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Evaluating the effect of different types of dried Automotive Paint Sludge as cement-based composite

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Abstract. In this project, we aim to probe four different automotive paint sludge (APS) types; primer coat, phosphate pretreatment coat, base coat and clear coat sludge, as potential additives in cement paste. Specifically, Portland Cement paste was doped with the different APS types which only underwent drying and milling on receipt from a vehicle assembly plant. The mixture was then cured for 7 days, and the resulting concrete was subjected to consistency, setting time, flexural strength and compressive strength tests. On comparison with the control cement paste, the primer coat sludge generally increased the setting time, by as much as 40 % for the final setting time. The compressive strength is negatively affected by the addition of all the different APS. This is somewhat mitigated if clearcoat sludge is used at a 1 wt.%: the difference is less than 10 % to the control. The phosphate pre-treatment coat is the worst performer with a difference of more than 90 %, even at a low APS concentration of 3 wt.% in the cement paste. In contrast, the flexural strength increases with the addition of all but one of the four APS types: phosphate pre-treatment coat. Primer coat sludge is associated with as much as 50 % increase in flexural strength. These results tentatively, show the utility of APS as an additive in cement paste to potentially tailor its properties, thereby decreasing the detrimental environmental impact of disposing of it. APS may also find application in refractory and clay brick manufacture.

Key words: Cement paste, admixture, setting time, automotive paint sludge.

1. Introduction

Cement has played a significant role in advancing human civilisation. This continues to be the case–with both sustainable development goal (SDG) 9 and 11 relying on cement as a fulcrum material. In South Africa, part of the Reconstruction and Development Program (RDP) aims to build and provide free housing units for unemployed and/or low-income families and individuals. Despite the importance of RDP housing, there have been several complaints about the quality of construction, due to the fact that contractors deviate from standards to try reducing the cost and increase profits. These often affects the quality materials, particularly the performance of concrete. There have been statistically significant numbers of RDP house recipients who have flagged issues such as cracking or poor durability among other issues. This spotlights the need for research on alternative materials and additives that cost effective but do not compromise basic safety, ergonomics and longevity (Nokulunga, Didi and Clinton, 2018; Ogunfiditimi, 2008).

SDGs are a successor to the Millennial Development Goals. At the heart of SDG 9 is resilience in infrastructure and industrial processes. SDG 13 explicitly states the need for a concerted effort and action to curb climate change and its effects. This may be considered in tandem with SDG 12—which speaks to a circular economy whereby industrial waste is reduced by reuse, thereby decreasing the propensity to overuse earth's scarce resources. Given that the cement industry contributes an estimated 8 % to the global CO_2 emissions, the status quo cannot be sustained. This pressure has given impetus to the industry to consider industrial by-products and waste additives in keeping with the discussed SDGs (Aboulnaga, Amer and Al-Sayed, 2020; Cheng *et al.*, 2023).

One of these is automotive paint sludge (APS). According to Ruffino *et al.* (2023) the average APS production is 3 kg/car on a wet basis. Mostly these sludges are landfilled which poses a danger to underground water due to the leaching of heavy metals. Automotive paint sludge is made of organic as well as inorganic metal compounds that are used to improve the quality of the paint. During the automotive painting process, up to five different layers of different coating materials (phosphating, electrocoating, primer coat, basecoat, and clearcoat) are applied to provide corrosion protection, durability, and colour. Each layer has unique performance criteria and must bond with the next to create a long-lasting coating that will not flake or peel (Salihoglu and Salihoglu, 2016).

Phosphating helps other coats to bind to the metal works, while electrocoating protects the metal from corrosion, the primer coat provides a smooth metal surface, and the basecoat and clearcoat provide colour, shine/gloss finish and protection (Salihoglu and Salihoglu, 2016). Since not all the paints reach the article being painted, the offspray collects in a sludge pit at the bottom of the spray booths where it is mixed with flotation agents, detackifiers and other coagulants. Therefore, paint sludge is a hazardous material made up of uncured polymer resins, pigments, curing agents, flotation agents, volatile organic compounds and other minor toxic and heavy metals (Avci *et al.*, 2017).

Despite the hazardous classification, the paint sludge has possible reuses and materials recovery, it contains metals that can be recovered as well as organic materials that can be used in other processes such as compositing, gasification, and combustion. Using industrial waste with minimal further treatment conserves energy and aligns with sustainable practices. Waste valorisation in the construction industry is a well-canvassed field. Material such as fly ash has been investigated as potential additives. APS falls in the same category of prospective pozzolanic material. The lower the pre-processing prior to use in cement paste, the higher the benefit with respect to valorisation and reduction of environmental impact. This is a boon for environmental and potentially, economic sustainability (Bui *et al.*, 2022; Marian, 2023).

The tonnage of APS is significantly lower than that of conventional supplementary cementitious materials (SCM), such as coal fly ash or limestone powder. Additionally, the same amount of APS produced is less valuable than an equal quantity of waste products, such as coal fly ash. This is primarily due to the significant water content of APS, which can be as high as 60 to 90 wt.%, necessitating pretreatment to dry it to a solid form (Ruffino *et al.*, 2021). Furthermore, even when dried, its chemical composition is noticeably less homogeneous and only contains minor pozzolanic constituents. As a moderately hazardous industrial waste, its value proposition is not in outperforming conventional SCMs, but rather in recovering value from a waste product and avoiding disposal costs.

The cost of landfill disposal for moderate hazardous waste in South Africa is lower than in regions with more stringent environmental regulations, such as European Union nations. This can be as high as €350 (R7050) per ton, whilst in South Africa it can be as low as an order of magnitude lower at €37 (R737) per ton (*Solid-waste disposal tariffs for 1 July 2018 – 30 June 2019*, 2018; Salihoglu and Salihoglu, 2016). Furthermore, the drying, grinding and general handling of APS to be fit for the purpose may attract costs in excess of €150 (R3000) per ton (Ruffino *et al.*, 2021). At face value, this may serve as a disincentive to valorisation of APS: its cost of disposal is not prohibitive, and the cost of treatment is substantial.

This is a recurring cost that may increase as the regulatory framework and costing are brought closer to European Union standards. Thus, cheaper and more sustainable alternatives to landfill disposal are warranted, even though there are no significant current financial penalties. The chemical makeup of APS may include polymeric resins, curing agents, surfactants and pigments.

For older formulations, this may entail heavy metals such as lead, zinc, chromium, cadmium, barium, etc (Câmara *et al.*, 2024).

This is an obvious leachate risk; thus, it has been well researched regarding the usage of APS as a cement admixture.

As recently as 2024, Hossain *et al.* (2024) reported that heavy metal leaching, such as chromium, in concrete blocks incorporating APS, remains lower than the documented safety limits. Other authors have concurred (Câmara *et al.*, 2024). This may have to do with the cement hydration process, resulting in a pH of 12 to 13 due to the presence of calcium silicate hydrate, calcium hydroxide, ettringite, etc. Thus, the heavy metals likely form insoluble hydroxides and/or are trapped in the structure of the hydrates, effectively immobilising them in a solid, low-permeability matrix and limiting the leaching potential. In fact, the reported leaching potential in the literature is largely based on the Toxicity Characteristic Leaching Procedure (TCLP), which simulates mildly acidic conditions of a municipal-solid-waste landfill. This is obviously not applicable for normal applications of concrete structures: rainwater is neutral. Thus, the leaching risk of heavy metals is likely even lower than indicated by the literature studies.

Civil engineering applications, including road construction, concrete, pavements, and bricks, offer practical ways to utilise APS directly. Automotive paint contains inorganic materials that can act as pozzolanic agents—siliceous and aluminous substances that react with calcium hydroxide to produce cementitious compounds. It is thus the intention of this study to evaluate the use of APS in civil and construction applications by first testing it as a partial replacement for cement paste.

Since the paint sludge has five different layers, in this study we separate the layers and determined the influence of each different type of automotive paint sludge (APS) and content (1 wt.%, 3 wt.%, 5 wt.%, 8 wt.%, and 11 wt.%) on the physical and mechanical properties of cement paste. The cement paste's were first evaluated on early state properties of consistency and setting times and its behaviour with when APS is added in the paste. The hardened properties of cement paste such as density, thickness swelling, compressive and flexural strength were then evaluated after 7 days of water curing.

2. Methodology

2.1. Materials

During the investigation, Portland limestone cement (PLC) of grade 42.5 was used. Four distinct kinds of automotive paint sludges—clearcoat, primer coat, base coat, and phosphate pre-treatment coat were used in this study. The cement used was supplied by Afrisam Cement Pty Ltd and the APS was supplied by VW South Africa Pty Ltd. Ordinary tap water was used for these experiments. APS was analysed at the Technical Research Services, University of Alicante, Spain. It was found that its major constituents include ash, LHV organics and metal cations.

2.2. *Sample preparations*

The automotive paint sludge (APS) was dried in an oven at 102 ^{o}C for 24 h. Subsequently, the dried APS was milled in a rod mill for 2 hours each and fine particles less than 180 um were used for the test. In respect of the preparation, formulations with 0, 1, 3, 5, 8 and 11 wt% of the dried different APS, were used. The consistency and setting times of the cement paste was determined using approximately 500 g of cement and 150 g of water.

For the composite APS-cement paste, the same density ratio was used whereby the dried APS was added into the cement with increment of 1, 3, 5, 7, and 10% by weight. Variations in water were necessary in order to meet the consistency standard. For hardened properties, the cement paste was place in the standard size moulds of 40 X 40 X 160 mm block of three pairs for repeatability. After 7 days of curing, the cubes were tested. A control sample and 5 cement paste formulations were used, making a total of 63 specimen produced with the moulds used in this project. X-ray fluorescence (XRF) spectroscopy was used to speciate the metallic elements and the LHV organics in the APS.

2.3. *Early state properties test*

Fig. 1 shows the equipment used to determine the early-cure state properties. The cement, APS and water were placed inside the mixing bowl and mixed for 240 seconds shown in Fig. 1(a). The consistency and setting times of the pastes were determined using a Vicat apparatus as per procedure outlined in SANS 50196 - 3:2006, and EN 196-3 (Kilani, Ikotun and Abdulwahab, 2025). The Vicat test for the consistency determination is performed by applying a 300 g load on the cement paste surface through a plunger (cylindrical flat-ended needle) with a 1 mm diameter and measuring the penetration depth in mm as has been described by Tsardaka *et al.* (2023)—relative to the standard consistency of a cement paste: 6 ± 2 mm. The apparatus is depicted in Fig. 1(b). In Fig. 1(c), a set of Vicat measurements was performed on cement pastes with different composition and their initial and final setting times (penetration vs. time) were recorded, according to EN 196-3.

(a) (b) (c)

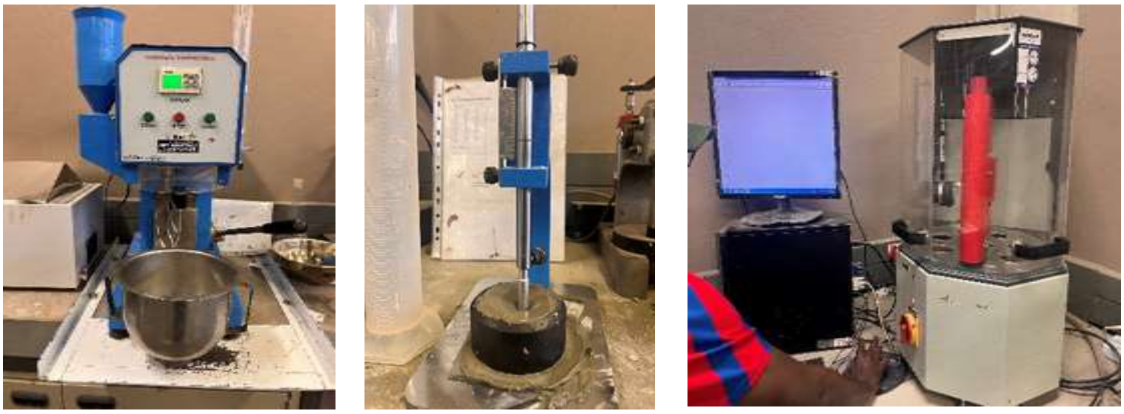

Fig. 1. Methods of determine the Consistency of cement and cement – rubber pastes

Table 1 indicates the formulation for the doping of the APS relative to the cement, and water proportion. In the case of the clearcoat APS, the water content ranges from 23.3 wt.% to 23.7 wt.%. For Base Coat, it ranges from 22.5 wt.% to 23.4 wt.%. Similar ranges are used for Primer Coat and Phosphate Pre-treatment APS, with 22.4 wt.% to 23.4 wt.% for both APS types.

Table 1. Mix design compositions for the composite cement.

Percentage of dried APS replacement	Cement, g	APS, g	Water, g			
			Clear Coat	Base Coat	Primer	Phosphate
Control 0 wt.%	500	0	152.4	152.4	152.4	152.4
1 wt.%	495	5	152.5	149	151.5	151.5
3 wt.%	485	15	155	146.9	150.3	150.3
5 wt.%	475	25	155	145	149.5	149.5
8 wt.%	460	40	155	145.2	148	148
11 wt.%	445	55	155	145	144	144

2.4 Compressive test after curing

To determine the compressive strength, all samples underwent compressive strength test using Compression and Bending Test Plant ToniPRAX with a capacity of 3000kN. Final compressive strength for this research was determined from the average of three cubes.

3. Results and discussion

3.1 APS Characterisation

In Table 2, the elemental chemical composition of the clear coat, primer coat, base coat, electro coat and the phosphate pre-treatment coat, is reported. The clearcoat APS has nearly 4 times as the concentration of elemental nitrogen than primer. This is likely due to the use of hindered amine light stabilizer (HALS) chemicals that are found predominantly in clearcoats (Akafuah *et al.*, 2016). Of all the APS samples analysed, the clearcoat has the least amount of ash content, as much as an order of magnitude less compared to the others.

Table 2. Elemental, ash, and high heat value of different automotive paint sludge samples on dry basis.

APS Sample	N	C	H	S	O*	Ash	HHV
	wt.%						MJ/kg
Clear	5.21	54.70	8.09	0.00	27.16	4.84	26.57
Primer	1.52	22.81	2.79	4.62	8.02	60.24	9.88
Base	1.12	37.75	5.05	0.00	19.91	36.17	18.64
Electro	1.50	30.78	4.33	0.29	11.81	51.28	14.70
Phosphate	0.56	3.17	2.98	0.07	19.76	73.46	0.611

Calculated by difference

Primer coat has a non-negligible amount of elemental sulphur. This is in stark contrast to the other coats. The genesis of this could be due to the presence of sulphur containing compound such as 6-(4-vinylbenzyl-n-propyl) amino-1,3,5-triazine-2.4-dithiol (VBATDT), thiosphosphoric acid derivatives (MEPS), 6-methacryloyloxyhexyl 2-thiouracil-5-carboxylate (MTU-6), 10-methacryloyloxydecyl-6,6-dithiooctane (MDDT) etc., that are frequently used with primers to aid in adhesion with metal surfaces (Yoshida, 2017). The clear coat APS has a higher elemental carbon, hydrogen and even a higher heating value (HHV) than the others. This could be indicative of the presence of a higher content of organics in clearcoat.

Table 3 and Table 4 show the mineral composition of the paint sludge with elemental ICP-MS and XRF analysis respectively. All the coats have significant amounts of elemental aluminium and calcium. The elemental silicon content is on the lower end of the scale, with only the phosphate pretreatment APS. XRF confirms that the form of the elemental aluminium is alumina (Al_2O_3) in compound form. In the case of elemental calcium—calcium oxide (CaO), silicon—silica (SiO_2). The presence of silica and calcium oxide is said to enhance pozzolanic activity, whereby the alumina plays a supportive role (Katare and Madurwar, 2020). The potential for the use of APS as a cement paste additive, may in someway, depend on the presence of these compounds and their accessibility to the cement paste.

3.2. Setting time

Fig. 2 shows the setting times for the respective cement paste dope with primer, base, phosphate and Clear Coat APS. In the case of the primer, the setting time increases with increasing amount of APS. Where as the base-coat does not exhibit a clearly defined trend: it appears that there is no effect in the setting time for the cement paste. A somewhat similar trend is observed for the clear coat, with only a marginal increase in the setting time of the cement paste, relative to cement paste without APS. In the case of the Phosphate APS, a more interesting trend emerges there is an initial increase in the setting time with increasing amount of APS, up to 3 wt.% APS. Then the trend reverses, whereby the setting time decreases at amounts of APS above 5 wt.% APS.

Table 3. Mineral composition of different automotive paint sludge samples using ICP-MS

Elements (mg/Kg)	APS Sample				
	Clear	Based	Primer	Electro	Phosphate
Na	2522.37	324.71	1111.35	1464.54	6642.02
Mg	1231.70	254.77	1791.10	1126.00	200.49
Al	17301.19	10273.76	26983.06	22484.43	10085.90
Si	687.59	525.88	960.74	657.86	7487.79
P	120.83	210.94	856.03	51228.28	52217.54
K	31.38	32.53	655.46	5382.55	23049.91
Ca	2170.97	4338.47	1794.33	12507.52	8265.87
Ti	18.08	106.50	237.91	88.05	2.71
Cr	65.17	108.98	199.07	192.34	183.45
Fe	459.72	886.81	4816.78	18750.34	15482.90
Ni	9.86	9.03	244.08	9243.34	3974.27
Cu	2.65	103.74	70.30	421.96	10.11
Br	2.89	8.91	22.14	34.88	3.16
Sr	24.97	1585.06	47.65	290.76	82.22
Zr	2.15	504.81	63.82	124.04	82.84
Cd	0.00	0.09	0.01	0.32	0.42
Te	0.00	0.00	0.00	0.03	0.05
Ba	276.65	22973.44	1244.51	4796.26	181.20
Th	0.00	0.04	0.04	0.70	0.19

Table 4. Compound composition of APS through XRF

Compound Wt.%	APS Sample				
	Electro	Phosphate	Primer	Based	Clear
F	1.58	11.3	0	0	0
Na_2O	0	5.27	0.449	0	0.727
MgO	0.616	0.146	1.12	0.176	0.559
Al_2O_3	6.77	1.65	11.5	3.92	7.35
SiO_2	1.72	2.46	4.6	3.47	0.608
P_2O_5	19.2	22.2	0.621	0.528	0.105
SO_3	1.44	1.24	0.413	16.6	0.249
Cl	0.16	0.0819	0.211	0.083	0.315
K_2O	1.79	3.7	0.197	0.0322	0.0303
CaO	4.66	1.27	0.623	0.681	1.49
TiO_2	5.12	0.133	51.8	21.4	0.0878
Cr_2O_3	0.105	0.0662	0.0793	0.0454	0.0491
MnO	4.26	2.9	0.0189	0.0329	0
Fe_2O_3	6.96	15.6	1.63	0.348	0.265
NiO	3.14	1.8	0.116	0.0144	0.0131
CuO	0.19	0.00785	0.0334	0.0547	0.00811
Br	0.00424	0	0.00354	0	0.00201
ZnO	2.17	1.84	0.0161	0.0107	0.0155
SrO	0.0262	0.00531	0.0078	0.506	0.00839
Y_2O_3	0	0.00125	0	0	0
ZrO_2	0.58	0.0306	0.0147	0	0
BaO	0.896	0.0218	0.182	40.7	0.032
Bi_2O_3	0.32	0.00937	0	0	0
CeO_2	0	0	0.252	0	0.091
Au	0	0	0.0113	0	0
Co_3O_4	0	0	0.0541	0	0
SnO_2	0	0	0.0208	0	0

Speculatively, the difference in setting time of the cement paste doped with different APS types may be correlated to the difference in composition of the APS and how that affects the hydration process. For instance, Primer APS is known to contain binders and fillers that improve adhesion of the paint onto the body of the vehicle. In the case of cement paste, this manifests in the increase of the setting time possibly due to improved dispersion in the paste as influenced by the binders and fillers, keeping the paste liquid longer. Clearcoat and base coat APS, composed of resins and solvents for finish and colour, show no clear trend, perhaps due to inconsistent interactions with the cement paste. Phosphate APS has compounds that bond with metals. Initially, it takes longer to set, perhaps due to the phosphate ions slowing down the process of hydration with competitive reactions interfering with the cement hydration reaction. In higher concentrations, the nucleation of calcium phosphate compounds might be more favourable, appearing as a faster setting time (Webster, Xiaozheng and Aisha, 2015; Akafuah *et al.*, 2016).

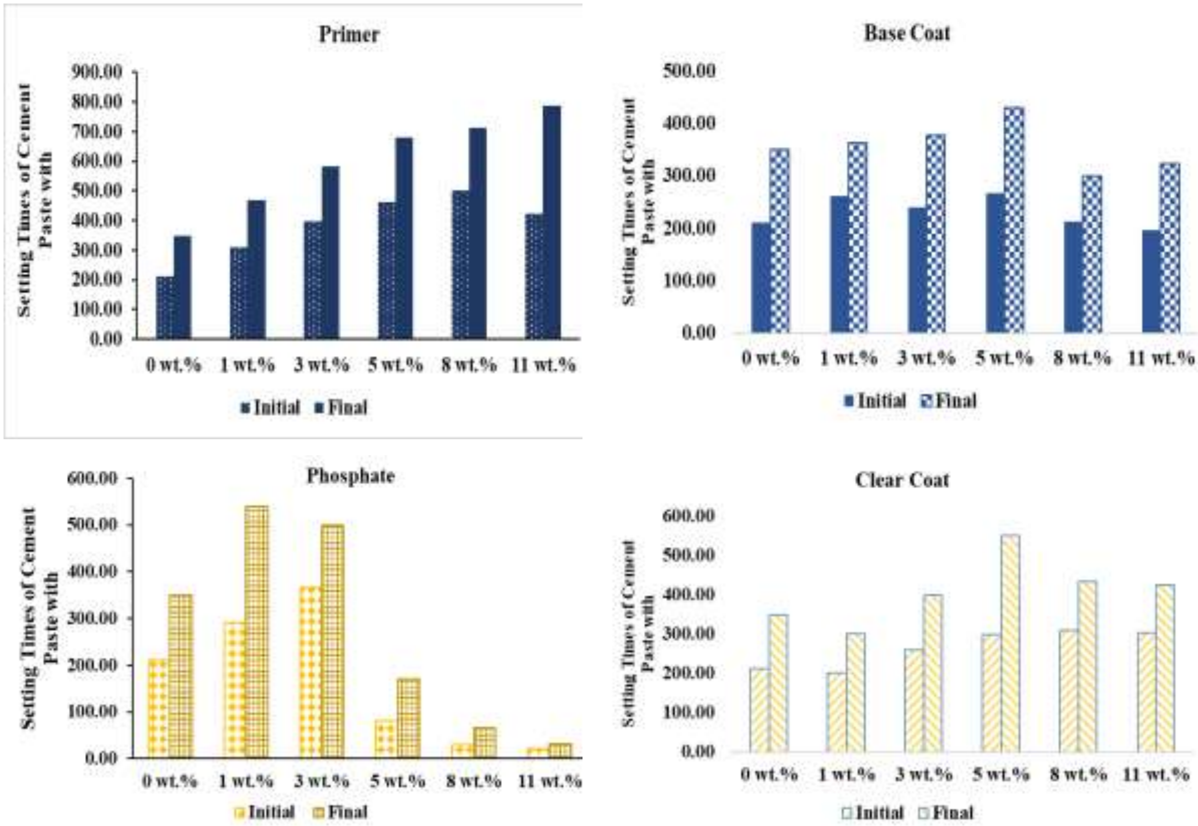

Fig. 2. Setting times of cement pastes with automotive paint sludge

3.3. Compressive strength

In Fig. 3, you can see the compressive strength of cement cubes made from a control sample (0 wt.% APS) and composite cement-APS samples with different amounts of APS (1–11 wt.%). A curing period of 7 days was selected to assess the early strength of the cement pastes. The findings indicate that the inclusion of APS in the cement paste diminishes compressive strength compared to the control specimen, which exhibited a compressive strength of 75 N/mm^2. The reduction in strength seems to be associated with rising APS content.

In this project, the maximum compressive strength was achieved with a 1 wt.% APS doping weight using Clear Coat APS—yielding a value of 69.79 N/mm^2. Increasing the APS content to 3 wt.% caused a significant reduction in compressive strength, with declines observed as follows: 26% for the clear coat, 30% for the base coat, 68% for the primer, and nearly 95% for the phosphate sludge. This trend intimates that a higher APS substitution ratio negatively affects the mechanical performance of the composite, as shown in Fig. 3.

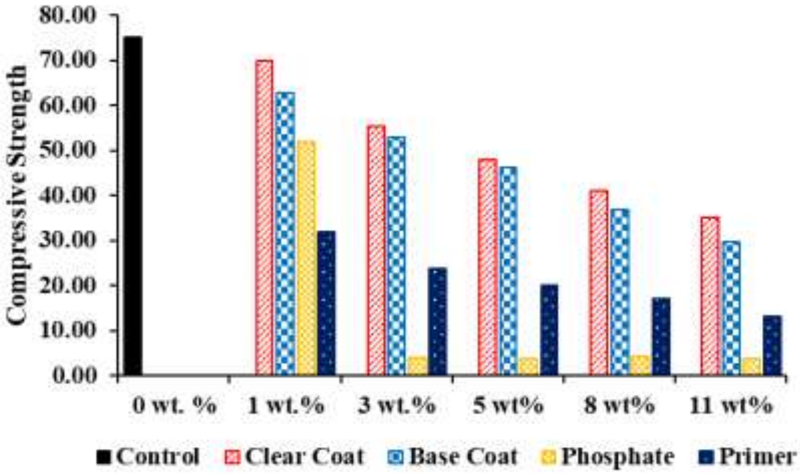

Fig. 3. Compressive Strength of APS – Cement Paste

The weakening in compression strength might be due to reactions between APS and calcium hydroxide, which is formed when cement hydrates. These kinds of interactions might help make a weak interfacial transition zone (ITZ) between the APS particles and the cement material (Bakar *et al.*, 2022). This weak ITZ may lead to a compromised total and capillary porosity in cement pastes that contain APS compared to the control cement paste. Concomitantly, this may result in APS-doped cement having lower strengths due to presence of fault lines and cracks.

The negative impact of APS on the microstructure was especially pronounced in primer APS, as illustrated in Fig 4, which shows visible swelling and cracking. In this respect the primer APS; which has significant organic components, may result in free water under the influence of immiscibility, escaping the cement paste on drying, leaving behind porosity. It's possible that extra water was reabsorbed into the cement paste through capillary action during the drying phase, after the plastic had settled. This caused the paste to swell and eventually crack very small (Bakar *et al.*, 2022). This caused paste thickness swelling of around 0.5 mm, reducing compressive strength.

It was found that adding small amounts of APS may keep some of the compressive strength, but adding more APS may make the hardened, finished cement structure much weaker. More study is needed to figure out the factors that affect adding APS to cement paste and making a more stable structure.

Fig. 4. Evidence of Swelling

Among the investigated sludges, phosphate sludge had the most negative impact on cement strength. When phosphate sludge is added at levels greater than 3 wt.%, the setting time of the cement paste reduces substantially, while compressive strength diminishes dramatically-by up to

95 % at ratios greater than 1 wt.%. This significant drop in strength shows that phosphate interferes with cement hydration processes, notably those that produce calcium silicate hydrate (C-S-H), the major strength-giving phase in hydrated cement paste.

Xie *et al.* (2021) noted that the microstructure of cement pastes with phosphorous is generally looser and more porous compared to conventional cement pastes. The presence of the phosphorous-based compound may confound the process of solidification of the cement paste through the formation of the C-S-H matrix, which would end up weakening the whole structure. This could be due phosphate interfering with the calcium hydroxide ($Ca(OH)_2$), thereby retarding the hydration reaction that forms C_3S and C_2S phases in cement, which are primarily responsible for the strength of hardened cement. These competing reactions may affect the matrix, leading to a drop in the strength.

Fig. 5 displays a white deposit which may be linked to efflorescence. Potentially, the more porous the microstructure of the cement paste, the more likely the calcium hydroxide to migrate to the surface and reacting with CO_2 from the atmosphere and forming $CaCO_3$, a whitish deposit. This effect may be more pronounced in cement paste contaminated with phosphorous, as its porous microstructure may enable $Ca(OH)_2$ and other calcium containing ions to move to the surface. Gong *et al.* (2016) also reported that phosphorous-containing chemicals might modify porosity and diminish compressive strength, thus increasing susceptibility to efflorescence. Although not structurally damaging on their own, the observed whitish deposits (potentially calcium carbonate) may reflect an underlying increase in porosity and pointing to weakened bonds in the cement matrix.

Phosphate sludge may accelerate the setting time but is detrimental to C-S-H formation, thus it weakens the cement paste matrix by making it more porous. The compressive strength of the cement paste is compromised.

Fig. 5. Phosphate reaction with Cement Paste

3.4. Flexural Strength

Fig. 6 shows the flexural strength of cement paste cured for 7 days. It is clear that prime coat APS admixture is associated with an increase in flexural strength relative to the control. This is true from 1 wt.% all the way to 11 wt.% APS in cement paste. The flexural strength is highest at 3 wt.% APS and starts tapering off at higher concentrations. The base coat APS admixture shows a statistically insignificant increase in flexural strength at concentrations ranging from 1 wt.% to 11 wt.% APS.

Clear coat APS admixture is associated with a gradual increase in flexural strength from a flexural strength that is lower than that of the control at 1 wt.% APS, to slightly higher from 3 wt.% to 8 wt.% and significantly higher at 11 wt.%. The phosphate APS blended cement paste's flexural strength starts off higher than the control's at 1 wt.% APS. It then deleteriously decreases to less than a third of the flexural strength of the control at higher concentrations of APS.

The addition of APS as an admixture in cement paste, especially when the APS is derived from clear, base and primer coats, is generally associated with an increase in flexural strength. This is not withstanding the likely decrease in the compressive strength and a longer setting time for the cement paste. Literature reports that adding APS up to 10 wt.%, enhances pozzolanic reactions with compounds such as MgO, SiO_2, CaO, Fe_2O_3, TiO_2, and Al_2O_3, facilitating the development of calcium-silicate-hydrate (C-S-H) or similar gel. Structural integrity and resistance to bending stresses is thus engendered by the addition of the APS (Goñi *et al.*, 2012; Yeganeh and Khatamgooya, 2023)

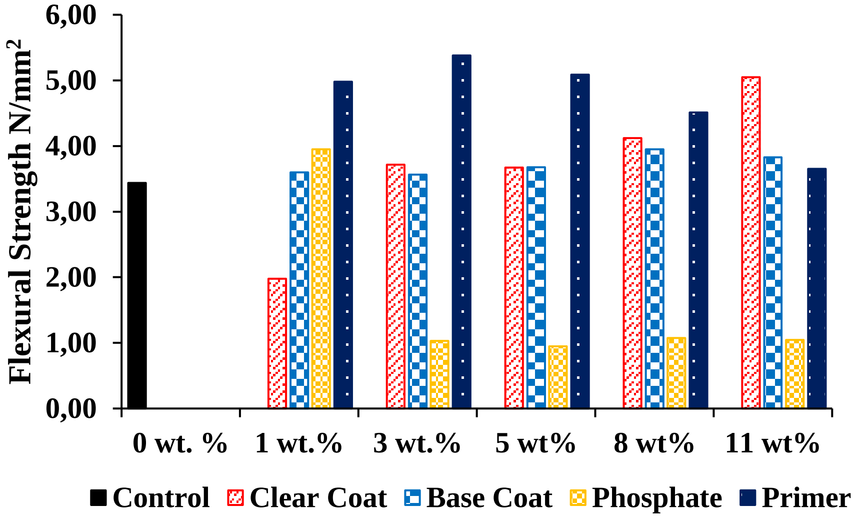

Fig. 6. Flexural Strength of APS - Cement Paste

It is posited that the components within APS may assist in energy dissipation and crack deflection, thus creating a tougher and more durable matrix when subjected to bending forces, akin to the impact of fibre orientation (anisotropy) in fibre-blended cement (Hambach *et al.*, 2016). However, it is noteworthy that, when APS content exceeds a certain threshold level, the decrease in the compressive strength due to the dilution of cementitious material and the presence of unreacted constituents, may introduce weak points in the structure (Liang *et al.*, 2022; Yeganeh and Khatamgooya, 2023).

It is worthwhile to delineate the response of the APS sourced from phosphate coats: it does not follow the trend of the other coat admixtures for cement paste. The observation has been that both the compressive and the flexural strengths are generally lower than the control. A possible explanation for this could be the lack of pozzolanic contribution that clear, base and primer coat APS provide. This would make it less effective as an additive for improving flexural performance in cementitious applications. Consequently, impractical for use in construction materials.

4. Conclusions

The South African Automotive Manufacturing industry produces a substantial amount of automotive paint sludge (APS). Reuse, instead of discarding this industrial waste, would help in the transition to a linear economy, to a more sustainable circular economy. This study shows that automotive paint sludge can be tailored to work as an additive in cement paste, by potentially increasing its flexural strength compared to the cement paste without APS. Of the different types of APS, the phosphate pretreatment coat seems unsuitable, even though it has the most silica content relative to the other forms of APS. It has the least compressive and flexural strength of performance, even lower than the control. This is based on a curing period of only 7 days. Future work will focus on a longer curing period. Equally, it is recommended that the APS should be calcined to remove the volatile matter content before its application in cement-based composites to reduce the apparent plasticity presented by the organics. Other recommendation includes the use of APS in clay bricks and other ceramic products where heat treatment above the curing temperature of the raw APS, activates the sludge to increase binding properties.

5. References

Aboulnaga, M., Amer, A. and Al-Sayed, A. (2020) 'Towards sustainable development: Mega project's strategic environmental assessment to attain SDG 7, 9, 11, 12 and 13', Sustain. Mediterr. Constr, 2020, pp. 101-106.

Akafuah, N. K., Poozesh, S., Salaimeh, A., Patrick, G., Lawler, K. and Saito, K. (2016) 'Evolution of the automotive body coating process—A review', Coatings, 6(2), pp. 24.

Avci, H., Ghorbanpoor, H., Topcu, I. B. and Nurbas, M. (2017) 'Investigation and recycling of paint sludge with cement and lime for producing lightweight construction mortar', Journal of environmental chemical engineering, 5(1), pp. 861-869.

Bakar, N. F. A., Sidek, M. N. M., Suharman, S. M. and Abd Rahman, N. (2022) 'Characterization and evaluation of dried automotive paint sludge as cement-based composite', Materials Today: Proceedings, 63, pp. S301-S305.

Bui, T.-D., Tseng, J.-W., Tseng, M.-L. and Lim, M. K. (2022) 'Opportunities and challenges for solid waste reuse and recycling in emerging economies: A hybrid analysis', Resources, Conservation and Recycling, 177, pp. 105968.

Câmara, C. M., Ferrazzo, S. T., Levandoski, W. M. K., da Silva, C. V. and Korf, E. P. (2024) 'Paint booth waste as an alternative aggregate for the production of interlocking concrete blocks', Scientific Reports, 14(1), pp. 3180.

Cheng, D., Reiner, D. M., Yang, F., Cui, C., Meng, J., Shan, Y., Liu, Y., Tao, S. and Guan, D. (2023) 'Projecting future carbon emissions from cement production in developing countries', Nature Communications, 14(1), pp. 8213.

Gong, T., Wang, Z., Zhang, Y., Zhang, Y., Hou, M., Liu, X., Wang, Y., Zhao, L., Ruse, N. D. and Troczynski, T. (2016) 'A comprehensive study of osteogenic calcium phosphate silicate cement: material characterization and in vitro/in vivo testing', Advanced healthcare materials, 5(4), pp. 457-466.

Goñi, S., Frias, M., Vegas, I., García, R. and De La Villa, R. V. (2012) 'Effect of ternary cements containing thermally activated paper sludge and fly ash on the texture of C–S–H gel', Construction and Building Materials, 30, pp. 381-388.

Hambach, M., Möller, H., Neumann, T. and Volkmer, D. (2016) 'Portland cement paste with aligned carbon fibers exhibiting exceptionally high flexural strength (> 100 MPa)', Cement and Concrete Research, 89, pp. 80-86.

Hossain, R., Mrinmoy, H. S., Arsh, K., Hoque, A. and Masum, M. M. H. 'Partial Replacement of Cement with Paint Sludge in Concrete Block & its Environmental Impacts'. Proceedings of the 7th International Conference on Civil Engineering for Sustainable Development (ICCESD 2024): Springer Nature, 347.

Katare, V. D. and Madurwar, M. V. (2020) 'Design and investigation of sustainable pozzolanic material', Journal of Cleaner Production, 242, pp. 118431.

Kilani, A. J., Ikotun, B. D. and Abdulwahab, R. (2025) 'Enhancing the Structural Properties of Mortar with Treated Rubber Crumb', AHFE, [Preprint].

Liang, R., Liu, Q., Hou, D., Li, Z. and Sun, G. (2022) 'Flexural strength enhancement of cement paste through monomer incorporation and in situ bond formation', Cement and Concrete Research, 152, pp. 106675.

Marian, N. M. (2023) 'The role of mineralogy in circular economy: from inorganic special wastes to secondary raw materials'.

Nokulunga, M., Didi, T. and Clinton, A. 'Challenges of reconstruction and development program (RDP) houses in South Africa'. Proceedings of the International Conference on Industrial Engineering and Operations Management, 1695-1702.

Ogunfiditimi, O. (2008) Assessment of structural quality of houses delivered through the people's housing process in South Africa. University of Johannesburg (South Africa), p. 64 to 92.

Ruffino, B., Campo, G., Idris, S. S., Salihoğlu, G. and Zanetti, M. (2023) 'Automotive Paint Sludge: A Review of Pretreatments and Recovery Options', Resources, 12(4), pp. 45.

Ruffino, B., Farina, A., Dalmazzo, D., Blengini, G., Zanetti, M. and Santagata, E. (2021) 'Cost analysis and environmental assessment of recycling paint sludge in asphalt pavements', Environmental Science and Pollution Research, 28, pp. 24628-24638.

Salihoglu, G. and Salihoglu, N. K. (2016) 'A review on paint sludge from automotive industries: Generation, characteristics and management', Journal of environmental management, 169, pp. 223-235.

Solid-waste disposal tariffs for 1 July 2018 – 30 June 2019 (2018), Cape Town: Water & Waste Services Department, City of Cape Town. Available at: https://greencape.co.za/assets/Uploads/CCT-Solid-Waste-Disposal-Tariff-Letter-June-2018.pdf (Accessed: 22 May 2025 00:22 a.m.).

Tsardaka, E.-C., Sougioultzi, K., Konstantinidis, A. and Stefanidou, M. (2023) 'Interpreting the setting time of cement pastes for modelling mechanical properties', Case Studies in Construction Materials, 19, pp. e02364.

Webster, M. J., Xiaozheng, W. and Aisha, Z. (2015) 'Rheology and setting time of cement paste', Am. J. Civ. Eng. Archit, 3, pp. 208-211.

Xie, L., Deng, M., Tang, J. and Liu, K. (2021) 'Hydration and strength development of cementitious materials prepared with phosphorous-bearing clinkers', Materials, 14(3), pp. 508.

Yeganeh, B. and Khatamgooya, A. (2023) 'The feasibility study of stabilizing the automotive paint sludge by recycling, to produce green concrete blocks, considering environmental and mechanical factors', Journal of Material Cycles and Waste Management, 25(2), pp. 931-943.