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学　位　論　文　内　容　の　要　旨

博士の専攻分野の名称　　博士（工学）　　氏名　Orozco Christian Rodriguez

学　位　論　文　題　名

Environmental Sustainability Assessment of Cement Replacing Materials for Concrete Applications in Selected Southeast Asian Countries
(東南アジア諸国におけるコンクリート用セメント代替材料の環境持続可能性評価)

Waste materials such as fly ash and slag as partial substitutes for cement have been widely used to enhance the sustainability of concrete production. However, in many emerging economies, the impact of these cement-replacing materials has not been adequately quantified, particularly for mass concrete. The main research objective involves quantifying the economic and environmental impacts of fly ash and slag as cement-replacing material on a wide range of concrete mixtures used in the Philippines and Thailand. Environmental and economic assessments were conducted on 60 mass concrete mixtures in the Philippines (31 mixtures) and Thailand (29 mixtures). In the Philippines, concrete mixtures from batching plants utilized varying percentages of fly ash (0%, 10%, 15%, and 20%) as cement replacements, with 28-day strength designs ranging from 13.8 to 69.0 MPa. In Thailand, the analysis involved 27 concrete mixtures using different types of fly ash (low and high calcium oxide) and higher fly ash percentages (0%, 25%, and 50%) as cement replacements for compressive strengths of 30 MPa, 35 MPa, and 40 MPa, with specified design ages of 28 and 56 days. Additionally, two Thai mixtures designed for 30 MPa mat foundation mass concrete with 65% slag and 50% fly ash as cement replacement were examined. Environmental assessment of mass concrete mixtures was carried out using a cradle-to-gate life cycle assessment in SimaPro 9.3.

High calcium oxide (CaO) fly ash exhibited more substantial environmental savings than low CaO fly ash when utilized as a cement replacement for mass concrete applications in Thailand, without considering fly ash transportation. The environmental benefits of high CaO fly ash over low CaO fly ash are most pronounced in a 40 MPa concrete mix with 50% fly ash replacing cement at 56 days of age, particularly reducing mineral resource scarcity (10.19%), global warming potential (8.82%), and water consumption (8.22%), excluding transportation. For the endpoint indicators, at 50% cement replacement, the beneficial impact of fly ash is more substantial, with a reduction in endpoint impacts equal to 42-49.5% for human health, 42-49.2% for the ecosystem, and 35-40.5% for resources in comparison with pure cement concrete. The use of fly ash, regardless of its type, reduced the global warming potential (GWP) of concrete by 22-30.6% and 44-51.4% when fly ash was incorporated by 25% and 50% as replacements for cement, respectively, compared to pure cement concrete. Interestingly, the environmental impact of the mass concrete mixture does not necessarily decrease with increasing percentages of fly ash as cement replacement when actual fly ash transport is considered. The highest critical distance estimated using terrestrial ecotoxicity (355 km) is 8,120 km shorter than the critical distance computed based on global warming potential (8,475 km), implying that terrestrial ecotoxicity is more crucial (limiting) than global warming potential. In terms of economic benefits, the utiliza-

tion of 25% and 50% fly ash as a cement replacement significantly reduces the cost of pure cement concrete.

The use of 65% ground granulated blast furnace slag (GGBS) as a cement replacement in Thailand mass concrete shows significant reductions in global warming potential (60.5%), ozone formation (51.1%), and fossil resource scarcity (49.4%) compared to pure cement concrete. However, additional processing steps involved in the preparation of GGBS resulted in increased impact, particularly on human carcinogenic toxicity. Moreover, long-distance import of GGBS from Tokyo to Bangkok by sea transport has a significant environmental impact. Long-distance sea import is responsible for the largest proportion of terrestrial acidification (92%), ozone formation (90%), and fine particulate matter (88.3%).

Based on the environmental assessment of mass concrete mixtures in the Philippines, the GWP of concrete using pure ordinary Portland cement (OPC) ranges from 255 to 550 kg CO2 equivalent. The introduction of fly ash as a partial replacement for cement, at weight percentages of 10%, 15%, and 20%, reduces GWP by 8.5-9.4%, 8.5-12.6%, and 2.4-19.2%, respectively. In the case of low-strength mass concrete mixtures (e.g., 13.8 MPa) with a design age of 28 days, increasing the fly ash replacement from 10% to 20% results in further reductions in environmental impact across only four impact categories. In contrast, for high-strength concrete (41.37 MPa), the environmental burden is reduced across all 18 midpoint categories. Replacing cement with 20% fly ash reduces GWP from 427 to 345 kg CO2, mineral resource scarcity (20%), and water consumption (18.5%). Regarding economic considerations, a 20% fly ash replacement of 41.4 MPa concrete results in an 8% (5.39 USD) cost savings per cubic meter. Our analysis demonstrates that concrete batching plant operators in the Philippines, driven by cost reduction motives, do not reap significant savings when employing more fly ash in lower-strength designs. Learning from the Thai practice, designing the mixtures for a longer specified strength age of 56 days will significantly improve the sustainability of mass concrete utilizing fly ash as partial cement replacement compared to the 28-day specified age design, including economic benefits.

The findings of this study will assist policymakers, concrete manufacturers, engineers, researchers, and other stakeholders in formulating policy recommendations and developing a comprehensive roadmap that incorporates sustainability in concrete production.