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Engineering Rapid Hardening Repair Mortar for Ballast-Less Track Maintenance

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Abstract

Cement asphalt mortar is a cushion layer performing the role of vibration absorption in the ballast-less tracks under high-speed rail infrastructure. The compressive strength of hardened CAM, satisfying the 1, 7 and 28-day strength requirement stands as a crucial performance parameter. Strength development is governed by the asphalt content and the choice of cementitious component and hydration aiding agents added during production. The present study relates to the development of rapid-hardening CAM for repair applications where achieving the strength in the short duration is crucial considering the seamless operation. It examines the influence of cementitious component choice, its chemical composition, and blending proportion on CAM compressive strength. Seven CAM combinations were evaluated, and results identifying ordinary Portland cement and calcium aluminate cement in a 90:10 ratio as superior to ordinary Portland cement with calcium sulphoaluminate. Significant impacts of CAC grade and sulphate proportion on CAM strength are noted, correlated with strength development. Mass percentages of oxides demonstrate positive Al_2O_3 dependence and negative SO_3 dependence on strength development. Optimized cementitious component for CAM formulation includes 10% CAC with 50-75% Al_2O_3 content blended with 90% OPC and hardening admixture, for rapid-hardening repair mortar, ensuring strength within short durations.

Keywords: cement asphalt mortar, high speed rails, rapid hardening, ballastless track, expansive cements, asphalt emulsion.

1 Introduction

The introduction of high-speed rail (HSR) has necessitated the development of advanced track systems to replace traditional ballasted tracks. The ballasted tracks for high-speed trains often suffer damage from ballast crushing under the train's high-frequency loading resulting in disturbed track geometry raising safety concerns. To address this issue, the Japanese National Railways introduced the Shinkansen slab track system, a non-ballast track system now used in HSR networks, including China, and Korea. This system offers several advantages over traditional ballasted tracks, such as reduced height, lower maintenance needs, improved damping properties, and longer service life [1–3]. A key component of this track system is the cement asphalt mortar (CAM), which is placed between a concrete roadbed and a precast reinforced concrete track slab. CAM acts as a cushion layer, absorbing vibrations from high-speed trains [4]. It is a composite material made of Portland cement, asphalt emulsion, water, sand, and other chemical admixtures. During construction, the mortar is injected between the track slab and the roadbed through an inlet valve. CAM serves two important functions: dissipating vibrations and transferring stress from passing trains to the underlying structure. There are two types of CAM used in HSR, depending on whether enhanced strength or improved damping is required. CAM II (asphalt (A)/cement (C) ratio: 0.2-0.6) is high-strength and used in the Bögl slab track system in Germany, while CAM I (A/C ratio: 0.6-1.2) has lower strength but excellent damping properties, used in the Shinkansen slab track system in Japan [5]. This study focuses on CAM I, hereafter referred to as CAM.

Originating from Japanese Railways and widely adopted in North-East China, CAM was serviced in temperature ranges, from sub-zero temperatures to ambient conditions (25°C). As a composite material, CAM faces challenges in strength development due to the presence of asphalt emulsion and polymer dispersions, which retard its hydration behavior, potentially leading to delayed setting and strength development [6]. Z. Leiben et.al examined how varying asphalt content in CAM impacts damping and strength properties. The study found that increased asphalt content in CAM leads to greater damping characteristics, attributed to asphalt's viscoelastic nature, but reduces compressive strength due to a retarding effect [7]. Thus, designing CAM with high asphalt content, while meeting compressive strength standards, proves advantageous for vibration absorption. Further, CAM is seen to demonstrate early age volume change (shrinkage) owing to the high surface area to volume ratio and the rapid loss of water due to hydration [8]. Considering the delayed hydration of cement and plastic shrinkage in CAM, existing specifications specify the usage of a calcium sulphoaluminate (CSA) cement as an expansive component and as a partial replacement to OPC to address the early strength development and shrinkage characteristic observed in CAM [9]. The compressive strength requirements of CAM with 0.1 MPa, 0.7 MPa and 1.8 MPa at 1, 7, and 28 days respectively are crucial milestones, signifying key operational phases in track construction. Additionally, meeting technical specifications regarding fluidity and working time is imperative for successful on-site application and service.

Performance of a HSR slab track system is related to factors such as resistance to edge debonding and permanent deformation [10]. Instances of CAM interlayer degradation due to high-frequency vibration and repeated loads have been reported, leading to the deterioration of the CAM layer and the creation of voids, which can compromise the comfort and safety of high-speed rail travel [11,12]. In such events of CAM deterioration, the damaged or deformed mortar must be removed and grouted with a repair mortar. However, the repair mortar must possess the same strength and performance requirements as CAM during service, with the added constraint of achieving the required 1.8 MPa strength at a relatively early rate, typically within 7 days instead of 28 days. This is to accommodate the time constraints of track maintenance and minimize disruptions to train operations. A noticeable research gap exists in the exploration of alternative materials and methods for enhancing the early strength of CAM. While existing literature extensively covers the performance evaluation of CAM and the interaction mechanisms between cement and asphalt emulsion, there are limited or no studies focusing on incorporating rapid setting cements, ternary binders constituting high alumina cements, and chemical admixtures into CAM formulations specifically for maintenance applications. Understanding the adaptability of these alternatives to asphalt emulsion and their impact on strength development remains largely unexplored within the landscape of CAM production. Therefore, it is essential to study the selection and blending of cementitious components and to develop a CAM formulation specifically tailored for repair and maintenance events, considering the time constraints and the need to achieve the required strength and performance characteristics within a shorter timeframe compared to the standard CAM used in new construction.

2 Materials and Methodology

2.1 Materials

The cementitious component (CC) of CAM constitutes ordinary Portland cement (OPC) and expansive component system (ECS). ECS comprises an expansive cement and anhydrite (anhydrous calcium sulfate, C$). Considering the objective of the study, OPC used was a high-grade cement having a minimum compressive strength of 53 MPa. With a focus on the ECS component, the study examines two types of expansive cements specified in ACI 223R-10: calcium sulphoaluminate (CSA) and calcium aluminate cement (CAC), in combination with anhydrite. The composition details of OPC, expansive cements, and anhydrite derived from X-ray diffraction (XRD) analysis are provided in Table 1, while the combinations of the cementitious component and the resulting chemical composition from X-ray fluorescence (XRF) study are outlined in Table 2. In addition to the cementitious components mentioned earlier, a hardening admixture composed of a blend of aluminium sulphate, aluminates, nitrates, and thiocyanates was employed to impart rapid hardening properties upon CAM. The choice of hardening admixture was made carefully to ensure it had no impact on the setting time of CAM.

	Chemical composition, %				
	SiO_2 (S)	Fe_2O_3 (F)	Al_2O_3 (A)	CaO (C)	SO_3 ($\$$)
OPC	21.20	3.71	4.98	64.40	4.27
CSA	1.64	0.80	3.00	50.39	39.83
CAC:1	5.50	3.71	45.00	34.00	0.00
CAC:2	0.50	0.25	72.00	26.00	0.00
$C\$$	0.00	0.00	0.00	28.38	71.39

	Phase composition, %									
	C_3S	C_2S	C_3A	C_4AF	CaO	$C\underline{S}H_x$	$C_4A_3\$$	CA	CA_2	C_2AS
OPC	62.15	11.62	6.19	17.04	0.20	1.0	0.00	0.00	0.00	0.00
CSA	11.36	3.39	11.51	8.94	1.49	42.2	15.54	0.00	0.00	0.00
CAC:1	0.30	6.98	12.63	3.80	0.00	3.36	0.00	17.95	1.42	43.30
CAC:2	0.00	0.30	0.00	0.38	0.35	0.80	0.00	26.35	64.94	1.85
$C\underline{\$}$	0.00	0.00	0.00	0.00	0.00	100	0.00	0.00	0.00	0.00

Table 1: Chemical and phase composition of cementitious components used in the study

Code	Blend composition	Chemical composition, %				
		SiO_2	Fe_2O_3	Al_2O_3	CaO	SO_3
CC1 (control)	90% (OPC) + 10% (CSA)	19.24	3.41	4.78	63.17	7.82
CC2	90% (OPC) + 10% (CAC:1)	19.63	3.78	8.98	61.54	3.84
CC3	90% (OPC) + 7% (CAC:1) + 3% ($C\$$)	19.46	3.654	7.63	61.37	5.98
CC4	90% (OPC) + 5% (CAC:1) + 5% ($C\$$)	19.35	3.564	6.73	61.25	7.41
CC5	90% (OPC) + 10% (CAC:2)	19.13	3.36	11.68	60.74	3.84
CC6	90% (OPC) + 7% (CAC:2) + 3% ($C\$$)	19.11	3.35	9.54	60.81	5.98
CC7	90% (OPC) + 5% (CAC:2) + 5% ($C\$$)	19.10	3.35	8.08	60.85	7.41

Table 2: Composition of cementitious component followed in the present study

Apart from the cementitious component, slow-setting asphalt emulsion (AE) satisfying the requirements of IS 3117 was used in the production of CAM, while enhancing asphalt stiffness was achieved through the incorporation of synthetic polymer dispersion (PD). Together, they form the organic binder. These chosen organic binders and cementitious components exhibit stability when mixed resulting in mortar with fluidity ranging from 16 to 28 seconds and a working time exceeding 50 minutes. Tap water (W) and dry river sand (S) with a fineness modulus of 1.6 were used. Along with the above constituents, aluminium (Al) as an expansive agent, rosin-type air-entraining agent (AEA) and silicone based defoamer to arrest foam produced during mixing of organic binders, were used to meet the technical requirements of CAM as adopted in Japanese HSR and CRTS-1.

2.2 Methodology

The methodology comprised two main phases of laboratory experimentation. Initially, the focus was on assessing the impact of expansive cement composition and sulphate content on the compressive strength characteristics of CAM. Subsequently, the investigation progressed to incorporate a hardening admixture into the most effective combination identified from the initial step, aiming to enhance the rapid hardening properties of CAM for repair applications.

The first phase involved evaluating the 28-day compressive strength of CAM under varied cementitious components, as detailed in Table 2, to identify the optimal combination. This assessment also included an analysis of the cement's hydration using XRD to quantify the amorphous content and understand the influence of different expansive cements and sulphate content. Additionally, correlation analyses were performed between chemical composition and compressive strength to identify the factors significantly affecting strength development.

In the second phase, the selected combination from the first phase underwent further testing with the addition of a hardening admixture. Strength evaluations were conducted at intervals of 1, 7, and 28 days to evaluate the effect of the added hardening admixture on rapid hardening.

2.3 CAM design and production

Production of CAM involves mixing the constituents to form a homogenous mortar. Table 3 presents the constituent proportions employed in CAM production. Notably, while the asphalt emulsion content varies between the first phase (MCC1 to MCC7) and the second phase (MCC5-a), it is essential to recognize that the initial phase assessment aims solely to identify the most effective combination. The proportions specified for the second phase represent the targeted asphalt emulsion proportion crucial for ensuring the desired damping characteristics. The manufacturing process involved introducing liquid components, including asphalt emulsion, polymer dispersion, water, and defoamers, into a planetary mixer. This was followed by the addition of cementitious components, sand, and air-entraining agents. The constituents were mixed for a duration of 270 seconds.

Mortar combination	Asphalt emulsion	Polymer dispersion	Cementitious component	Water	Sand	Hardening admixture
MCC1 to MCC7	1.2	0.2	1	0.17	2	-
MCC5-a	1.4	0.2	1	0.17	2	0.04

Table 3: Proportions of constituents used in the CAM production

Where, MCC1 is read as mortar with CC1 blend, MCC2 with CC2 blend and so on. The relative ratios are expressed w.r.t cementitious component. Constituent ratios of admixtures, DF: 0.001; AEA: 0.00025; Al: 0.00025

2.4 Test methods

Compressive strength involves producing CAM to the desired proportions and consistency and poured into 2-inch (50 mm) cubes for assessing compressive strength. The samples were demoulded after 24 hours before curing at 25 °C and a relative humidity of 65 ± 5. Samples were conditioned for 6 hours at desired testing temperature of 25 °C before the test. Compressive strength was determined at a loading rate of 1 mm/min.

X-ray diffraction test is carried out on un-hydrated cementitious components to know the initial phase composition and on hydrated cementitious paste to evaluate the hydration kinetics. The samples were grounded to powder with a fineness less than 45 μm for XRD and XRF analysis. From the XRD data, qualitative analysis was performed using the mineral data base in order to identify crystalline phases. Once all phases were identified, Profex 5.2 software was used for quantitative phase analysis using Rietveld method which relies on minimization of the difference between the measured and the calculated intensities using non-linear least square fitting algorithm. To evaluate the amount of amorphous phase (C-S-H), 10% Al_20_3 relative to the weight of cementitious component was blended before mixing to serve as an internal standard. The chemical composition of cementitious components is determined through XRF.

3 Results

3.1 Influence of expansive cement grade and sulphate proportioning on the compressive strength

The impact of expansive cement type and sulphate proportion on the compressive strength characteristics of CAM, taking into account the reaction kinetics of various cementitious raw materials with sulphates is evaluated in this study. Figure 1 illustrates the compressive strength of CAM combinations (on the left axis) in relation to the type of expansive component system incorporated, while the right axis indicates the quantity of amorphous phase (C-S-H). The amorphous phase data in Figure 1 is derived from the phase quantification by Reitvield refinement based on XRD analysis of hydrated pastes. XRD patterns of grounded samples of hydrated cementitious component blends, tested at 28 days, are presented in Figure 2.

Among the mortar combinations, it was observed that MCC5, specifically with OPC and CAC:2 in the ratio 90:10, exhibited the highest compressive strength of 2.22 MPa after 28-day curing. In contrast, the specification-recommended cementitious component CC1 yielded a compressive strength of 1.37 MPa, marking a 40% decrease compared to MCC5. This is due to the high percentages of calcium aluminates (C_3A, CA, CA_2 and C_2AS) present in the CAC which assists mortar in the early setting property. Mortar combinations incorporating CAC demonstrated higher compressive strength compared to the control mortar with CSA (MCC1), indicating the influence of expansive cement type. Table 4 shows the unhydrated (0 day) and the evolution of and hydrated phases (1 and 28 day) in different cementitious components derived from Rietveld analysis. The consumption of phases and the evolution of portlandite (CH) and C-S-H over time can be seen from the table across different cementitious pastes. The change of phase compositions over time explains the hydration of blended cementitious components.

Further analysis of compressive strength across mortar combinations (MCC2 to MCC7) and their corresponding chemical composition (Table 2) revealed that the grade of calcium aluminate cement (CAC) in terms of Al_2O_3 content and the proportion of calcium sulphate significantly influenced the strength of CAM. The amount of C-S-H by quantitative analysis through XRD demonstrated a correlation with the strength of the mortar.

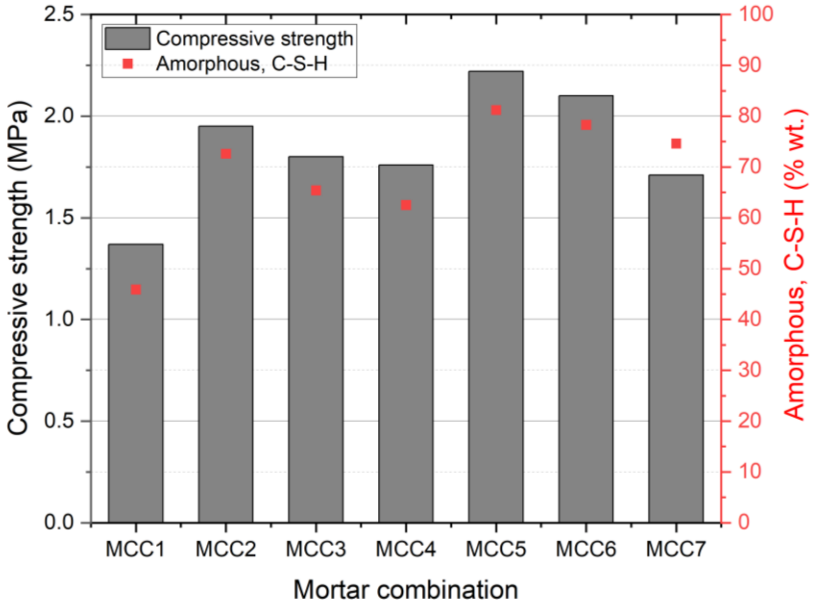

Figure 1: 28-day compressive strength of CAM under different cementitious component blends

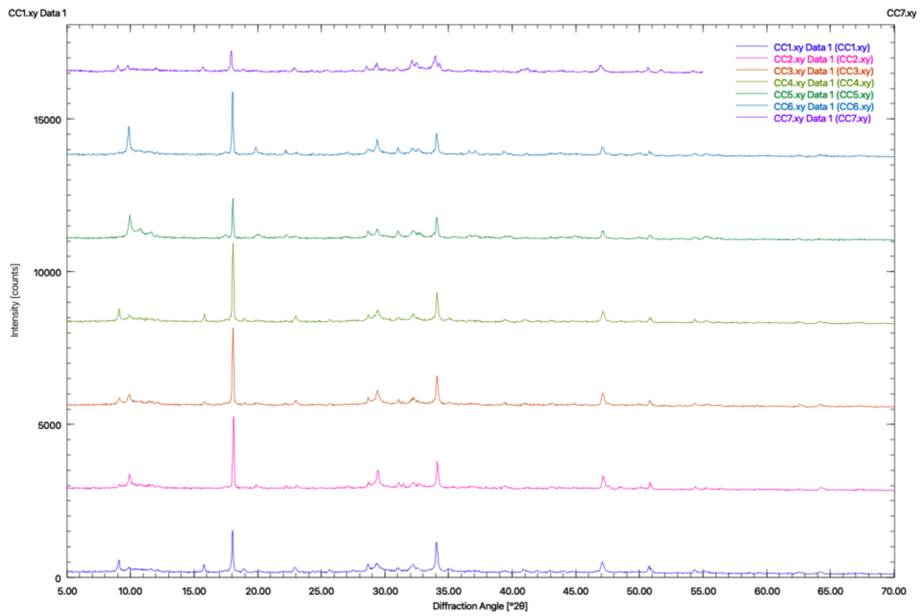

Figure 2: XRD patterns of hydrated cementitious component blends

	Age	Phase composition (%)						
		C_3S	C_2S	C_3A	C_4AF	$C_4A_3$$	CH	CSH
CC1	0	57.0	10.8	6.7	16.2	1.55	0	0
	1 day	18.2	12.2	6.8	10.74	0.27	11.6	17.9
	28 day	4.6	7.1	0.2	2.3	0	14.1	45.9
CC2	0	55.9	11.1	6.8	15.7	0	0	0
	1 day	17.3	7.8	3.2	6.1	0	3.1	50.2
	28 day	2.3	4.1	1.5	2.1	0	7.1	72.6
CC3	0	55.9	10.9	6.4	15.6	0	0	0
	1 day	15.1	12.5	3.8	10.0	0	9.6	24.0
	28 day	2.6	4.5	1.7	2.3	0	7.9	65.4
CC4	0	55.9	10.8	6.2	15.5	0	0	0
	1 day	16.8	13.8	4.3	11.2	0	10.6	26.7
	28 day	3.2	4.2	0	2.5	0	6.4	62.5
CC5	0	55.9	10.4	5.5	15.3	0	0	0
	1 day	19.9	9.0	4.7	4.4	0	0.9	48.4
	28 day	2.6	2.7	0.9	0.6	0	2.4	81.2
CC6	0	55.9	10.4	5.5	15.3	0	0	0
	1 day	15.4	8.1	5.3	7.4	0	5.3	42
	28 day	2.2	2.9	0.6	1.0	0	3.2	78.3
CC7	0	55.9	10.4	5.5	15.3	0	0	0
	1 day	16.5	11.9	5.5	9.3	0	11.5	13.8
	28 day	2.1	2.7	0	1.1	0	10.9	75.1

Table 4: Phase composition of cementitious components used in the study

To assess the impact of the chemical composition of cementitious components on compressive strength, the relationship between compressive strength measured at 28 days ($Strength_{28}$) and the mass ratios of metal oxides (Al_2O_3, CaO, SO_3) was analyzed. Figure 3 illustrates the graphs plotted between $Strength_{28}$ and oxide mass ratios, providing insight into their correlations. Correlation analysis was conducted to visualize and quantify the relationships among multiple variables in the dataset. Table 5 displays the correlation of Al_2O_3, CaO and $SO_3$with $Strength_{28}$.

The correlation matrix indicates a strong positive dependence of $Al_2O_3$and a negative dependence of CaO and SO_3 on strength development in the landscape of ternary binder system. Moreover, a high correlation between Al_2O_3 and CaO is observed, attributed to their interdependent roles in chemical composition and clinker formation (C_3A and C_4AF). Figure 3.d presents the compressive strength as a function of oxides in the form of $Al_2O_3/(CaO*SO_3)$, which offers a better explanation of mortar strength behavior. The study underscores that calcium aluminate cement, with an Al_2O_3 content ranging from above 50% to below 75%, proves most suitable for the production of repair mortar, especially when rapid strength development is essential.

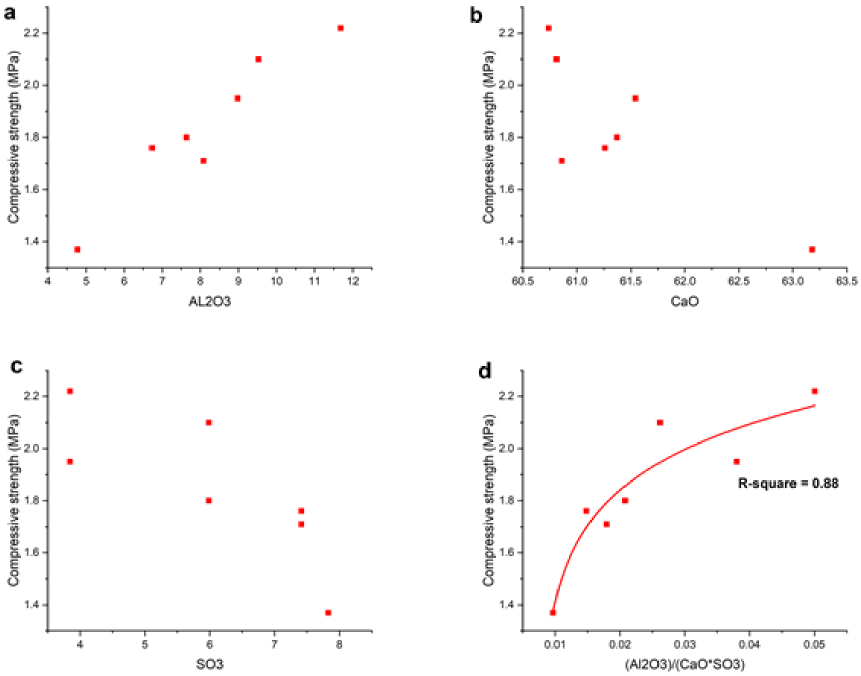

Figure 3: Plot between Str28 and mass ratios

	$Strength_{28}$	Al_2O_3	CaO	SO_3
$Strength_{28}$	1			
Al_2O_3	0.8708	1		
CaO	-0.4298	-0.7483	1	
SO_3	-0.8508	-0.6574	0.0416	1

Table 5: Correlation matrix of data sets

3.2 Material selection and proportioning for rapid hardening repair mortar

Upon the understanding of chemical composition and its impact on strength development, MCC5 incorporating CAC:2 was selected for further investigation to develop rapid-hardening repair mortar. The constituent proportions incorporating hardening admixture (MCC5-a) outlined in Table 3 were utilized in the production of CAM. Samples were demolded and conditioned at 25°C for 6 hours prior to testing. Figure 4 displays the compressive strength of the repair mortar tested at 1, 7, and 28 days. The plot reveals that the formulated repair mortar meets the 7-day strength requirement within 1 day and achieves the 28-day requirement by day 7. The is attributed to the rapid hydration of cement phases in the presence of hardening admixture. This rapid strength gain indicates that the grouted repair mortar is suitable for operations such as the loading of track materials and heavy objects within 1 day, and can be serviced within 5-7 days.

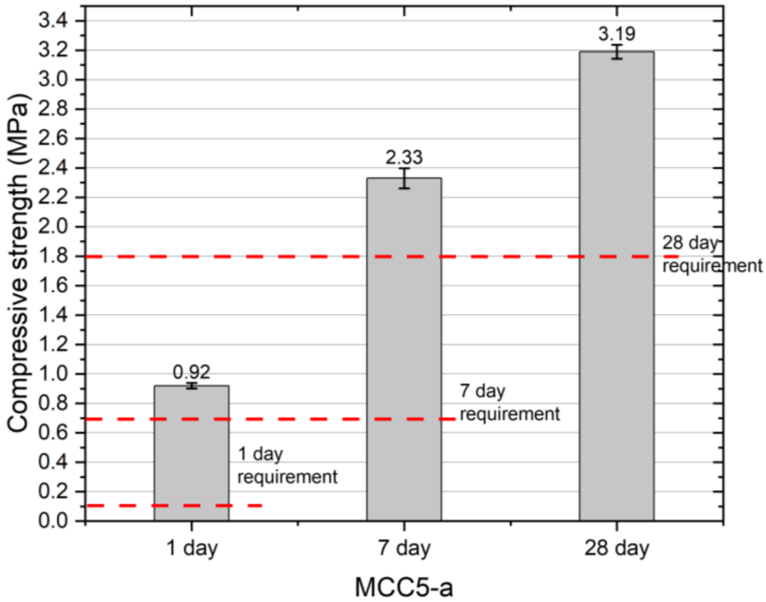

Figure 4: Compressive strength of repair mortar (CAM)

4 Conclusions

To produce cement asphalt mortar for repair applications in ballast-less tracks, selection of cementitious constituents is crucial considering the time limitation for maintenance. Hence, the primary objective of the study was to develop a rapid hardening repair mortar for maintenance activities concerning ballast-less tracks. Based on the results, the following conclusions can be drawn:

1. The study investigates the influence of expansive cement type and sulphate proportion on the compressive strength characteristics of CAM, accounting for the reaction kinetics of various cementitious raw materials with sulphates.
2. Observation of mortar combinations highlights that MCC5, particularly with OPC and CAC:2 in a 90:10 ratio, exhibits the highest compressive strength after 28-day curing, surpassing the specification-recommended cementitious component (OPC and CSA) CC1 by 40%.
3. Analysis across mortar combinations (MCC2 to MCC7) and their chemical composition reveals that the grade of calcium aluminate cement (CAC) and the proportion of calcium sulphate significantly affect CAM strength, with a correlation observed between the amount of C-S-H produced and mortar strength.
4. Examination of the relationship between compressive strength at 28 days ($Strength_{28}$) and oxide mass ratios (Al_2O_3, CaO, SO_3) further explains the impact of chemical composition on strength development, indicating a strong positive dependence of Al_2O_3 and a negative dependence of CaO and SO_3.
5. Notably, calcium aluminate cement with an Al_2O_3 content between 50% and 75% emerges as a suitable rapid-hardening component for CAM production, facilitating meeting strength requirements within short durations.
6. The study demonstrates that incorporating hardening admixture to OPC+CAC:2 combination for CAM production accelerates strength gain,

enabling the formulated repair mortar to meet 7-day strength requirements within 1 day and achieve 28-day requirements by day 7, thus enhancing operational efficiency in ballast-less track maintenance.

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