkit, P., Ouzia, A., Uppalapati, S. & Huet, B. (2023). Low clinker systems - towards a rational use of SCMs for optimal performance. *Cement and Concrete Research*, 174, 107312. https://doi.org/10.1016/j.cemconres.2023.107312

Hewlett, P., Liska, M. (2019). *Lea's Chemistry of Cement and Concrete*. Butterworth-Heinemann.

Hossain, M.U., Cai, R., Ng, S.T., Xuan, D. & Ye, H. (2021). Sustainable natural pozzolana concrete - a comparative study on its environmental performance against concretes with other industrial by-products. *Construction and Building Materials*, 270, 121429. https://doi.org/10.1016/j.conbuildmat.2020.121429

Huang, L., Tang, L., Löfgren, I., Olsson, N., Yang, Z. & Li, Y. (2022). Moisture and ion transport properties in blended pastes and their relation to the refined pore structure. *Cement and Concrete Research*, 161, 106949. https://doi.org/10.1016/j.cemconres.2022.106949

Ioanna Dedousi, N. (2021). The correlation of workability and mechanical strength in air lime binders with different aggregates and pozzolan. Student essay, GUPEA.

Khan, M.N.N., Jamil, M., Karim, M.R., Zain, M.F.M. & Kaish, A.B.M.A. (2017). Filler effect of pozzolanic materials on the strength and microstructure development of mortar. *KSCE Journal of Civil Engineering, 21*(1), 274-284. https://doi.org/10.1007/s12205-016-0737-5

Knight, K.A., Cunningham, P.R. & Miller, S.A. (2023). Optimizing supplementary cementitious material replacement to minimize the environmental impacts of concrete. *Cement and Concrete Composites*, 139, 105049. https://doi.org/10.1016/j.cemconcomp.2023.105049

Krishna, E.M., Azaruddin, S. (2018). Experimental investigation on partially replacements of cement and fine aggregate with stone dust and crushed fine aggregate and its effects on mechanical properties of normal strength concrete (M20). *International Research Journal of Engineering and Technology (IRJET), 5*(7), 2445.

Kupwade-Patil, K., Chin, S., Ilavsky, J., Andrews, R.N., Bumajdad, A. & Büyüköztürk, O. (2018). Hydration kinetics and morphology of cement pastes with pozzolanic volcanic ash studied via synchrotron-based techniques. *Journal of Materials Science*, *53*(3), 1743-1757. https://doi.org/10.1007/s10853-017-1659-4

Luo, T., Hua, C., Li, L., Zhang, T., Lu, X., Li, L.G. & Mostafa, S.A. (2024). The effect of micro silica fume (MSF) content on pore fractal dimension (PFD) and mechanical properties of self-consolidating concrete. *Case Studies in Construction Materials*, 21, e04065. https://doi.org/10.1016/j.cscm.2024.e04065

Maddalena, R. (2018). Synthesis of calcium silicate hydrate (CSH) and novel cementitious materials: Characterisation, engineering applications and environmental aspects. Doctoral dissertation, Department of Civil and Environmental Engineering, University of Strathclyde.

Marangu, J.M., Nyabuto, A.O., Pfeiffer, T., Kruschwitz, S., Völker, C. & Schmidt, W. (2024). Sustainability potentials of the precast industry in Kenya. In *The International Conference on Net-Zero Civil Infrastructures: Innovations in Materials, Structures and Management Practices (NTZR)*, 1699-1710. https://doi.org/10.1007/978-3-031-69626-8_141

Mohsen, M.O., Aburumman, M.O., Al Diseet, M.M., Taha, R., Abdel-Jaber, M.T., Senouci, A., & Abu Taqa, A. (2023). Fly ash and natural pozzolana impacts on sustainable concrete permeability and mechanical properties. *Buildings*, *13*(8), 1927. https://doi.org/10.3390/buildings13081927

Monteiro, P.J., Geng, G., Marchon, D., Li, J., Alapati, P., Kurtis, K.E. & Qomi, M.J.A. (2019). Advances in characterizing and understanding the microstructure of cementitious materials. *Cement and Concrete Research*, 124, 105806. https://doi.org/10.1016/j.cemconres.2019.105806

Mutitu, K.D., Munyao, M.O., Wachira, M.J., Mwirichia, R., Thiong'o, K.J. & Marangu, M.J. (2019). Effects of biocementation on some properties of cement-based materials incorporating Bacillus species bacteria - a review. *Journal of Sustainable Cement-Based Materials, 8*(5), 309-325. https://doi.org/10.1080/21650373.2019.1640141

Navarrete, I., Valdes, J., Lopez, M. & Vargas, F. (2023). Replacement of pozzolanic blended cement by supplementary cementitious materials: Mechanical and environmental approach. *Construction and Building Materials*, 394, 132263. https://doi.org/10.1016/j.conbuildmat.2023.132263

Ngui, F., Muhammed, N., Mutunga, F.M., Marangu, J. & Kınotı, I.K. (2022). A review on selected durability parameters on performance of geopolymers containing industrial by-products, agro-wastes and natural pozzolan. *Journal of Sustainable Construction Materials and Technologies*, *7*(4), 375-400. https://doi.org/10.47481/jscmt.1190244

Oliveira, D.R.B., Leite, G., Possan, E. & Marques Filho, J. (2023). Concrete powder waste as a substitution for Portland cement for environment-friendly cement production. *Construction and Building Materials*, 397, 132382. https://doi.org/10.1016/j.conbuildmat.2023.132382

Panesar, D.K., Zhang, R. (2020). Performance comparison of cement replacing materials in concrete: Limestone fillers and supplementary cementing materials - a review. *Construction and Building Materials*, 251, 118866. https://doi.org/10.1016/j.conbuildmat.2020.118866

Poudyal, L., Adhikari, K. & Won, M. (2021). Mechanical and durability properties of Portland limestone cement (PLC) incorporated with nano calcium carbonate ($CaCO_3$). *Materials, 14*(4), 905. https://doi.org/10.3390/ma14040905

Raj, I.S., Somasundaram, K. (2021). Sustainable usage of waste materials in aerated and foam concrete: A review. *Civil Engineering and Architecture*, *9*(4), 1144-1155. https://doi.org/10.13189/cea.2021.090416

Ramezanianpour, A.A., Ghiasvand, E., Nickseresht, I., Moodi, F. & Kamel, M.E. (2010). Engineering properties and durability of concretes containing limestone cements. In *2nd International Conference on Sustainable Construction Materials and Technologies*, Ancona, Italy, 12.

Sahoo, K.K., Sathyan, A.K., Kumari, C., Sarkar, P. & Davis, R. (2016). Investigation of cement mortar incorporating Bacillus sphaericus. *International Journal of Smart and Nano Materials, 7*(2), 91-105. https://doi.org/10.1080/19475411.2016.1205157

Santana, J.J., Rodríguez-Brito, N., Blanco-Peñalver, C., Mena, V.F. & Souto, R.M. (2022). Durability of reinforced concrete with additions of natural pozzolans of volcanic origin. *Materials*, *15*(23), 8352. https://doi.org/10.3390/ma15238352

Saxena, P., Singh, R.P., Agrahari, S.K. & Singh, N.H. (2016). Use of stone dust & granite powder as a partial replacement of cement. *International Journal of Engineering Research and Application, 6*(6), 75-77.

Shyam Prakash, K., Rao, C.H. (2016). Study on compressive strength of quarry dust as fine aggregate in concrete. *Advances in Civil Engineering*, *2016*(1), 1742769. https://doi.org/10.1155/2016/1742769

Soriano, L., Monzó, J., Bonilla, M., Tashima, M.M., Payá, J. & Borrachero, M.V. (2013). Effect of pozzolans on the hydration process of Portland cement cured at low temperatures. *Cement and Concrete Composites*, 42, 41-48. https://doi.org/10.1016/j.cemconcomp.2013.05.007

Srinivas, D., Dey, D., Panda, B. & Sitharam, T.G. (2022). Printability, thermal and compressive strength properties of cementitious materials: A comparative study with silica fume and limestone. *Materials*, *15*(23), 8607. https://doi.org/10.3390/ma15238607

Suliman, M.O., Masoud, T., Abuaddous, M.Y. & Alsharie, H. (2020). Effect of stone cut powder and limestone powder on the properties of Portland pozzolan cement concrete. *International Journal of Advanced Research in Engineering and Technology (IJARET), 11*(12), 2427-2436. https://doi.org/10.34218/IJARET.11.12.2020.229

Ulusu, H., Aruntaş, H.Y., Gültekin, A.B., Dayı, M., Çavuş, M. & Kaplan, G. (2023). Mechanical, durability and microstructural characteristics of Portland pozzolan cement (PPC) produced with high volume pumice: Green, cleaner and sustainable cement development. *Construction and Building Materials*, 378, 131070. https://doi.org/10.1016/j.conbuildmat.2023.131070

Villar-Cociña, E., Frías, M., Savastano, H., Rodier, L., Sánchez de Rojas, M.I., Sáez del Bosque, I.F. & Medina, C. (2021). Quantitative comparison of binary mix of agro-industrial pozzolanic additions for elaborating ternary cements: Kinetic parameters. *Materials, 14*(11), 2944. https://doi.org/10.3390/ma14112944

Waghmare, J.D., Patil, S.S., Patil, S.M. & Maske, M. (2021). Study and review of properties and applications of Portland pozzolana cement. *ASEAN Journal of Science and Engineering, 1*(1), 13-18. https://doi.org/10.17509/ajse.v1i1.37980

Wang, D., Shi, C., Farzadnia, N., Shi, Z., Jia, H. & Ou, Z. (2018). A review on use of limestone powder in cement-based materials: Mechanism, hydration and microstructures. *Construction and Building Materials*, 181, 659-672. https://doi.org/10.1016/j.conbuildmat.2018.06.075

Xie, G., Jingwei, G., Gong, J., Jin, Q., Gong, M. & Jiang, C. (2022). Competitive hydration between C3a and C3s in the rapid dissolution stage affects the hydration of low-heat Portland cement blended pastes. *SSRN Journal*, 23. https://doi.org/10.2139/ssrn.4196940

Zahir, M.H., Irshad, K., Shafiullah, M., Ibrahim, N.I., Islam, A.K., Mohaisen, K.O. & Sulaiman, F.A.A. (2023). Challenges of the application of PCMs to achieve zero energy buildings under hot weather conditions: A review. *Journal of Energy Storage*, 64, 107156. https://doi.org/10.1016/j.est.2023.107156