A Review of the Engineering Properties of Concrete with Paper Mill Waste Ash — Towards Sustainable Rigid Pavement Construction

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REVIEW PAPER

A Review of the Engineering Properties of Concrete with Paper Mill Waste Ash — Towards Sustainable Rigid Pavement Construction

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Abstract
The drastic surge in urbanisation and construction-related activities is increasing the demand for cement and aggregates, especially for concrete production. Concrete is utilised for a wide variety of structural applications, including rigid pavements construction, due to its superior strength and durability performance. However, the production of cement increases carbon footprint; and the source of natural aggregates depletes. Hence, there is an increased demand for pavement designs that incorporate sustainable materials and maintain a consistent level of service. In rigid pavements construction, this can be achieved with the integration of alternate binder systems, such as paper mill ash (PMA). This paper presents a systematic review of the engineering properties of PMA as a partial cement replacement material for sustainable concrete production. The review is focused on the influence of PMA on the engineering properties of concrete. The main advantages and limitation of using PMA were highlighted and discussed. Grey areas for possible research exploit were also identified. Based on the superior tensile strength (2.68–3.98 MPa) and flexural strength (4.04–5.01 MPa) documented in the various works of literature reviewed, it can be concluded that PMA is a feasible alternative binder material for rigid pavement applications. This, coupled with its negligible CO_{2e} emission value, indicate that PMA is beneficial to the sustainability and serviceability states of rigid pavements. The viewpoint of this review will be useful for researchers and stakeholders in the construction industry to acquire more understanding of PMA concrete.

Keywords Supplementary cementitious materials · Rigid pavements · Sustainability · Paper mill ash

1 Introduction

Concrete is the most used material in the construction sector, owing to its superior mechanical properties (versatility, superior strength and durability properties). Approximately, more than 1 m^3 of concrete is evaluated to be produced universally per individual every year [1]. The cement manufacturing industry accounts for about 5 to 7% of the total carbon dioxide (CO_2) emissions worldwide [1–3]. In 2020, the global annual cement production is expected to be 5.9 billion tons with more than 4.8 billion tons of CO_2 production [4]. Other harmful greenhouse gases such as sulphur trioxide (SO_3) and nitrogen oxides (NO_X) are also emitted during the cement manufacturing process and can have a detrimental effect on the environment. In addition to releasing harmful compounds into the atmosphere, the production of portland cement PC consumes significant quantities of raw materials and energy.

Concrete pavements, more commonly known as rigid pavements, are used predominantly in roadways and for other transportation applications such as parking lots, bridge decks, ports, airport aprons, toll stations and military facilities [5, 6]. Di Mascio et al. [7] revealed that rigid pavements are 35% cheaper than flexible pavements over the service life of 20 years and are more suitable for areas with weak subgrade soil and poor drainage conditions [8]. According to Jiao [9], fuel consumption decreases by 3.2% for passenger vehicles and 4.5% for heavy vehicles while operating on rigid pavements. Also, there is a lower emission of CO_2. Based on these benefits, most of the national highways and expressways are being constructed as rigid pavements [8]. The total proclaimed

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roads in South Africa amounts to approximately 535,000 km in length, with 366,872 km classified as non-urban roads and 168,000 km categorised as urban roads [10]. It has been well documented that the pavement structure of numerous roadways within South Africa's ever-expanding road network are experiencing rapid mechanical and physical deterioration. This results in the reduction of the functional and structural levels of service provided by the roadway [11]. Anderson et al. [12] attribute this to poor design and construction practices, increased traffic volumes, inadequate materials selection and a service life that is higher than the design life.

Plati [5] reported that high bearing capacity, resistance to static and dynamic vehicular loading and long-term durability are the most important mechanical characteristics of rigid pavements. It is also established that rigid pavements achieve an improved service life and reduced maintenance costs when the available design guidelines and correct construction practices are followed [8, 11]. Large quantities of PC and aggregates are utilised during the construction of rigid pavements. However, the production of cement increases carbon footprint; and the source of natural aggregates depletes [13, 14]. The construction of rigid pavements comes at the expense of the environment [8]. Therefore, a pavement design that incorporates sustainable materials and achieves a consistent level of quality is one of the primary goals for improving the sustainability of rigid pavements. Besides, there is an increased demand for alternate binder systems to address the growing concerns regarding the CO_2 emissions from the cement manufacturing [2–4, 8, 15]. The amount of cement being manufactured for concrete production purposes can be reduced by incorporating supplementary cementitious binder materials, such as paper mill ash (PMA).

In 2014, global paper production exceeded 400 million tonnes per year, which was also the year that atmospheric CO_2 levels surpassed 400 ppm [16]. Environmental Paper Network [16] reported that Africa consumes 2% of the total paper produced on a global scale, which is equivalent to approximately 8 million tonnes per year. As of 2018, South Africa had consumed 2.344 million tonnes of paper, which increased by 4% in comparison with 2017s consumption levels [17]. South Africa is the 15th largest producer of pulp in the world and is ranked 24th when it comes to global paper production [18]. However, PMA is still a relatively new binder material to South Africa's concrete industry.

The use of PMA, as a partial cement replacement material in concrete production significantly affects the performance of concrete (Table 1). In order to use such concrete in rigid pavement construction, it is vital to understand its engineering properties thoroughly. Therefore, this systematic review aims to consolidate the existing research findings from reported studies to gain more understanding on the performance of concrete containing PMA as an alternative binder material, with a focus on its engineering properties and structural behaviour. The engineering properties under consideration comprised of the fresh state, mechanical and durability properties.

2 Methodology and Material Properties of Paper Mill Ash

First, a rigorous search of published research articles on the use of PMA, as alternative binder material for concrete production, from different peer-reviewed sources, was carried out. Major search engines (ScienceDirect and Google Scholar) were used. The focus was on literature published on PMA as an alternative binder material. The articles were selected based on their relevance to this review. Note that the number of citations of individual articles was not used as a selection criterion. The second step was the collection and categorisation of the relevant articles into those dealing with the fresh state, mechanical and durability properties of concrete (Table 1, Fig. 1). The various engineering properties discussed in the collected research articles were carefully extracted. After that, each engineering property was thoroughly reviewed from the numerous collected articles, including the findings and conclusions arrived by the authors. The differences or similarities were identified and discussed extensively. Therefore, this contribution can be used as a valuable source of data for researchers for their future studies and guide stakeholders in the construction industry, since it critically summarises the recent findings on the use of PMA in concrete. The contribution is divided into six sections. Section 2 discusses the methodology and the material properties of PMA, including its manufacturing process, hydration process, morphology, carbon footprint and the chemical compositions. The fresh state properties of PMA concrete are reviewed in Section 3. A review of the mechanical properties such as compressive, flexural and tensile strength and shrinkage is presented in Section 4. Section 5 and 6 present the durability properties and the concluding remarks.

2.1 Manufacturing Process and Chemical Composition

Paper mill sludge is a waste product generated during the deinking and re-pulping stages in the pulp and paper manufacturing process and is often viewed as being a substantial economic and environmental problem to the pulp and paper industry [28]. Likon and Trebše [29] reported that for every unit of paper manufactured, up to 23.4% of the waste generated is classified as paper mill sludge. Over 4.7 million tonnes of paper mill sludge is produced each year by the member countries of the Confederation of European Paper

Table 1 Previous studies on the concrete properties of cement-based materials with varying amounts of paper mill ash (PMA)

Research Study	Concrete /Mortar	PMA (%)	Water-Binder Ratio	Properties Researched	Findings
[19]	Mortar	5 to 20	0.4 to 0.6	Mechanical	Compressive strength decreased as the w/b ratio increased
[20]	Mortar	20 to 100*	–	Mechanical	Low development of initial strength up until 28 days; 50% PMA-GGBS blend achieved optimum results
[21]	Concrete	5 to 15	–	Mechanical	PMA reduced the compressive strength; optimum tensile strength results for 5% PMA
[22]	Concrete	10 to 30**	0.55	Fresh	Workability decreased as the PMA content increased
				Mechanical	Strength of PMA samples are equivalent or superior to the control samples
				Durability	Water absorption results decreased as the PMA content increased
[23]	Concrete	5 to 30	–	Mechanical	Compressive strength improved up until 20% PMA
[24]	Concrete	5 to 20	–	Mechanical	10% PMA attained the optimum strength results
[25]	Mortar	10 to 20	0.5	Fresh	Workability decreased as the PMA content increased
				Mechanical	20% PMA achieved the highest results
[26]	Concrete	5 to 20	0.45	Fresh	Workability decreased as the PMA content increased
				Mechanical	5% PMA obtained the optimum results; strength decreased after 28 days
				Durability	Water absorption results increased as the PMA content increased
[27]	Concrete	30 to 70*	0.4 & 0.5	Fresh	Workability decreased as the PMA content increased
				Mechanical	50% PMA and GGBS achieved the optimum compressive strength

*blended with various proportions of ground granulated blast furnace slag (GGBS)

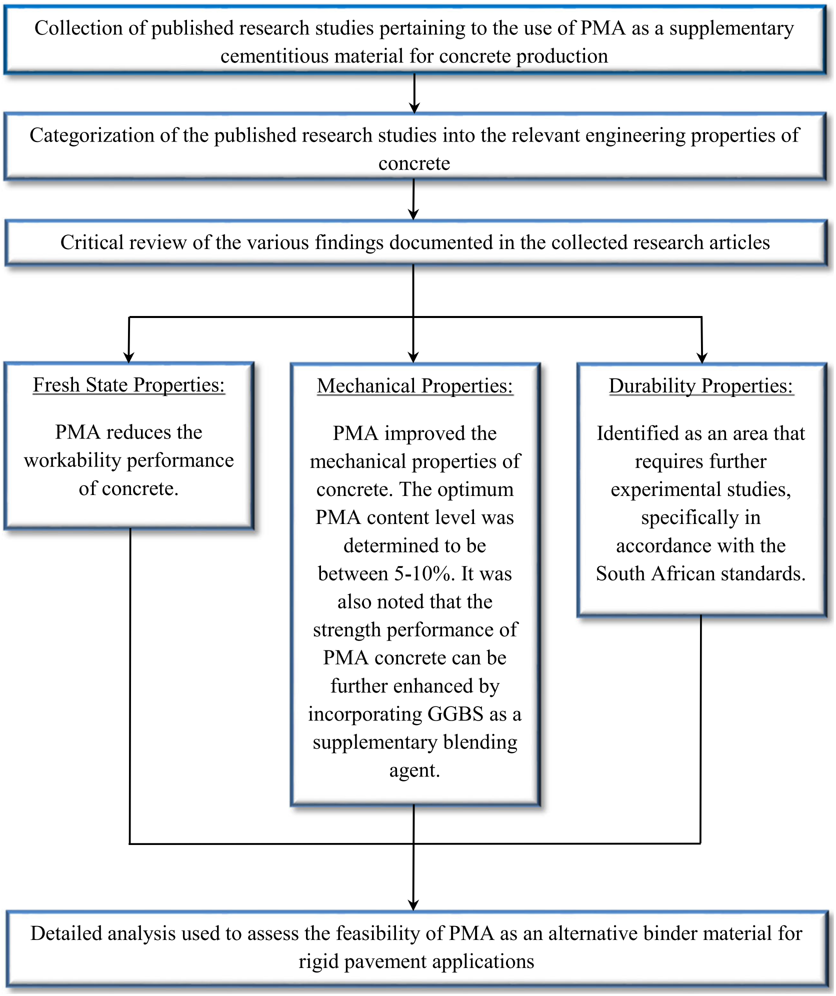
**blended with various proportions of GGBS, pulverised fuel ash (PFA) and metakaolin (MK)

Industries (CEPI). However, based on current trends, this value is expected to rise by 48 to 86% across the next fifty years [29, 30]. Paper mill sludge comprises of cellulose fibres, mineral fillers, water, inorganic salts and organic compounds [19, 31]. Paper mill sludge is commonly recycled and disposed of via land spreading (serves as an agricultural fertiliser) or landfill. Land spreading proves to be inefficient as an ample land space is required, while strong odours prevent it from being applied close to residential areas [29]. More than 69% of the paper mill sludge that is produced by the pulp and paper industry is disposed of via landfill, which places an additional strain on landfill operations and can have a hazardous effect on nearby groundwater [32, 33].

In order to minimise landfill volumes and recover energy, paper mill sludge can also be dewatered and incinerated in combined heat and power plants located within the paper mill. The resultant fly ash, which is classified as a waste, is known as paper mill ash (PMA) and has high contents of silicon dioxide (SiO_2), aluminium trioxide (Al_2O_3), calcium oxide (CaO), ferric trioxide (Fe_2O_3) and magnesium oxide (MgO) [19]. Since these oxides are commonly found in PC, PMA can also serve as a potential supplementary cementitious binder material in concrete [34]. This will assist in alleviating the costs associated with the disposal of paper mill sludge, maintain land capacity, safeguard the decreasing supply of raw materials and mitigate the adverse environmental impacts related to the cement manufacturing industry [35].

The chemical composition of PMA is mostly dependent on the incineration temperature [36]. If the combustion temperature ranges from 700 °C to 750 °C, then the clay minerals (e.g. kaolinite) present in the paper mill sludge are converted into metakaolinite, and the resultant PMA exhibits pozzolanic properties [37–40]. Furthermore, if the calcination temperature lies between 850 °C and 1200 °C, then there are minimal amounts of metakaolinite in the PMA. At this stage, it will longer behave like a pozzolanic material [36, 41, 42]. This may be attributed to the fact that the higher combustion temperatures prevent the kaolinite mineral in the sludge from being converted into metakaolin, which is responsible for pozzolanic activity in cementitious materials [42].

ASTM [43] states that the percentage of the three main oxide constituents, i.e. SiO_2, Al_2O_3 and Fe_2O_3 must summate to a minimum of 50%, for a material to be classified as being pozzolanic. Based on this, only



Collection of published research studies pertaining to the use of PMA as a supplementary cementitious material for concrete production

Categorization of the published research studies into the relevant engineering properties of concrete

Critical review of the various findings documented in the collected research articles

Fresh State Properties:

PMA reduces the workability performance of concrete.

Mechanical Properties:

PMA improved the mechanical properties of concrete. The optimum PMA content level was determined to be between 5-10%. It was also noted that the strength performance of PMA concrete can be further enhanced by incorporating GGBS as a supplementary blending agent.

Durability Properties:

Identified as an area that requires further experimental studies, specifically in accordance with the South African standards.

Detailed analysis used to assess the feasibility of PMA as an alternative binder material for rigid pavement applications

Fig. 1 Schematic diagram showing the methodology, results and recommendations

the PMA samples utilised by Kumar and Rani [21], Poojitha and Bhanu Pravallika [44] and Sudha et al. [24] may be deemed to be pozzolanic (Table 2).

2.2 Hydration Process

In contrast with cementitious materials like PC, PMA absorbs water at a much faster and more extensive rate [45]. The hydration process in PC concrete commences upon the addition of water and progresses at a decreasing rate inward from the individual particle surfaces. Furthermore, PMA displays significant variations in chemical composition and particle size, as shown in Table 2, which prevents it from similarly undergoing hydration as PC. According to Mozaffari et al. [45], this disparity in chemical composition and particle size distribution enables rapid reactions to occur in some phases. It also produces a chemical environment that is suitable for hydration and pozzolanic reactions in other phases, while some phases may also be deemed to be inert [45]. When water is added to PMA, two key processes occur, namely the dissolution of available free lime to produce slaked lime and the dissolution of silica and alumina resulting from a pH increase [45].

Hydration of the free lime triggers the release of hydroxyl ions to create an alkaline solution. The hydration of the α'-C_2S and the bredigite and the dissociation of the glassy phases then occurs, which releases alumina and silica [45]. The hydration process culminates when the calcium ions bind with the Al_2O_3 and SiO_2 to produce additional calcium silicate hydrate (C-S-H) gel [45]. The hydration products commonly found in PMA cement pastes are: CH, C_4AH_{13}, $C_3A.0.5C\overline{C}.0.5CH.H_{11.5}$, C_2ASH_8, $C_3A.3CS.H_{32}$ and C-S-H gel [20]. However, when PMA is used as the sole binder material in concrete, it is not particularly cementitious in nature. This can be attributed to the unsound hydration of CaO, resulting from the presence of a significant amount of non-hydraulic products, such as gehlenite, that are inaccessible by water [45]. Various research [46–48] have

Table 2 Chemical composition of PMA samples used in past research studies

Research Study	Oxides (%)														
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	P_2O_5	SO_3	Na_2O	Li_2O	TiO_2	MnO	BaO	SrO	LOI
[26]	43.51	25.70	18.86	0.87	5.15	1.31	0.52	1.05	1.56	0.01	0.68	0.04	0.04	0.09	1.2
[27]	8.69	59.47	10.45	10.45	3.13	–	–	–	–	–	–	–	–	–	–
[28]	43.51	25.70	18.86	0.87	5.15	1.31	0.52	1.05	1.56	0.01	0.68	0.04	0.04	0.09	–
[29]	8.69	59.47	10.45	10.45	3.13	–	–	–	–	–	–	–	–	–	–
[30]	55.87	15.16	6.06	1.11	2.00	0.34	0.48	0.78	0.19	–	0.45	0.05	–	–	17.51
[31]	12.45	67.33	2.62	1.42	2.74	0.64	0.05	–	12.05	–	0.16	–	–	0.02	–
[32]	19.82	18.01	10.14	0.55	2.58	0.21	0.10	0.33	0.25	–	0.26	–	–	–	47.62

shown that the PMA hydration process can be improved by blending the PMA with ground granulated blast-furnace slag (GGBS), which will be discussed in great detail later in this research study.

2.3 Morphology

The performance of PMA as a partial cement replacement in concrete is largely dependent on the morphology and particle size of the PMA sample [49]. The morphological properties of PMA directly influence the fresh state, mechanical and durability properties of concrete containing PMA [50]. Morphology is an effective property for assessing the feasibility of PMA as supplementary cementitious material, with a Scanning Electron Microscope (SEM) investigations being the most used method for determining the morphology of PMA.

The SEM observations documented in various research studies indicate that PMA particles are porous, agglomerated and heterogeneous in nature [36, 45, 51–53]. The SEM analysis undertaken by [54] also found that PMA particles are predominantly wide, flat and hexagonally shaped. Consequently, this agglomeration is a result of the incineration stage when manufacturing the PMA. The increased porosity of the PMA particles points towards a higher water demand and reduced workability properties when PMA is incorporated as a partial cement replacement in concrete [55]. The high-water demand is linked to the high microporous structure of PMA, which leads to an increased particle surface area and a hypothesised high free lime content [56–59]. The poor workability of PMA concrete can be compensated with the addition of a water-reducing admixture or increasing the water-binder (w/b) ratio [52].

Mozaffari et al. [45] also found that the surface of a single PMA particle displayed a degree of roughness (see Fig. 2[a]). Figure 2(b) shows that some individual mineral constituents are bound together with other mineral grains, which may also be attributed to the incineration process followed to produce the PMA [45].

Aini et al. [60] investigated the effect of PMA particle size on the morphological properties of PMA. This involved observing SEM images of unsieved PMA and PMA retained on the 63 µm sieve, 45 µm sieve and pan. From the SEM images, it was noted that the PMA particles become more densely packed as the particle size decreased. This suggests that the much finer PMA particles will have a more positive contribution towards the filler effect, by filling the voids present in the cement matrix of conventional concrete [61]. Aini et al. [60] also found that the PMA particles have a porous structure and are irregularly shaped, which is in agreement with the findings from the other research studies discussed earlier.

2.4 Equivalent Carbon Dioxide

Owens [62] uses the equivalent carbon dioxide (CO_{2e}) values for each concrete constituent to ultimately determine the carbon footprint of concrete. From a sustainability perspective, this study only focuses on the environmental impact of producing the most frequently used raw materials (i.e. cement, GGBS, FA, admixtures, aggregates and water). It is worth noting from Table 3 that the CO_{2e} of PMA is zero.

3 Fresh State Properties of Concrete Containing Paper Mill Ash

Concrete exists in its fresh state from the time of mixing, up until setting takes place [62]. The fresh state lifecycle of concrete usually lasts for a few hours, from the time the fresh concrete is handled, transported, poured and vibrated. The consistency and workability of fresh concrete decrease after the mixing procedure, which is indicative of a direct correlation between the fresh and hardened state properties of the concrete. In addition, the fresh state consistency and level of

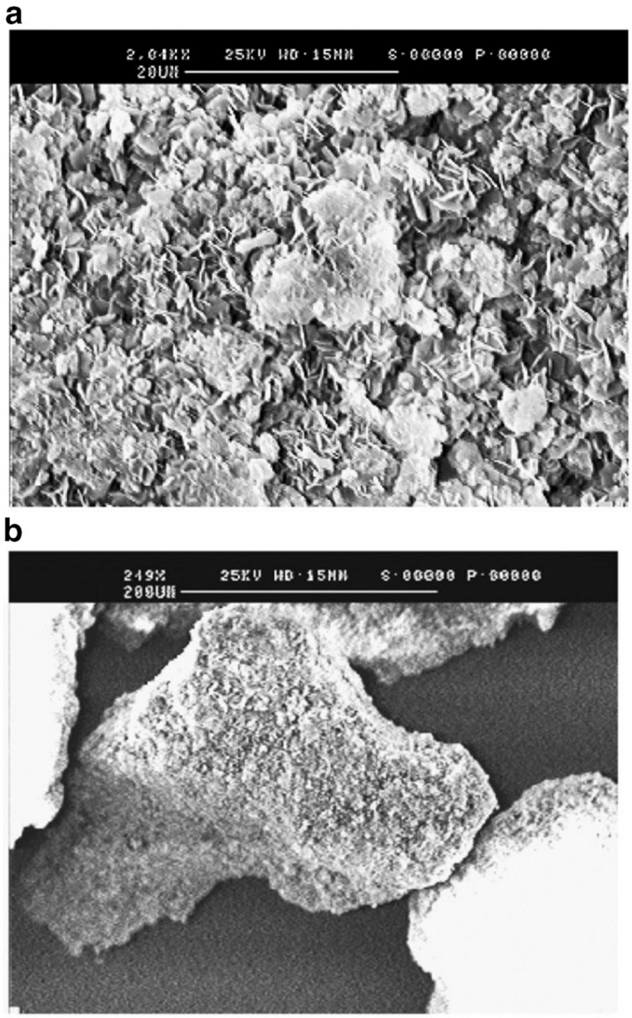


Fig. 2 (a) SEM image depicting roughness of PMA particle surface [45], (b): SEM image depicting the individual mineral grains of PMA [45]

compaction applied to the concrete mix plays an integral role in the development of strength and durability in hardened concrete. From a rigid pavement engineering perspective, the fresh state properties of concrete influences the surface finish and riding quality of the finished pavement [66]. The main fresh state properties of concrete considered for rigid pavement construction includes workability, consistency, flowability, place-ability, cohesiveness, bleeding and texture ability. The addition of paper mill ash, as a partial cement replacement, has a significant effect on the fresh state properties of concrete. This section includes an evaluation of the experimental results obtained from previous studies on the fresh state properties of concrete containing paper mill ash.

3.1 Workability

Concrete slump is the most widely used variable for quantifying the workability of fresh concrete. Babafemi et al. [67] state that particle size distribution, particle shape, water-binder (w/b) ratio, temperature and the quantity of admixture added to the concrete mix has a direct impact on the workability of fresh concrete. Concrete used for rigid pavement applications is required to have sufficient workability to ensure adequate compaction is achieved. Still, the compacted concrete must also retain sufficient rigidity to resist flow on roadways with steep grades and cross falls [66].

Ahmad et al. [26] investigated the fresh state properties of concrete containing varying amounts (i.e. 5, 10, 15 and 20%) of wastepaper sludge ash (or PMA) as supplementary cementitious material. This was achieved by conducting a slump test to determine the effect of PMA on the workability characteristics of concrete. As depicted in Fig. 3, the authors revealed that the slump decreased as the PMA content increased. This indicates that PMA particles absorb more water than ordinary Portland cement (OPC), which leads to reduced workability in fresh concrete.

Mavroulidou et al. [22] further examined the workability of different concrete mixes containing various percentage of PMA as a partial replacement for OPC. The slump test results obtained in this experimental investigation shows that increasing the PMA content results in a reduction of the workability and consistency of the mix, with a 30% PMA content achieving a slump of zero (Fig. 3). This can be attributed to the high-water demand required by PMA for the formation of hydration products [22].

The setting time and slump properties of cement mortar samples blended with 0, 10 and 20% of calcined paper sludge or PMA was investigated by Vegas et al. [25]. A w/b ratio of 0.5 was adopted for all the cement mortar mix designs. The results, as indicated in Table 4, show that PMA reduces the setting time of blended cement mortars. This can be associated with the presence of metakaolin and calcium carbonate ($CaCO_3$) in the PMA sample, which accelerates the hydration of C_3S and reduces the setting time [25]. The study also revealed that slump decreases as the PMA replacement level increases (Fig. 3). The authors reported that PMA is much finer than OPC and requires more water for hydration, therefore increasing the PMA content results in the production of more interparticle attractions.

It was also noted that the PMA sample used in the experimental investigations conducted by Mavroulidou et al. [22] had higher percentages of CaO, SiO_2, Al_2O_3 and Na_2O in comparison with the sample used by Vegas et al. [25]. This may explain the significantly lower slump test result obtained for the 20% PMA replacement level in [22], as the higher oxide concentration of PMA sample is expected to accelerate the hydration process, reduce the setting time and consequently decrease the workability performance of the fresh concrete.

Gailius and Laurikietytė [27] studied the workability properties of fresh concrete containing different proportions of PMA and GGBS as a combined binder replacement for cement. The

Table 3 Average CO_{2e} emission values for various concrete constituents

Material Type	Notation	Average Emission Values (kg CO_{2e}/ton)	Source
Portland Cement	CEM I	985	[62]
Portland-Limestone Cement	CEM II A-L	840	[62]
	CEM II B-L	720	[62]
Portland-Slag Cement	CEM II A-S	815	[62]
	CEM II B-S	730	[62]
Portland-Fly Ash Cement	CEM II A-V	790	[62]
	CEM II B-V	690	[62]
Blast furnace Cement	CEM III A	560	[62]
Pozzolanic Cement	CEM IV A	640	[62]
	CEM IV B	570	[62]
Composite Cement	CEM V A	590	[62]
	CEM V B	415	[62]
Admixtures	–	220	[62]
Aggregates	–	5	[62]
Water	–	1	[62]
Paper Mill Ash	PMA	0	[19, 63–65]

concrete mixes used in the research study were designed for two water-binder (w/b) ratios – 0.4 and 0.5, with the following PMA to GGBS proportions (replacement by percentage weight): 30:70, 40:60, 50:50, 60:40 and 70:30. Furthermore, Daracem SP1 (a superplasticiser) was added to the mixes that achieved a slump below 30 mm. The results obtained show that higher amounts of superplasticiser were required as the PMA content increased (Table 5). This can be attributed to the 35% of CaO present in the PMA sample used in the experimental investigations, which when hydrated forms Ca $(OH)_2$ and result in rapid initial hydration and setting [27]. The increased need for a superplasticiser to achieve desirable slump points to reduced workability in fresh concrete containing PMA.

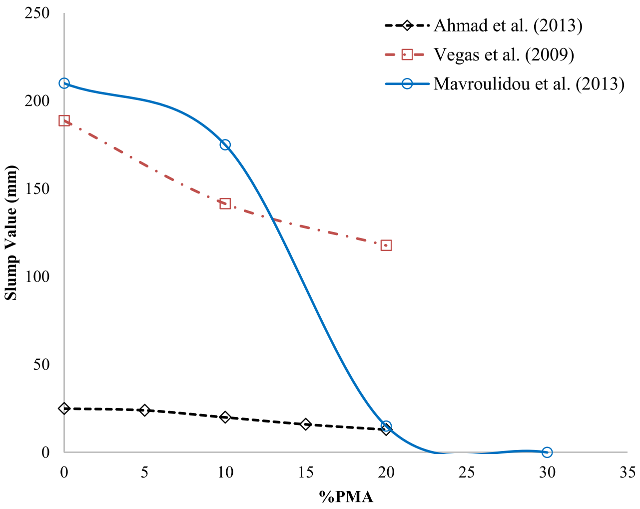


Fig. 3 Effect of wastepaper sludge ash on concrete workability [22, 25, 26]

Gailius and Laurikietytė [27] found that the addition of a superplasticiser or water-reducing admixture helps to improve the fresh state properties of concrete containing PMA; however, a higher amount of superplasticiser was required for the concrete mixes designed to a lower w/b ratio. Babafemi et al. [67] attribute this to the impact of w/b ratio and the amount of cement paste on the concrete slump and the mobility of the constituents. It was observed that the w/b ratios used in the existing research studies ranged from 0.4 to 0.55; therefore, additional experimental investigations are required to examine the impact of higher w/b ratio (>0.55) towards improving the fresh state properties of PMA concrete.

Even though a minimal amount of research has been conducted on the fresh state properties (namely workability and consistency) of concrete containing PMA, a common trend of results was observed in the available experimental studies. The slump test results obtained in all the research studies indicate that the incorporation of PMA into the concrete mix as a partial cement replacement results in a reduction of the workability.

Table 4 Setting time for cement mortar specimens [25]

% PMA	Initial Set (min)	Final Set (min)
0% PMA	145	255
10% PMA	120	170
20% PMA	60	130

Table 5 Concrete mix designs and slump test results [27]

Mix WSA: GGBS	Amount of SP1% by weight of binder		Slump (mm)	
	0.5	0.4	0.5	0.4
30:70	0	6.5	42	32
40:60	3.2	8.0	38	30
50:50	3.8	9.7	35	30
60:40	3.8	9.7	34	32
70:30	8.1	18.3	58	28

4 Mechanical Properties of Concrete Containing Paper Mill Ash

The mechanical properties of concrete are determined by manufacturing, handling, curing and testing concrete samples in a laboratory setting, with strength (compressive, flexural and tensile), creep, shrinkage and modulus of elasticity being the main mechanical characteristics in concrete [68]. The strength of concrete in its hardened state is a crucial variable used for both structural and pavement design purposes. It often serves as a guide for predicting the performance and quality of concrete [62]. Concrete used in structural and pavement engineering applications is continuously subjected to multiaxial variable loads. However, concrete strength is quantified in accordance with test results obtained from subjecting laboratory samples to a uniform loading rate and uniaxial stresses. Therefore, the measured strength determined from laboratory investigations is merely an indication of the true concrete strength [62]. The incorporation of paper mill ash, as supplementary cementitious material, has a significant effect on the mechanical properties of concrete [69]. This section includes an assessment of the experimental results attained from the literature relating to the mechanical properties of concrete containing paper mill ash.

4.1 Compressive, Tensile and Flexural Strengths

Compressive strength is the most widely used variable for structural design and engineering purposes [62]. In concrete, compressive strength is determined by dividing the maximum uniaxial load the concrete can withstand with the cross-sectional area of the laboratory sample. The most commonly used testing methods for quantifying compressive strength in concrete are the cube and core test. Tensile or flexural strength is the defining variable used for the design of rigid pavements. The tensile strength of concrete can be indirectly quantified by either using the flexural strength test or the tensile splitting test. According to Owens [62], the flexural strength test involves subjecting concrete beam specimens to either a single load located at midspan or two loads placed at third points. The tensile splitting test comprises of exposing cylindrical, or cube samples to compressive forces applied along two opposed lines [62].

The compressive strength of concrete is significantly higher than the tensile strength; however, there is no definitive relationship between compressive and tensile strength [62]. This can be attributed to the fact that variables such as w/b ratio, curing conditions, concrete age, aggregate properties and mix proportions have varying degrees of influence on the compressive and tensile strength.

Gailius and Laurikietytė [27] examined the compressive strength properties of concrete containing various amounts of PMA and GGBS as a combined binder replacement for OPC. The concrete samples contained the following ratios of PMA to GGBS – 30:70, 40:60, 50:50, 60:40 and 70:30, and were designed using two w/b ratios (0.4 and 0.5). The results indicate that the 50:50 mix ratio between PMA and GGBS achieved the highest compressive strength across all curing periods. The author hypothesised that this occurred because PMA and GGBS complemented one another when incorporated as supplementary binder materials in concrete. The study also found that the mixes containing a higher amount of PMA (i.e. 60:40 and 70:30) and a w/b = 0.4 attained lower compressive strength results than those specimens with a w/b = 0.5, which is due to the increased water requirement of mixes containing a higher ratio of PMA to GGBS [27].

Likewise, Bai et al. [20] explored the strength development and compressive strength properties of blended pastes containing the following ratios of wastepaper sludge ash (WSA or PMA) to GGBS – 20:80, 30:70, 40:60, 50:50, 60:40 and 70:30. Samples containing 100% PMA and 100% PC acted as a control to ensure an accurate comparison. As displayed in Fig. 4, the compressive strength of the 100% PC specimens is significantly higher than the strength of the PMA-GGBS and 100% PMA blended pastes. It is also worth noting that the pastes containing PMA achieved a low development of initial strength up until the 28-day period.

The relative strength results presented in Fig. 5 are the calculated ratio of the compressive strength for each paste to the compressive strength of the 100% PC paste for the same age [20]. From the results obtained, it is evident that blending the PMA with GGBS improves the compressive strength across all curing ages, with the 50% PMA – 50% GGBS blend achieving the highest strength results for the blended pastes, thus making it the optimum replacement content.

The effect of partial replacement of cement with 5, 10, 15 and 20% PMA on the compressive strength, and tensile splitting strength of concrete was also investigated by Ahmad et al. [26]. As shown in Fig. 6, the 5% PMA mix achieved the optimum compressive strength results for both the 7- and 28-day curing period, with the compressive strength decreasing after that. The strength increase displayed in the 5% PMA samples is approximately 15% at the 28-day mark. Similarly,

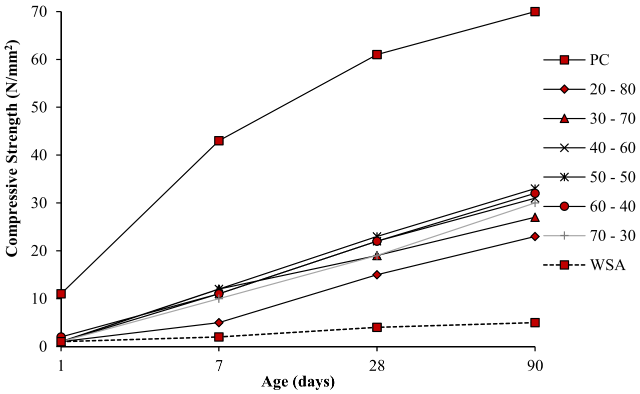


Fig. 4 Strength development of blended pastes containing PC, PMA-GGBS and PMA (w/b = 0.5) [20]

the 5% PMA replacement level was also determined to be the optimum content for the tensile splitting strength, with the results reducing for the following PMA contents (Fig. 7).

Fava et al. [19] examined the outcomes of replacing Portland-Limestone blended cement with 5, 10, 15 and 20% of PMA (replacement by weight of cement) in mortar mixtures designed to various w/b ratios (i.e. 0.4, 0.5 and 0.6). From the results presented in Fig. 6, it is evident that the compressive strength of the 5% PMA mixture after 7-, 28- and 60-days of curing is relatively similar to that of the 0% PMA samples. The general trend present in the results obtained indicates that the compressive strength decreases as the PMA replacement level increases, with the 5% PMA mixture being the only exception. The results also show that the compressive strength of the mortar mixes decreases as the w/b ratio is inflated (Fig. 8). The authors revealed that the proportion of PMA to OPC should be kept below 10% to maximise the contribution of PMA towards the hardening of the cement paste and development of the mechanical properties in concrete.

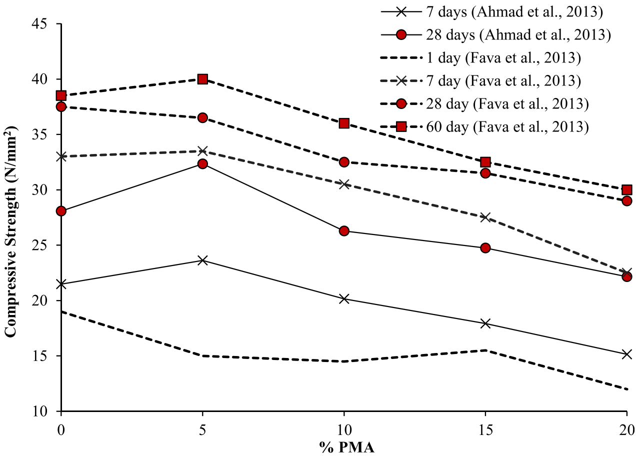


Fig. 6 Compressive Strength Results for concrete samples containing various amounts of PMA [19, 24, 26]

Sudha et al. [24] further researched the mechanical properties of concrete containing various proportions of PMA to OPC. This included conducting the standard cube, cylinder splitting and beam tests to determine the respective compression, tensile splitting and flexural strength for concrete samples containing 5% (WPSA1), 10% (WPSA2), 15% (WPSA3) and 20% (WPSA4) PMA. The compressive strength results in Table 6 shows that 10% replacement of PMA is the optimum content for both 7- and 28-day tests.

The flexural and tensile splitting strength results presented in Table 6 indicates the optimum replacement level as being 10% for both the 7- and 28-day curing periods. The authors concluded that the feasibility of PMA as an alternative binder material could be improved by ensuring that the cement replacement with PMA does not exceed 10%, which is in agreement with the research study conducted by Fava et al. [19]. In a similar investigation, Poojitha and Bhanu Pravallika [44] examined the compressive, tensile and flexural strengths of concrete specimens containing 5, 10 and 15% of PMA as a supplementary cementitious material. The concrete strength results attained indicates that PMA improves the compressive, tensile splitting and flexural strengths over a 28-day time period, with 10% being the optimum PMA content. Furthermore, the authors reported that PMA produced a

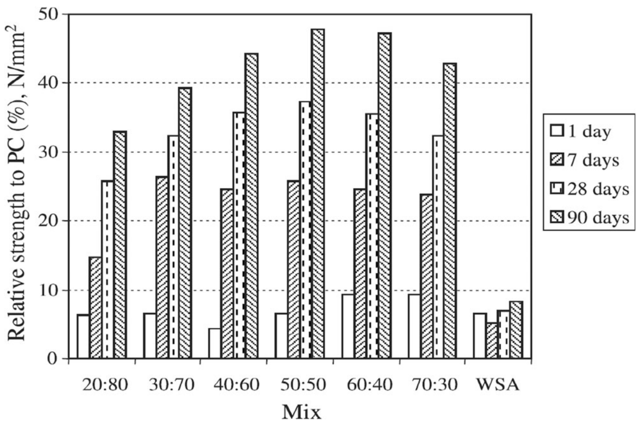


Fig. 5 Relative compressive strength of blended pastes containing PMA-GGBS and PMA to PC (w/b = 0.5) [20]

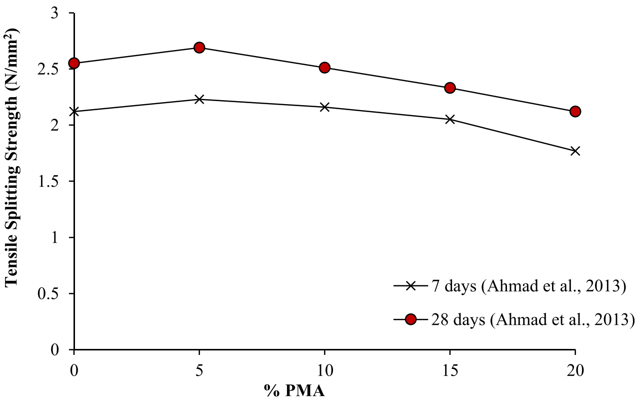


Fig. 7 Tensile Splitting Strength Results (7 & 28 day) for concrete samples containing various amounts of PMA [26]

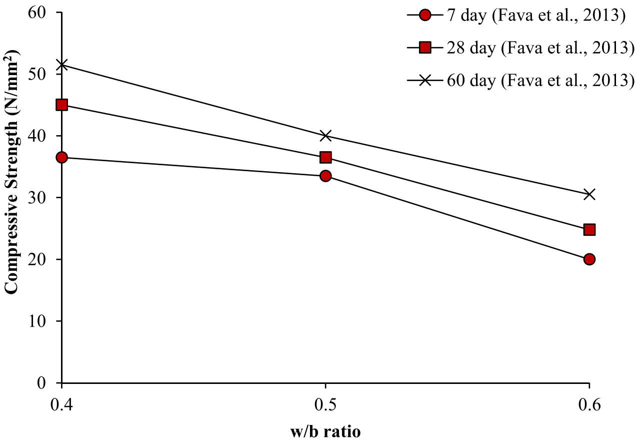


Fig. 8 Compressive Strength Results for concrete samples with 5% PMA and varying containing w/b ratios [19]

15.86% increase in concrete strength when compared to conventional concrete.

Table 6 shows that the compressive, flexural, and tensile splitting strength results attained for the 10% PMA samples in Poojitha and Bhanu Pravallika [44] are higher than the respective results achieved by Sudha et al. [24]. This could be associated with the higher percentages of Al_2O_3 and Fe_2O_3 (which are two of the main oxide constituents in pozzolanic materials) found in the PMA sample that was used. The increased oxide concentration of the PMA sample results in the development of additional C-S-H gel and improved concrete strength [64].

Vegas et al. [25] conducted experimental investigations to determine the compressive strength properties of cement mortar samples blended with 0, 10 and 20% of calcined paper sludge or PMA. From Fig. 9, it can be seen that the early compressive strength (i.e. after 2 days of curing) of the 10 and 20% PMA samples is similar to that of the control samples. After a curing time of 7 days, the mortar specimens containing 10 and 20% of PMA achieved higher compressive strength results than the control. This can be attributed to the presence of metakaolin in the PMA sample used in the research study, which impacts on the hydration reaction thus creating additional C-S-H gel and improving the strength results attained [25]. In addition, the metakaolin also serves as a filler material, which subsequently reduces the porosity and produces a more densified microstructure. The results also show that 20% of PMA is the optimum replacement level achieved in this research study.

Sharipudin and Ridzuan [23] examined the concrete strength properties of foamed concrete containing 5, 10, 15, 20 and 30% of PMA as supplementary cementitious material. The results attained indicate that the incorporation of 5–20% PMA improved the strength of the foamed concrete samples, with 20% PMA achieving the optimum 28-day strength. The authors also noted that increasing the percentage PMA to 30% resulted in a decrease of the compressive strength. This can be attributed to the increased levels of PMA, resulting in reduced pozzolanic reactivity and decreased strength development in foamed concrete.

Mavroulidou et al. [22] studied the compressive and tensile strength of concrete mixes containing various proportions of PMA, GGBS, PFA and MK as supplementary cementitious materials. Figure 10 shows that all mixes containing OPC and PMA only achieved a compressive strength either equivalent or superior to that of the control samples for both the 7- and 28-day curing period. The tensile strength of the specimens was evaluated using the tensile splitting test and the beam or modulus of rupture (MoR) test [22]. Much like the compressive strength results obtained in [23], Mavroulidou et al. [22] observed that the tensile strength of the specimens comprising of OPC and PMA only was either similar or higher than the control mix strength (Fig. 11).

The 7 and 28-day compressive strength results obtained for the 5 and 10% PMA replacement level in Mavroulidou [22], are significantly higher than the results achieved by Poojitha

Table 6 Effect of PMA on the compressive, tensile splitting and flexural strengths of concrete [24, 44]

%PMA	Compressive Strength		Tensile Splitting Strength		Flexural Strength	
	7 Days	**28 Days**	**7 Days**	**28 Days**	**7 Days**	**28 Days**
Sudha et al. [24]						
0%	22.35	29.76	1.52	2.13	3.3	3.81
5%	23.59	30.54	1.63	2.25	3.39	3.86
10%	24.89	33.46	1.72	3.25	3.49	4.04
15%	21.54	26.48	1.65	2.3	3.24	3.6
Poojitha and Bhanu Pravallika [44]						
0%	19.38	34.50	2.12	2.34	4.01	4.21
5%	23.84	35.11	2.21	2.45	4.05	4.38
10%	25.52	38.26	2.32	2.68	4.38	5.01
15%	24.54	36.89	2.24	2.54	4.12	4.62

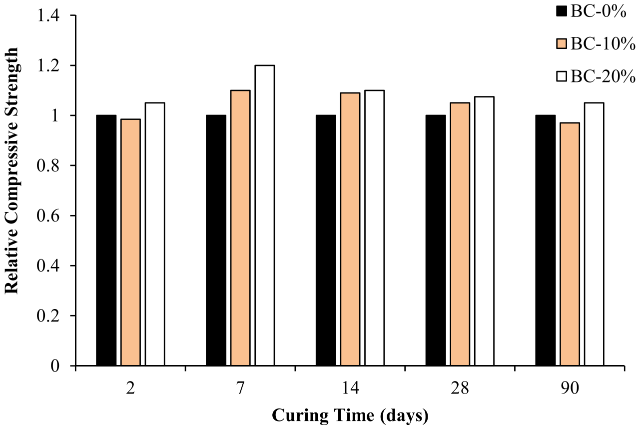


Fig. 9 Compressive strength results of PMA blended cement mortar specimens [25]

and Bhanu Pravallika [44]. This can be attributed to higher concentrations of CaO and Al_2O_3 present in the PMA sample used in [22, 64], which improves the pozzolanic properties of these concrete specimens and thereby enhances the strength performance of the PMA concrete.

Kumar and Rani [21] investigated the strength properties of concrete containing 5, 10 and 15% of paper sludge ash (or PMA) as a partial cement replacement (by mass). The compressive strength and tensile strength of the laboratory specimens were determined using the cube and tensile splitting tests, respectively. The strength results obtained in Table 7 indicate that PMA reduces the compressive strength across all curing periods. Kumar and Rani [21] also found that there was an increase in the tensile strength of the mix containing 5% of PMA, with a gradual decrease existing for the subsequent increments of PMA.

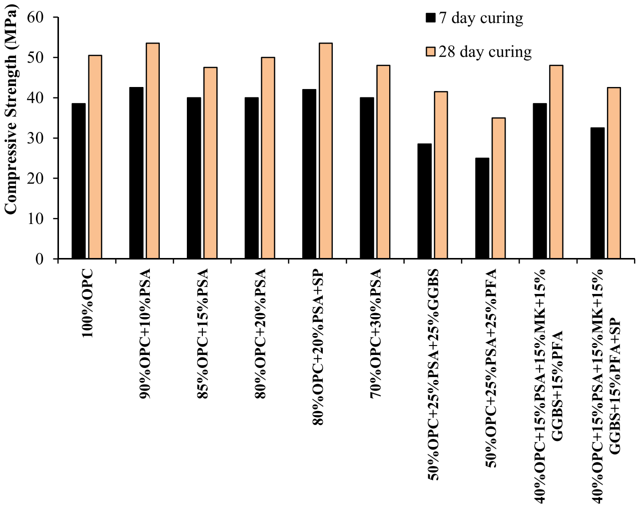


Fig. 10 Compressive strength test results for concrete mixes containing various combinations of PMA, GGBS, MK and PFA [22]

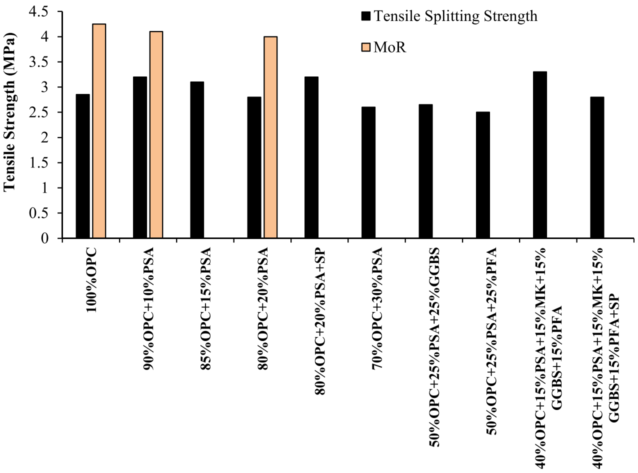


Fig. 11 Tensile strength test results for concrete mixes containing various combinations of PMA, GGBS, MK and PFA [22]

As discussed above, experimental investigations conducted by [19, 24, 26, 44] showed that PMA enhanced the mechanical properties, with 5–10% PMA content level achieving the optimum concrete strength results. Likewise, Vegas et al. [25] also documented a significant improvement in the strength properties of mortar samples containing PMA. However, the study found the optimum replacement content to be 20%. The improved mechanical properties noted in most of the previous experimental studies can be attributed to the presence of metakaolin in the PMA samples. Metakaolin has a direct correlation with the hydration process of PMA, which leads to the development of additional C-S-H gel and improved concrete strength properties. Besides, the characteristics of metakaolin are similar to that of filler material, which improves the concrete microstructure and reduces the porosity. Gailius and Laurikietytė [27] and Bai et al. [20] revealed that GGBS serves as a good blending agent with PMA to replace OPC. The studies reported that the replacement ratio of 50% PMA to 50% GGBS achieved favourable concrete strength properties. Bai et al. [20] attributed the strength development to the following:

- Addition of GGBS to the system, which reduces the quantity of expansive product available per unit of internal pore space and reduces the amount of disruption experienced by the hardened cement paste
- Increased w/b ratio resulting in a higher amount of CaO hydration taking place before the commencement of setting
- Reduction of expansion with the subsequent provision of a surface upon which lime can be absorbed and used to activate the slag hydration process
- Minimal hydration of GGBS during the early stages combined with more advanced hydration of the PMA

The results obtained by [20, 27] indicated that the optimum PMA content level increases with the addition of GGBS. This can be attributed to the complementary relationship existing between the two blending agents. Thus, the strength

Table 7 Compressive strength and tensile splitting strength test results obtained [21]

Designation of specimen	Avg. Compressive Strength of specimen in N/mm^2 at curing period in days of			Avg. Tensile Strength of specimen in N/mm^2 at curing period in days of		
	7 days	14 days	28 days	7 days	14 days	28 days
CC (0%)	28.04	30.48	33.19	2.12	2.98	3.67
PSA$_1$ (5%)	26.99	28.80	32.81	2.83	3.53	3.98
PSA$_2$ (10%)	23.40	26.54	29.03	2.24	2.62	3.01
PSA$_3$ (15%)	22.51	23.03	23.25	2.16	2.54	2.83

performance of concrete containing PMA as a partial cement replacement can be further improved by incorporating GGBS as a supplementary blending material. However, additional experimental investigations are needed to determine the optimum replacement ratio of PMA to GGBS.

In contrast with the studies mentioned above, Kumar and Rani [21] noted a decrease in the compressive strength of PMA concrete. This variation in test results can be attributed to the different chemical compositions and particle sizes of the various PMA samples used in the experimental studies. Therefore, additional research is required to determine the definitive optimum content level, chemical composition and particle size distribution of PMA for use as a supplementary cementitious material.

The South African Engineering Pavement Manual (SAPEM) [66] recommended a target flexural strength of not less than 4 MPa at 28 days for concrete pavement minor roads. Generally, this flexural strength requirement can be satisfied through a minimum 28-day characteristic compressive strength of 30 MPa [66]. The SAPEM target flexural and compressive strength for concrete pavement is achieved for the respective optimum PMA replacement levels in the research studies conducted by [19, 24, 26, 44].

4.2 Drying Shrinkage

Drying shrinkage is defined as the loss of moisture in concrete which occurs once the curing process ceases [62]. Shrinkage produces an increase in tensile stress that results in cracking, internal warping and external deflection of concrete prior to experiencing loading [70]. Concrete experiences drying shrinkage or a loss of capillary water as concrete age progresses. According to Owens [62], drying shrinkage is dependent on the properties of each concrete component, proportions of the concrete constituents, the mixing process followed, amount of moisture present during curing and relative humidity.

Vegas et al. [25] investigated the drying shrinkage properties of mortar samples manufactured with a blended cement containing 0, 10 and 20% of PMA. The results indicated that the incorporation of PMA into the mix design increased the drying shrinkage by up to 2.5 times more than the control samples. This trend of results can be attributed to the following [25]:

- The crystallisation of the calcite particles presents in the PMA, which increases the hydration process and accelerates shrinkage.
- Pozzolanic reaction of metakaolin from the PMA with the calcium hydroxide produced by the cement.

Increased capillary tension resulting from the fine particle size distribution of the PMA sample.

5 Durability Properties of Concrete Containing Paper Mill Ash

The durability of a concrete element is the ability to withstand extreme environmental conditions over its design life, without disproportionate loss of serviceability or need for drastic repair and rehabilitation strategies [62]. The durability of properties of concrete considered for both structural and pavement design purposes is directly related to the concrete performance properties, which suggest that it may be durable in a certain setting but not in another [62]. Concrete durability is directly related to the porosity, permeation and microstructure properties of the specimen [6, 71]. The durability performance of concrete can be enhanced with the addition of a supplementary cementitious material that has the holistic effect of strengthening the internal pore structure and improving the permeation properties [71]. According to Owens [62], the transport (permeation, absorption, diffusion and migration), mechanical, physical and chemical properties are the most influential on the durability performance of both concrete structures and pavements. Each of the properties mentioned above should be linked to the prevalent environmental conditions during the concrete production and construction phase. The incorporation of paper mill ash, as a partial cement replacement, has a meaningful effect on the durability properties of concrete. This section includes an overview of the experimental results obtained from the literature pertaining to the durability properties of concrete containing paper mill ash.

5.1 Resistance to Acid Attack

An acid attack usually takes place when concrete is exposed to liquids with a pH below 6.5, while the severity of the attack increases as the pH value decreases. The progression of acid attack in concrete results in the deterioration and leaching away of the cement compounds present in the hardened cement paste. Owens [62] explains that it is impossible to produce acid-resistant concrete using PC; however, an acid-resistant coating may be applied as a protective layer to concrete that is exposed to severe acidic environments.

Poojitha and Bhanu Pravallika [44] investigated the durability properties of concrete incorporating PMA as supplementary cementitious material. This was achieved by observing the acid resistance results obtained from the acid attack factor test and acid durability factor test. In the research study, concrete samples containing 10% of PMA and varying amounts of steel and glass fibres were exposed to hydrochloric acid (HCl) and sulphuric acid (H_2SO_4). In order to simulate a very severe acid attack, both acids had a concentration of 5% and pH values of 3.01 and 2.75, respectively.

From the durability results presented in Tables 8 and 9, it can be determined that the specimens exposed to H_2SO_4 displayed a higher percentage weight loss after 28 days and reduced compressive strengths, which can be attributed to increased deterioration and greater severity of acid attack experienced. The study also proved that glass fibres had a better effect on improving the durability properties of concrete containing PMA.

5.2 Water Absorption and Porosity

Water absorption by submersion is a key variable for assessing concrete performance. It indicates the porosity properties of concrete by determining the percentage of water absorbed into the microstructure when the sample is immersed and is related to the square root of time [67]. Ahmad et al. [26] conducted a water absorption test on specimens containing 5, 10, 15 and 20% PMA, which served as an indirect measure of the concrete durability properties. This was determined by measuring the average weight of concrete cube samples after the samples are demoulded and again after 28 days of curing. The results graphically depicted in Fig. 12 indicate that the percentage of water absorption rose as the PMA content increased. This can be attributed to the high-water demand required to form hydration products.

Mavroulidou et al. [22] also used the percentage of water absorption to quantify the durability properties of concrete mixes containing various amounts of OPC, PMA, MK, GGBS and PFA. The water absorption test procedure involved oven-drying 100 × 100 × 100 mm cubes for 72 h, before leaving the samples to cool in an airtight container for 24 h. The percentage water absorption was calculated by measuring the mass increase of the cube after submerging it in water for 30 min and dividing it by the dry mass of the cube [22]. The results attained show that the percentage of water absorption decreases as the PMA replacement level increased (Fig. 12). This contradicts the results obtained by Ahmad et al. [26] (Fig. 12).

Based on the review of the existing studies undertaken in this section, it can be seen that minimal research has been conducted on the durability properties of concrete incorporating PMA as supplementary cementitious material. It is also worth noting that there is no research pertaining to the microstructure properties of concrete containing PMA. Besides, the durability performance of PMA concrete has not been investigated in accordance with the South African durability index tests. Therefore, further experimental studies are required to examine the durability properties of concrete containing PMA as a partial cement replacement.

6 Concluding Remarks

Incineration of paper mill sludge in combined heat and power plants to produce PMA serves as an alternative to disposing of the waste via land spreading or landfilling operations. This research study included an extensive review of the

Table 8 Durability results for concrete samples exposed to HCl [44]

% Replacement	% weight loss after 28 days	Compressive Strength (N/mm^2)	
		7 days	28 days
0.1% Glass Fibres	2.3	16.12	28.88
0.2% Glass Fibres	2.46	17.22	29.76
0.3% Glass Fibres	2.66	18.44	30.23
0.4% Glass Fibres	2.69	16.81	28.11
0.5% Steel Fibres	2.33	16.67	28.41
1% Steel Fibres	2.41	18.81	30.41
1.5% Steel Fibres	2.58	17.16	28.12
2% Steel Fibres	2.63	16.81	27.41

Table 9 Durability results for concrete samples exposed to H_2SO_4 [44]

% Replacement	% weight loss after 28 days	Compressive Strength (N/mm^2)	
		7 days	28 days
0.1% Glass Fibres	4.16	12.66	22.35
0.2% Glass Fibres	5.59	13.58	23.44
0.3% Glass Fibres	6.34	14.99	24.68
0.4% Glass Fibres	6.35	13.24	23.33
0.5% Steel Fibres	4.46	14.44	23.04
1% Steel Fibres	5.66	15.85	24.81
1.5% Steel Fibres	6.41	15.50	24.54
2% Steel Fibres	7.11	14.21	24.11

performance properties of concrete incorporating PMA as a supplementary cementitious material. The concrete properties under consideration in this review comprised of the following: fresh state, mechanical and durability properties. The main findings noted in existing research studies on the concrete properties of cement-based materials with varying amounts of PMA are summarised in Table 1. From the presented review of previous literature, the following conclusions can be deduced:

- Workability, namely slump and setting time, declined as the PMA content increased.
- Mechanical properties, specifically compressive, flexural and tensile splitting strength, improved as the PMA replacement level increased. The optimum PMA content level was deemed to lie between 5 and 10%, with concrete strength decreasing beyond this level. However, it was also shown that the optimum PMA content level increases when GGBS is incorporated as a supplementary blending agent.
- Drying shrinkage properties increased, by up to 2.5 times, with the incorporation of PMA.
- A gradual increase in the percentage water absorption takes place with an increase in PMA content.

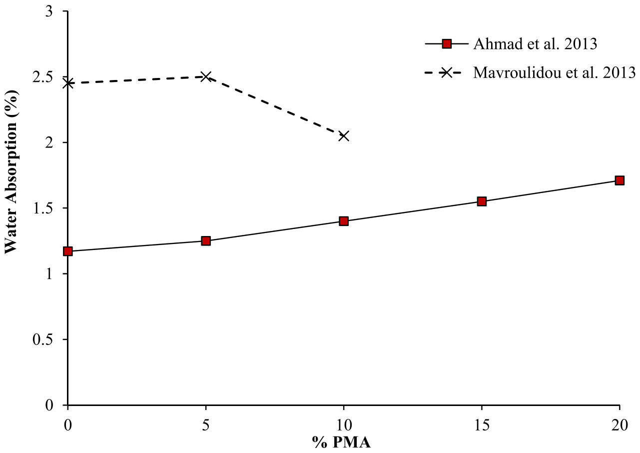


Fig. 12 Durability results from the water absorption test [22, 26]

The reduced workability of PMA concrete mixes can be attributed to the finer PMA particle size distribution in comparison with PC. This, coupled with the presence of metakaolin in PMA, means that PMA has a higher water requirement for the hydration reactions to occur. The high-water demand for PMA is also responsible for the increase in percentage water absorption, which is directly related to the porosity and durability properties in concrete. There was a consensus that the incorporation of PMA results in reduced concrete workability properties. However, there was a notable disparity in the w/b ratios applied across the various research studies. Therefore, future experimental investigations are required to determine the impact of higher w/b ratio towards enhancing the fresh state performance of PMA concrete.

The favourable development of concrete strength that has been documented in the majority of past experimental investigations can also be associated with the fact that metakaolin is a chemical constituent of PMA. The metakaolin found in PMA has a direct impact on the hydration process, which results in the formation of additional C-S-H gel and the subsequent improvement of concrete strength. Furthermore, metakaolin also behaves like a filler material, which reduces the porosity and produces a more densified concrete microstructure.

This study also found that the PMA hydration process can be improved by incorporating GGBS as a blending agent, with the replacement ratio of 50% PMA to 50% GGBS achieving superior concrete strength results. However, the experimental investigations conducted by Kumar and Rani [21] documented a decrease in the compressive strength of concrete containing PMA as an alternative binder material. This, in combination with the minimal research pertaining to the durability and microstructure properties of PMA concrete, highlights the need for additional research to determine the definitive optimum content level, chemical composition and particle size distribution of PMA for use as supplementary cementitious material. It is also worth mentioning that no experimental research has been undertaken to assess the microstructure and skid resistance properties of concrete containing PMA. This could provide additional information to determine the feasibility of PMA as supplementary cementitious material for rigid pavement applications.

According to the South African Engineering Pavement Manual (SAPEM) [66], the 28-day target flexural strength of concrete roads should be greater than 4 MPa. This requirement is generally satisfied when a minimum characteristic 28-day compressive strength of 30 MPa is achieved [66]. The 28-day flexural strength requirement has been achieved for the respective optimum PMA replacement levels in the research studies conducted by Fava et al. [19], Poojitha and Bhanu Pravallika [44], Sudha et al. [24] and Ahmad et al. [26]. Considering that tensile or flexural strength is the defining variable used for the design of rigid pavements, and the favourable flexural and tensile splitting strength results documented in this research study, it can be concluded that concrete incorporating PMA as a partial cement replacement is a viable option for use in rigid pavement applications. The advantageous development of long-term strength and durability of concrete containing PMA coupled with the negligible CO_{2e} emission value of PMA can have the beneficial effect of improving both the sustainability and serviceability states of rigid pavements.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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