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Analisis Kelayakan Teknis, Keberlanjutan Lingkungan, dan Ekonomi Silika Geothermal Sebagai Substitusi Semen dalam Pembuatan Paving block: Pendekatan Optimasi Response Surface Methodology
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INTISARI

Industri semen merupakan salah satu sektor yang bertanggung jawab atas 7–9% total emisi CO_2 antropogenik dunia. Di sisi lain, operasional Pembangkit Listrik Tenaga Panas Bumi (PLTP) di Indonesia menghasilkan limbah silika silika *geothermal* dalam jumlah besar belum termanfaatkan secara optimal. PLTP Karaha Bodas menghasilkan 16–18 ton per tahun endapan silika yang seluruhnya masih menjadi beban lingkungan.

Penelitian ini mengkaji silika silika *geothermal* dari PLTP Karaha sebagai substitusi semen portland dalam pembuatan *paving block* dengan variasi silika 0%, 5%, 10%, 15%, dan 20%. Karakterisasi material dilakukan melalui pengujian X-Ray *Diffraction* (XRD) dan *Energy Dispersive* X-Ray (EDX) guna memverifikasi reaktivitas pozzolan. Pengujian teknis meliputi kuat tekan pada umur 7 dan 28 hari, ketahanan aus, serta daya serap air. Analisis keberlanjutan lingkungan mencakup *embodied carbon* menggunakan pendekatan *Life Cycle Assessment* (LCA) *gate-to-gate, embodied energy, eco strength efficiency,* dan *sustainability index*. Analisis ekonomi membandingkan biaya produksi dan efisiensi biaya per kuat tekan terhadap semen portland dan *silica fume*. Optimasi menggunakan Respons*e Surface Methodology* (RSM) menggunakan *Optimal Composite Design* (OCD) pada pengujian performa teknis dan keberlanjutan lingkungan.

Karakterisasi EDX mengonfirmasi kandungan SiO_2 mencapai 95,82%, yang memenuhi kriteria pozzolan sesuai ASTM C618 serta uji XRD yang menunjukkan kristalinitas struktur amorf pada kandungan silila silika *geothermal*. Pada substitusi 20%, *paving block* menghasilkan kuat tekan maksimum sebesar 42,60 MPa, ketahanan aus rata-rata 0,096 mm/menit, dan daya serap air 5,88%, secara keseluruhan memenuhi klasifikasi mutu B SNI 03-0691-1996 yang layak digunakan sebagai area parkir. Pada aspek keberlanjutan lingkungan, substitusi 20% silika silika *geothermal* mampu mereduksi emisi CO_2 sebesar 17,79% dan energi sebesar 16,97% dibandingkan *paving block* berbasis semen Portland. Secara ekonomi, menghasilkan penghematan biaya produksi sebesar 5,77% per m^3 dan meningkatkan efisiensi biaya terhadap kekuatan sebesar 40%. Hasil optimasi menetapkan kadar 20% sebagai formulasi dengan nilai *desirability* sebesar 0,825 dan tingkat *error* di bawah 5%. Hal ini membuktikan silika dengan kadar 20% memiliki kelayakan yang baik sebagai substitusi semen.

Kata kunci: Silika *geothermal*, *Paving block*, Substitusi Semen, Keberlanjutan Lingkungan, *Reponse Surface Methodology*

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ABSTRACT

The cement industry accounts for approximately 7–9% of global anthropogenic CO_2 emissions. In parallel, the operation of Geothermal Power Plants (PLTP) in Indonesia generates substantial quantities of geothermal silica waste that remain underutilized. The PLTP Karaha Bodas facility alone produces 16–18 tons of silica sediment per year, all of which currently constitutes an environmental burden.

This study investigates geothermal silica from PLTP Karaha as a partial substitute for Portland cement in paving block production, with silica substitution levels of 0%, 5%, 10%, 15%, and 20%. Material characterization was conducted through X-Ray Diffraction (XRD) and Energy Dispersive X-Ray (EDX) analyses to verify pozzolanic reactivity. Technical performance evaluations include compressive strength at 7 and 28 days of curing, abrasion resistance, and water absorption. Environmental sustainability analysis encompasses embodied carbon using a Life Cycle Assessment (LCA) gate-to-gate approach, embodied energy, eco strength efficiency, and sustainability index. Economic analysis compares production costs and cost efficiency per unit of compressive strength relative to Portland cement and silica fume. Optimization was performed using Response Surface Methodology (RSM) employing Optimal Custom Design (OCD) for technical performance and environmental sustainability responses.

XRD characterization confirmed an amorphous structure with a SiO_2 content of 95.82%, satisfying the pozzolan criteria stipulated in ASTM C618. At 20% substitution, *paving block*s achieved a maximum compressive strength of 42.60 MPa, an abrasion resistance of 0.096 mm/min, and a water absorption rate of 5.88%, collectively meeting the B-grade quality classification under SNI 03-0691-1996, which is applicable for parking use. From an environmental standpoint, the 20% geothermal silica substitution reduced CO_2 emissions by 17.79% and energy consumption by 16.97% compared to Portland cement-based *paving block*s. Economically, it achieved a production cost saving of 5.77% per m^3 and enhanced cost-to-strength efficiency by 40%. Optimization results identified a 20% substitution level as the optimal formulation, with a desirability value of 0.825 and a target error below 5%. These findings confirm that geothermal silica at a 20% substitution level constitutes a technically, economically efficient, and environmentally responsible alternative to Portland cement..

Keywords: Geothermal Silica, *Paving block*, Cement Substitution, Environmental Sustainability, Response Surface Methodology