

Compressive Strength Performance of Cement-Treated Base (Class A) with Waste Paper Pulp as Partial Fine Aggregate Replacement

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The growing demand for sustainable road infrastructure has encouraged the use of alternative materials to reduce dependence on non-renewable natural resources. This study aims to evaluate the effect of waste paper pulp as a partial replacement for fine aggregate on the compressive strength of Cement-Treated Base (CTB) Class A and to determine an optimal and economical substitution level that meets technical requirements. An experimental program was conducted using Portland Pozzolan Cement (PCC), fine and coarse aggregates, and waste paper pulp as a fine aggregate substitute at replacement levels of 0%, 30%, 40%, 50%, 60%, and 70% by volume. Two mixture conditions were examined: mixtures without superplasticizer and mixtures containing 0.3% superplasticizer by weight of cement. Cylindrical specimens measuring 150 mm in diameter and 300 mm in height were prepared using a standard layered compaction method and cured under moist conditions. Compressive strength tests were performed after seven days of curing. The results show that compressive strength decreases as the proportion of waste paper pulp increases for both mixture conditions. A compressive strength of 48.12 kg/cm² was achieved at a 30% substitution level without superplasticizer, satisfying the CTB Class A requirement of 45–55 kg/cm². Although the addition of superplasticizer enhanced compressive strength, the 30% waste paper pulp mixture without superplasticizer was identified as the most economical and suitable composition. The findings indicate that waste paper pulp can be effectively utilized as a sustainable fine aggregate replacement in CTB Class A applications when applied at an optimal proportion.

Keywords: Waste paper pulp, Cement-treated base, Fine aggregate substitution, Compressive strength, Sustainable pavement materials

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Introduction

Cement-Treated Base (CTB) is a pavement foundation layer composed of aggregates stabilized with cement and is commonly classified into Class A, B, or C depending on its mechanical performance and application requirements. CTB Class A is widely used in road construction due to its high strength, durability, and resistance to water infiltration, making it suitable for areas with high rainfall or high groundwater levels. In regions with increasing heavy traffic volumes, such as industrial and port areas, CTB Class A is often selected as an alternative to Asphalt Treated Base (ATB) to improve structural performance and service life (Direktorat Jenderal Bina Marga, 2017).

However, road transportation contributes the largest share of greenhouse gas emissions among all transportation modes, accounting for approximately 72% of total transport-related emissions in 2019 (Agency, 2022). In addition, conventional pavement materials are primarily derived from non-renewable natural resources, which are becoming increasingly scarce. These conditions highlight the urgent need for alternative and sustainable materials in pavement construction to reduce environmental impacts and resource depletion (Prihatini et al., 2024). One promising approach is the utilization of waste materials to partially replace natural aggregates, thereby supporting sustainable infrastructure development and waste reduction.

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Flexible pavement performance is strongly influenced by material properties and construction design. Pavements constructed in areas with high groundwater levels and heavy traffic loads are particularly susceptible to premature deterioration. Therefore, the use of stabilized base layers, such as CTB, is essential to enhance bearing capacity and structural stability, both for new pavements and for the rehabilitation of existing roads with low subgrade strength (Hardiyatmo, 2019; Saepudin, 2019). Aggregates used in base layers must satisfy strict strength and durability requirements, which necessitates comprehensive material characterization before implementation (Irianto et al., 2021).

Waste paper represents a significant environmental challenge, as paper production relies heavily on timber resources, leading to deforestation when consumption rates increase (Kesuma, 2024). Paper pulp contains mineral components such as kaolinite and calcium carbonate, which have the potential to contribute to cementitious reactions under certain conditions. Previous studies have reported that the incorporation of waste paper or paper-based fibers in concrete can improve certain properties at low substitution levels; however, excessive replacement may lead to a reduction in compressive strength (Rafael et al., 2022; Shaleh & Johari, 2023). The fibrous nature of paper pulp can fill voids between fine aggregate particles, reducing porosity and forming an internal reinforcement network, although its influence on mechanical performance depends strongly on the substitution ratio.

Superplasticizers are commonly used in cement-based materials to improve workability and enhance compressive strength. While the addition of superplasticizer can increase strength and ease of compaction, excessive dosages may result in adverse effects on mechanical properties (Restu et al., 2023). In CTB mixtures, the role of superplasticizers must therefore be carefully evaluated, particularly when alternative materials are introduced.

Based on the above considerations, this study investigates the utilization of waste paper pulp as a partial replacement for fine aggregate in Cement-Treated Base Class A. The objectives of this research are to evaluate the effect of waste paper pulp substitution on compressive strength, to compare mixtures with and without superplasticizer, and to identify an optimal and economical composition that meets CTB Class A strength requirements.

Materials and Method

Materials

The materials used in this study consisted of Portland Pozzolan Cement (PCC) Type I, fine aggregate (natural sand), coarse aggregate (crushed stone), waste paper pulp, and a superplasticizer. The waste paper pulp was

produced from used HVS paper that was shredded, soaked, and processed into pulp prior to mixing. Sikament-LN was used as the superplasticizer at a dosage of 0.3% by weight of cement. All materials complied with the relevant standards for pavement construction materials.

Material Testing

Before mix preparation, all constituent materials were subjected to laboratory testing to determine their physical properties. Tests on fine aggregate included moisture content, silt content, gradation, fineness modulus, specific gravity, water absorption, bulk density, and organic content. Coarse aggregate testing covered moisture content, silt content, gradation, specific gravity, water absorption, abrasion resistance, and bulk density. Cement testing included bulk density, specific gravity, normal consistency, and setting time. These tests were conducted to ensure that the materials met the requirements for Cement-Treated Base mixtures.

Mix Design

The Cement-Treated Base (CTB) Class A mixtures were designed based on a volumetric proportioning method using PCC, fine aggregate, coarse aggregate, and waste paper pulp. Waste paper pulp was used as a partial replacement for fine aggregate at substitution levels of 0%, 30%, 40%, 50%, 60%, and 70% by volume. Two mix conditions were prepared for each substitution level: mixtures without superplasticizer and mixtures with 0.3% superplasticizer by weight of cement. The proportions of cement, fine aggregate, and coarse aggregate were maintained in accordance with CTB Class A specifications. The detailed mix proportions for each variation are presented in Tables 1 and 2.

Specimen Preparation and Curing

Cylindrical specimens with a diameter of 150 mm and a height of 300 mm were used for compressive strength testing. The constituent materials were weighed according to the designed mix proportions and mixed until a homogeneous mixture was achieved. The CTB mixture was placed into cylindrical molds and compacted in five layers, with each layer receiving 145 blows using a 4.5 kg rammer dropped from a height of 450 mm, following the standard procedure for CTB compaction. After casting, the specimens were stored in the molds in a moist environment for at least 12 hours. The specimens were then demolded, labeled, and cured under wet burlap conditions for seven days to maintain moisture.

Compressive Strength Testing

After seven days of curing, the specimens were weighed and tested for compressive strength. The compressive strength test was performed using a compression testing machine in accordance with the relevant standards for Cement-Treated Base materials.

Table 1 Mix Proportions of Cement-Treated Base (CTB) Class A with Waste Paper Pulp Substitution without Superplasticizer

Variation	Sample Code	Fine Aggregate (33%)			Coarse Aggregate (53%)	Cement (14%)	Total Mix Weight (kg)	Total Mix Percentage (%)
		Waste Paper Pulp (%)	Weight (kg)	Sand (kg)	Weight (kg)	Weight (kg)		
1	PP-NSP-0A	0	0	13.587	22.147	6	41.734	100
	PP-NSP-0B							
	PP-NSP-0C							
2	PP-NSP-30A	30	4.076	9.511	22.147	6	41.734	100
	PP-NSP-30B							
	PP-NSP-30C							
3	PP-NSP-40A	40	5.435	8.152	22.147	6	41.734	100
	PP-NSP-40B							
	PP-NSP-40C							
4	PP-NSP-50A	50	6.793	6.793	22.147	6	41.734	100
	PP-NSP-50B							
	PP-NSP-50C							
5	PP-NSP-60A	60	8.152	5.435	22.147	6	41.734	100
	PP-NSP-60B							
	PP-NSP-60C							
6	PP-NSP-70A	70	9.511	4.076	22.147	6	41.734	100
	PP-NSP-70B							
	PP-NSP-70C							

Table 2 Mix Proportions of Cement-Treated Base (CTB) Class A with Waste Paper Pulp Substitution with Superplasticizer

Variation	Sample Code	Fine Aggregate (33%)			Coarse Aggregate (53%)	Cement (14%)	Super-plasticizer (%)	Total Mix Weight (kg)	Total Mix Percentage (%)
		Waste Paper Pulp (%)	Weight (kg)	Sand (kg)	Weight (kg)	Weight (kg)			
1	PP-NSP-0A	0	0	13.587	22.147	6	0.3	41.734	100
	PP-NSP-0B								
	PP-NSP-0C								
2	PP-NSP-30A	30	4.076	9.511	22.147	6	0.3	41.734	100
	PP-NSP-30B								
	PP-NSP-30C								
3	PP-NSP-40A	40	5.435	8.152	22.147	6	0.3	41.734	100
	PP-NSP-40B								
	PP-NSP-40C								
4	PP-NSP-50A	50	6.793	6.793	22.147	6	0.3	41.734	100
	PP-NSP-50B								
	PP-NSP-50C								
5	PP-NSP-60A	60	8.152	5.435	22.147	6	0.3	41.734	100
	PP-NSP-60B								
	PP-NSP-60C								
6	PP-NSP-70A	70	9.511	4.076	22.147	6	0.3	41.734	100
	PP-NSP-70B								
	PP-NSP-70C								

The measured compressive strength values were used to evaluate the influence of waste paper pulp substitution and superplasticizer addition on the mechanical performance of CTB Class A.

Results and Discussion

Properties of Constituent Materials

The laboratory test results of the constituent materials confirm their suitability for use in Cement-Treated Base (CTB) mixtures. The fine aggregate exhibited a moisture content of 5.2% and a silt content of 4.8%, which are

within acceptable limits for CTB applications. Sieve analysis showed that the fine aggregate fell within Zone IV grading with a fineness modulus of 2.65, indicating relatively fine sand. However, the water absorption value of 3.31% exceeded the recommended maximum of 2.5%, suggesting a higher porosity that may influence water demand and strength development in cement-treated mixtures. Nevertheless, the organic content was classified as color standard No. 2, indicating low organic impurities and acceptable performance in cement-based materials (Irianto et al., 2021).

The coarse aggregate showed favorable characteristics, including low moisture content (1.25%), low silt content (1.25%), and acceptable water absorption (0.80%). Abrasion resistance testing yielded a wear value of 27.30%, satisfying durability requirements and indicating adequate resistance to shear and mechanical degradation. These properties are consistent with the requirements for CTB materials subjected to traffic loading (Hardiyatmo, 2019; Direktorat Jenderal Bina Marga, 2017).

Cement testing results indicated normal consistency at 26.60% and initial and final setting times of 70 and 120 minutes, respectively. These values confirm the suitability of Portland Pozzolan Cement (PCC) for CTB applications, particularly in semi-dry mixtures requiring controlled setting behavior (Hadijah & Atmoko, 2022).

Compressive Strength of CTB Class A without Superplasticizer

The compressive strength results of CTB Class A mixtures incorporating waste paper pulp without superplasticizer are presented in Table 3. The control mixture (0% substitution) exhibited a high average compressive strength of 98.14 kg/cm², exceeding the CTB Class A requirement of 45–55 kg/cm². While this strength level satisfies structural requirements, it may be considered uneconomical due to excessive cementitious performance relative to design needs.

At a 30% substitution level of waste paper pulp, the compressive strength decreased significantly to an average value of 48.12 kg/cm². Nevertheless, this value still met the CTB Class A specification, indicating that partial replacement of fine aggregate with waste paper pulp at this level is technically feasible. Further increases in substitution levels (40–70%) resulted in compressive strength values below the specified limits, indicating a progressive deterioration of mechanical performance.

The reduction in strength with increasing waste paper pulp content can be attributed to the lower stiffness and strength of paper pulp fibers compared to natural sand, as well as increased porosity within the cement matrix. Similar trends have been reported in previous studies on paper-based waste incorporation in concrete, where excessive replacement levels led to reduced compressive strength (Rafael et al., 2022; Shaleh & Johari, 2023).

Effect of Superplasticizer on Compressive Strength

The compressive strength results of CTB mixtures with the addition of 0.3% superplasticizer are shown in Table 4. For all substitution levels, the use of superplasticizer resulted in higher compressive strength compared to mixtures without superplasticizer. The control mixture achieved an average compressive strength of 148.15 kg/cm², indicating a substantial improvement in strength due to enhanced workability and compaction efficiency.

Table 3 Compressive Strength Test Results of Cement-Treated Base (CTB) Class A without Superplasticizer

Variation	Sample Code	Compressive Strength (kg/cm ²)	Average (kg/cm ²)	Remarks
1	PP-NSP-0A	113.234	98.136	Meets specification
	PP-NSP-0B	110.403		
	PP-NSP-0C	70.771		
2	PP-NSP-30A	45.294	48.124	Meets specification
	PP-NSP-30B	48.125		
	PP-NSP-30C	50.955		
3	PP-NSP-40A	42.463	40.576	Does not meet specification
	PP-NSP-40B	39.632		
	PP-NSP-40C	39.632		
4	PP-NSP-50A	33.97	34.914	Does not meet specification
	PP-NSP-50B	36.801		
	PP-NSP-50C	33.97		
5	PP-NSP-60A	28.309	29.252	Does not meet specification
	PP-NSP-60B	28.309		
	PP-NSP-60C	31.139		
6	PP-NSP-70A	25.478	26.421	Does not meet specification
	PP-NSP-70B	25.478		
	PP-NSP-70C	28.309		

At a 30% waste paper pulp substitution level, the mixture achieved an average compressive strength of 49.07 kg/cm², satisfying the CTB Class A requirement. However, similar to the mixtures without superplasticizer, higher substitution levels (≥40%) failed to meet the strength criteria for CTB Class A. These findings confirm that while superplasticizer improves strength performance, it cannot fully compensate for the mechanical limitations introduced by excessive waste paper pulp content.

The observed improvement in compressive strength due to superplasticizer addition is consistent with previous studies, which reported enhanced particle dispersion and reduced water demand in cement-based materials containing chemical admixtures (Restu et al., 2023).

Comparative Analysis and Optimal Mix Proportion

A comparative analysis of compressive strength results with and without superplasticizer is illustrated in Figure 1 and summarized in Table 5. As shown in Figure 1, mixtures containing superplasticizer consistently exhibited slightly higher compressive strength values across all substitution levels, with a pronounced effect observed in the control mixture (0% substitution).

Table 4 Compressive Strength Test Results of Cement-Treated Base (CTB) Class A with Superplasticizer

Variation	Sample Code	Compressive Strength (kg/cm ²)	Average (kg/cm ²)	Remarks
1	PP-NSP-0A	141.543	148.148	Meets specification
	PP-NSP-0B	135.881		
	PP-NSP-0C	167.021		
2	PP-NSP-30A	45.294	49.068	Meets specification
	PP-NSP-30B	48.125		
	PP-NSP-30C	53.786		
3	PP-NSP-40A	42.463	42.463	Does not meet specification
	PP-NSP-40B	39.632		
	PP-NSP-40C	45.294		
4	PP-NSP-50A	33.97	36.801	Does not meet specification
	PP-NSP-50B	39.632		
	PP-NSP-50C	36.801		
5	PP-NSP-60A	31.139	32.083	Does not meet specification
	PP-NSP-60B	33.97		
	PP-NSP-60C	31.139		
6	PP-NSP-70A	28.309	28.309	Does not meet specification
	PP-NSP-70B	25.478		
	PP-NSP-70C	31.139		

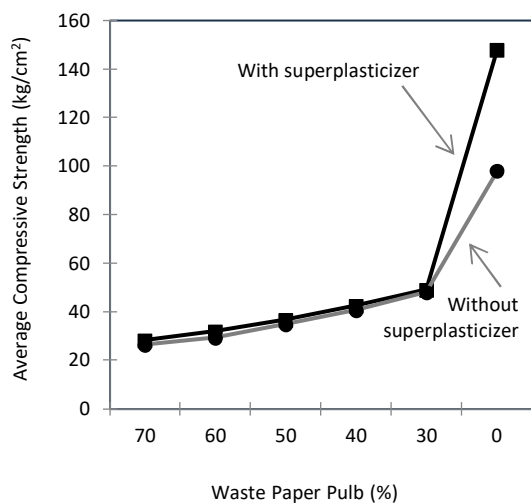


Figure 1 Relationship between Compressive Strength and Waste Paper Pulp Content in CTB Class A with and without Superplasticizer

Table 5 demonstrates that mixtures with 40–50% waste paper pulp substitution satisfied the requirements for CTB Class B (35–45 kg/cm²), indicating potential applicability for lower pavement layers. However, from a structural and economic perspective, the most optimal mixture for CTB Class A was identified as the mixture without superplasticizer at a 30% waste paper pulp substitution level, achieving a compressive strength of 48.12 kg/cm².

Although the use of superplasticizer enhances compressive strength, its additional cost reduces economic efficiency. Therefore, the mixture without

superplasticizer is considered more suitable for practical application in CTB Class A. This finding aligns with sustainable pavement strategies that prioritize both environmental benefits and cost-effectiveness (Prihatini et al., 2024).

Overall, the results indicate that waste paper pulp can be effectively utilized as a partial fine aggregate replacement in CTB mixtures when applied at controlled substitution levels. While paper pulp offers environmental advantages such as waste reduction and resource conservation (Kesuma, 2024), its influence on compressive strength necessitates careful optimization to balance sustainability and mechanical performance.

Conclusions

This study investigated the use of waste paper pulp as a partial replacement for fine aggregate in Cement-Treated Base (CTB) Class A mixtures, with and without the addition of superplasticizer. Based on the experimental results and analysis, the following conclusions can be drawn:

1. The compressive strength of CTB Class A is significantly influenced by the proportion of waste paper pulp used as a fine aggregate substitute. An increase in waste paper pulp content consistently resulted in a reduction in compressive strength for both mixtures with and without superplasticizer.
2. CTB mixtures without superplasticizer achieved the required compressive strength for CTB Class A at waste paper pulp substitution levels of 0% and 30%. The mixture containing 30% waste paper pulp without superplasticizer produced an average compressive strength of 48.12 kg/cm², satisfying the specified requirement of 45–55 kg/cm².
3. The addition of 0.3% superplasticizer improved compressive strength at all substitution levels. However, only the mixtures with 0% and 30% waste paper pulp substitution met the CTB Class A strength criteria.
4. Higher substitution levels (≥40%) did not meet the compressive strength requirements for CTB Class A but were suitable for CTB Class B applications, indicating potential use in lower pavement layers.
5. Considering both mechanical performance and economic efficiency, the mixture with 30% waste paper pulp substitution without superplasticizer was identified as the most optimal and practical composition for CTB Class A.

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Table 5 Average Compressive Strength Test Results of CTB Mixtures with and without Superplasticizer

Variation	Fine Aggregate		Coarse Aggregate	Cement	Average Compressive Strength (kg/cm ²)		Specification Requirement (kg/cm ²)		
	Waste Paper Pulp (%)	Sand (kg)	Weight (kg)	Weight (kg)	Without Superplasticizer	With Superplasticizer	(CTB) Class A	(CTB) Class B	
1	0	0	4.529	7.382	2	98.136	148.148		
2	30	1.359	3.17	7.382	2	48.125	49.068		
3	40	1.812	2.717	7.382	2	40.576	42.463	45-55	35-45
4	50	2.264	2.264	7.382	2	34.914	36.801		
5	60	2.717	1.812	7.382	2	29.252	32.083		
6	70	3.17	1.359	7.382	2	26.421	28.309		
	Meets CTB specification but not economical								
	Meets CTB Class A specification								
	Meets CTB Class B specification								

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