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Paving the Way to Sustainability: Exploring the Effects of Additives on Concrete Mixes in Enhancing Mechanical Properties and Cost Efficiency

Paolo Dizon, Kyla Luisa P. Guanlao, Keona R. Marqueses, Christian Jesus B. Oliva, Kathleen B. Aviso*, Angelo Earvin Sy Choi

Department of Chemical Engineering, De La Salle University, 2401 Taft Avenue, Manila, 0922, Philippines
kathleen.aviso@dlsu.edu.ph

Concrete production uses large amounts of cement and natural aggregates. This makes it costly and harmful to the environment. This paper reviews accessible alternatives that offer lower costs while maintaining mechanical performance. These incorporate laterite aggregates, fly ash, sisal fibers, and superplasticizers. Laterite replaces a portion of the coarse aggregate, lowering the demand for natural stone. Fly ash is a partial cement replacement, which helps cut carbon emissions and diminish overall cost. Sisal fibers improve crack resistance and contribute to higher tensile and flexural strength. Superplasticizers improve workability without adding more water. These additives were combined and tested using different concrete blend designs. In the various gathered literature, it was found that one of the best-performing mixes had 10.52 % fly ash, 1 % sisal fiber, and 1.48 % superplasticizer. It reached 47.24 MPa compressive strength, 4.92 MPa tensile strength, and 5.21 MPa flexural strength with a lower production cost. The paper also considered other additives such as ground calcium carbonate, silica fume, and styrene-butadiene rubber, which have been linked to enhancing the mechanical properties.

1. Introduction

The fundamental materials needed for concrete mix production are aggregates, cement, and water. Concrete is formed after these set of materials have been mixed and is allowed to dry into stone-like material (Gagg, 2014). The global demand its composite materials has seen a rise of 115-180 % since 1990 (Patil et al., 2024). The rising demand in concrete production also led to increased global carbon dioxide (CO_2) emissions. The CO_2 emissions of the concrete production industry is approximately 7 % of the overall global emissions (Hanifa et al., 2023). As demand continuously grow, the supply of the material components of concrete such as gravel, sand, cement, and crushed stone could not suffice the demand in developing countries. This led these countries to import materials from neighbouring countries at exorbitant costs (Bendixen et al., 2021). The raw materials in concrete require many natural resources. Several aggregates have been used to partially replace raw gravel aggregates. Materials such as recycled concrete (Shmlls et al., 2023), Laterite (Musembe, 2013), Incinerated solid wastes and plastic wastes (Janardhan et al., 2024), and glass waste (Rana et al., 2024). Concrete additives are often added to enhance the properties of concrete. Properties such as workability, mechanical, durability, and other desired properties are may may be enhanced (Ogunleye, 2023). It also identifies trends, research gaps, and possible research opportunities using bibliometric analysis. The rest of this paper is organized as follows. Section 2 focuses on concrete mixes with Section 2.1 summarizing the effects of additives and partial replacements on the mechanical properties of concrete.

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2. Concrete Mixes

The most basic ingredients to make concrete are aggregates, cement, and water. Several other additives can be added in the mixture, but most concrete mixes still incorporate a combination of these three main ingredients (Gagg, 2014). The purpose of aggregating in the concrete mix is to serve as an inert material at which the cement can bind itself. Outside of this, aggregates are also attributed to reducing shrinkage, acting as a heat sink during the process of the hydration reaction, and providing abrasion resistance (Purnell & Dunster, 2009). Water and cement on the other hand, act as a binding paste that holds the structure of the hardened concrete (Rosa et al., 2023).

2.1. Effects of Additives and Partial Replacements on the Mechanical Properties of Concrete

Fly ash is an industrial by-product that can reduce concrete costs compared to using only Portland cement clinker Moir (2003). Aggregates lower shrinkage, prevent abrasion, and help control heat during hydration (Purnell & Dunster, 2009). Additives in concrete that aim to reduce cost and improve workability or strength include fly ash (Moir 2003), recycled aggregates (Purnell & Dunster, 2009), laterite aggregates (Patil et al., 2024), sisal fibers (Amjad et al., 2023) superplasticizers (Martin, 2006) and (Fang et al., 2016), nano iron oxide particles (Amjad et al., 2023), silica fume (Yankelevsky, 2024), styrene-butadiene rubber (Shafieyzadeh, 2013), calcium carbonate (Yildizel et al., 2020), recycled powder from construction waste Xiao et al. (2018), and plastic fibers such as HDPE (Pešić et al. 2016). Laterite aggregates increase compressive strength by up to 11.85 % for M30 and 8.15 % for M45 concrete at 25 % replacement (Raja & Vijayan, 2021). Sisal Fibers at 1 % with nano iron oxide particles improve compressive, split testile, flexural, and shear strength by up tp 28.79 % (Amjad et al., 2023). Superplasticizers such as polycarboxylate-based dispersants improve workability by dispersing cement particles and reducing water demand (Martin, 2006) and (Fang et al., 2016). Durán-Herrera et al. (2011) reported that superplasticizers combined with fly ash improved fresh and hardened concrete properties. Key mechanical properties include compressive, flexural, and split tensile strength (Murugan, 2020) and (Ma et al., 2015). Xiao et al. (2018) and Pešić et al. (2016) showed that recycled powders and plastic fibers can reduce compressive strength, while silica fume and calcium carbonate can increase it up to an optimal point Yildizel et al. (2020). ASTM C496 defines split tensile strength (Gerges et al., 2015).

2.2.1 Cost Analysis of Plastic Incorporation in Concrete Mixes

Utilization of plastic waste as a material in production can lead to lowered production costs and be a sustainable component alternative. The study of Irlan et al. (2025) recycled polypropylene (PP) granules as fine aggregate replacement in concrete mix production. The study found that 10 % replacement of recycled PP granules led to the balance of recycled material use and compressive strength. The cost analysis of the study showed that a 30 % replacement of PP granules resulted in lowered water to cement ratio on this mixture, it still had an overall 5.5 % cost reduction compared to the control concrete. Another study that utilized plastic waste in the form of high density polyethylene (HDPE) aggregates as a partial replacement found that the value of 15 % replacement yielded just above the minimum requirement for compressive strength for structural applications (Habib et al., 2017). The cost analysis presented in the study suggests that the use of HDPE aggregates reduce the overall costs of concrete produced. The study of Alqahtani et al. (2021) utilized linear low density polyethylene (LLDPE) as recycled plastic lightweight aggregates (PLA). The compressive strength of the concrete produced was around 18 MPa. The percent replacement of PLA to natural aggregates was up to 70 % with water-cement ratio of 0.5. The study concluded that the use of LLDPE in structural concrete can save 7.23 % and 7.18 % in concrete and steel costs.

2.2.2 Cost Analysis of Recycled Concrete Aggregates and Fly Ash Concrete Mixes

Kurda et al. (2018) studied the effect on mechanical properties and the economic advantages of recycled concrete aggregates (RCA) and high-volume fly ash (FA) with incorporation of superplasticizers (SP). Results indicate that concrete mixes with SP had a higher mechanical performance. The cost of concrete mixes slightly decreased by up to 4 % with fine RCA and 7 % with coarse RCA. Fly ash at 30 % and 60 % replacement reduced costs by 9 % and 18 %, respectively. The concrete mixes with superplasticizers led to a 13 % increase in costs but can be offset by FA replacement. Optimization was done by comparing the mechanical performance ratio and costs of concrete mixes from a reference concrete mix without replacement and superplasticizer. The optimal mix was composed of 100 % coarse RCA, 50 % fine RCA, 30 % FA, and 1 % SP. The mix yielded 74.1 MPa of compressive strength, 4.1 MPa of split tensile strength, and 44.2 GPa of modulus of elasticity at 365 days. The cost difference between the reference concrete mix is 5.5 %. Simultaneous incorporation of RCA, FA, and SP has shown better performance in terms of mechanical properties and cost-efficiency than their individual incorporation.

2.2.3 Cost Analysis of Recycled Brick Aggregates, Recycled Stone Aggregates, and Recycled Concrete Brick Aggregates

Abdul Basit et al. (2023) analyzed three combinations of concrete mixes with partial replacement of recycled brick aggregates (RBA), recycled stone aggregates (RCSA), and recycled concrete brick aggregate (RCBA). The mixes were analysed in terms of compressive strength after 28 d at varying replacement ratios in coarse aggregates. Results show that compressive strength increases up to 30 % replacement of RCSA, and up to 10 % of RBA. A gradual decrease in compressive strength was observed for RCBA by 9 %, 23 %, 39 % and 53 % at 50 %, 60 %, 80 % and 100 % replacement. The optimal mixes were determined by finding the intersection of compressive strength and material cost trends. The intersection for RCSA shows that 22 % replacement yields 1875 psi of compressive strength and costs 61 BDT/ft^3. 12 % RBA replacement yields 2110 psi costs 55 BDT/ft^3 and 60 % RCBA yields 1220 psi with 48 BDT/ft^3.

2.2.4. Cost Analysis of Crumb Rubber as Fine Aggregates

The study of Xiong et al. (2024) utilizing crumb rubber as fine aggregates in concrete production versus ordinary Portland cement concrete. The study showed that as crumb rubber (CR) reaches 20 % replacement of fine aggregates, an increase of 6 % is observed for 30-40 MPa grade concrete. Despite the higher costs the advantages of CR infused concrete lay in the CO_2 content, which was found to have decreased by 15-17 % when compared to ordinary Portland cement concrete. The study of Kelechi et al. (2022) used CR, fly ash, and calcium carbide residue (CCR) as replacement components and additives. It was found that the use of fly ash in the mixture can lead to up to 14 % cost reduction at 40 % cement replacement. However, the use of CR led to a 2 % cost increase compared to the control mix. Up to a 35 % reduction in CO_2 emissions can be achieved at 40 % cement replacement by fly ash. Contrasting this, it was found that 10 % replacement using CR increases CO_2 emissions by less than 1 %, showing that the impact of CR utilization is less for the environment compared to fly ash and CCR.

Table 1: Summary of pertinent concrete mixes studies.

Reference	Additives	Mechanical Properties	Advantages of the additives	Disadvantages of the additives
Abdul Basit et al. (2023)	RCSA RBA RCBA	Compressive Strength	RCSA and RBA have shown an increase in compressive strength of up to 30 % and 10 % replacement, respectively. RCBA is the most cost-effective of the mixes in the study.	RCBA gradually decreases compressive strength with increasing amount. Increasing the RCSA replacement leads to higher material costs.
Alqahtani et al. (2021)	LLDPE as plastic aggregates	Compressive Strength	LLDPE can reduce the costs of concrete and steel of up to 7.23 % and 7.18 %. A replacement of up to 70 % can be made. Life cycle costs can reach up to 5.9 %	Compressive strength is reduced for concrete that utilizes LLDPE as plastic aggregates. LLDPE infused concrete cannot be utilized in structures that require bearing higher compressive strengths.
Irlan et al. (2025)	Recycled polypropylene granules	Compressive Strength	Recycled polypropylene granules lowered the water-to-cement ratio. This led to a 5.5 % overall reduction in costs.	Recycled polypropylene granules used as aggregates significantly reduced the compressive strength of the produced concrete.
Habib et al. (2017)	HDPE plastic aggregates	Compressive Strength Flexural Strength Split Tensile Strength	HDPE is a very common type of plastic waste, and the environmental impact of HDPE recycling can be significant. A replacement of up to 15 % HDPE as aggregates can produce concrete that above 17 MPa in compressive strength.	HDPE use in concrete have direct negative effects the compressive, flexural, and split tensile strengths as plastic content increases. The production costs of this type of concrete were still deemed to be too high.
Janardhan et al. (2024)	Incinerated solid wastes and recycled plastic waste	Compressive Strength	50 % replacement of incinerated solid waste was found to yield the maximum compressive strength.	The concrete grade of the study is limited to M20. Having a target of 20 N/mm^2 of compressive strength.

Reference	Additives	Mechanical Properties	Advantages of the additives	Disadvantages of the additives
Kurda et al. (2018)	RCA, FA and SP	Compressive Strength Split Tensile Strength Modulus of Elasticity	The costs decreased by up to 4 % with fine RCA and 7 % with coarse RCA. Fly ash at 30 % and 60 % replacement reduced costs by 9 % and 18 %, respectively. Simultaneous incorporation of RCA, FA, and SP can save up to 5.5 % of costs.	Both RCA and FA have shown a decrease in mechanical properties with increasing amounts and without the use of SP. The use of superplasticizers leads to a 13 % increase in costs.
Rana et al., (2024)	Glass waste coarse aggregates, waste glass fine aggregates, and waste glass powder	Compressive Strength Flexural Strength Split Tensile strength	Increase of 13.1-22.1 % in compressive strength.	Decrease of 0.18-0.43 MPa of flexural strength from the concrete. Decrease of 0.12-0.38 MPa in split tensile strength.
Kelechi et al. (2022)	Crumb rubber fine aggregates, fly ash, and calcium carbide residue	Compressive Strength Flexural Strength Split Tensile strength	Compressive strength of 45 MPa can be achieved at 0 % CR, 0 % fly ash, and 10 % CCR. Flexural strength of 6.7 MPa can be achieved at 0 % CR, 0 % fly ash, and 5 % CCR. Split tensile strength of 4.1 MPa can be achieved at 10 % CR, 0 % fly ash, and 5 % CCR.	The significance of CR in CO_2 reductions have been concluded to be negligible. Mechanical property decreases can be observed at higher replacement percentages.
Xiong et al. (2024)	Crumb rubber fine aggregates	Compressive Strength Flexural Strength Tensile strength	CR-infused concrete can reach concrete grades that are up to 30-40 MPa. A decrease of 15-17 % of CO_2 emissions can be observed when compared to ordinary Portland cement concrete.	An increase of 6 % in costs can be observed when utilizing CR as fine aggregates. Decreases in mechanical properties can be observed when CR amounts are more than 20 %

In this work, the authors focus on analyzing the effects of specific additives to concrete mixes in terms of mechanical properties. The authors gathered various literature to determine the effects of several additives and replacements for concrete mixes. Identify combinations of concrete mixes that yield high mechanical properties while maintaining low costs, as well as promoting the use of sustainable and recycled materials. Through searching for relevant literature, compressive and flexural strength were the two most common mechanical properties used by studies to measure the performance of concrete. It was also found that literature about additives and replacements does not provide a cost-analysis to support their claims of cost reduction. Additives and partial replacement studies that look into sisal fibers (Ren et al., 2024), amorphous alumina silicate (Nagrockienė et al., 2015), and coconut fibers (Bediako et al., 2025) have yet to have literature that contain a cost analysis. This indicates that there are still several concrete additives or partial replacements that have taken costing into consideration. The contents of the table above show concrete mix studies that include a cost analysis. Among the studies that include a cost analysis, it can be observed that most studies do not contain a predictive cost analysis model. Preferring to report the optimal costs through each level of percentage replacement of additive amount. This method fails to consider other specific optimal values outside of the levels. Furthermore, they also do not consider values that balance the mechanical properties of concrete and costs, since most literature aims to reach a target range or concrete grade instead of a particular optimal value. This review paper suggests that the limit amount of studies that contain a cost analysis, the lack of mechanical strength and cost balancing, and the absence of predictive models are significant research gaps in the topic of concrete additives and partial replacements.

3. Conclusion

The use of additives aimed at lowering the cost and improving the mechanical properties of concrete is a step towards sustainability in the construction industry. Each of the additives explored multiple advantages and disadvantages. High-density polyethylene plastic fibers increase the total compression that concrete structure can take and are easily accessible due to their abundance. Recycled powder from construction and demolition debris are a good way to lessen the carbon footprint. Addition of demolition debris in concrete mixes has a significant improvement in concrete properties at low concentrations. Abundant materials such as laterite aggregates, silica fume, styrene-butadiene rubber, ground calcium carbonate, and plant fibers have shown that cheaper options for additives can improve several mechanical properties at lower costs. While literature state that additives and replacements make the overall concrete mix more cost-effective, several concerns can still be observed. Unforeseen reactions due to the chemical compositions of the additives, increased air content, which will make the concrete more brittle, rapid setting, which reduces workability, or increased costing should not be ignored when conducting further research into additives that can be applied to concrete mixes. Furthermore, due to the nature of the studies being region-dependent, material costs can vary significantly, posing further irregularities in the costs of concrete mix production. Given that most studies consider the increments of amount of materials as the optimal solutions, utilizing a predictive model or mechanical property and cost balancing method can showcase specific optimal solutions that can be found in between levels. Lastly, an observed lack of cost analysis is still present in most of the readily available research on concrete mix production. Signifying that researchers should investigate the integration of a cost analysis in concrete mix research to create a more comprehensive study that incorporates more aspects of concrete mix production, such as the underlying costs behind it.

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References

Abdul Basit M., Sadiqul Hasan N. M., Jihad Miah M., Chandra Paul S., 2023, Strength and cost analysis of concrete made from three different recycled coarse aggregates, Materials Today: Proceedings, DOI: 10.1016/j.matpr.2023.03.247

Ahmed M., Mallick J., Abul Hasan M., 2016, A study of factors affecting the flexural tensile strength of concrete. Journal of King Saud University - Engineering Sciences, 28(2), 147–156.

Alqahtani F.K., Abotaleb I.S., ElMenshawy M., 2021, Life cycle cost analysis of lightweight green concrete utilizing recycled plastic aggregates. Journal of Building Engineering, 40, 102670.

Amjad H., Ahmad F., Irshad Qureshi M., 2023, Enhanced mechanical and durability resilience of plastic aggregate concrete modified with nano-iron oxide and sisal fiber reinforcement. Construction and Building Materials, 401, 132911.

Bediako M., Ametefe T.K., Asante N., Adumatta S., 2025, Incorporation of natural coconut fibers in concrete for sustainable construction: Mechanical and durability behavior. Case Studies in Construction Materials, 22, e04867.

Bendixen M., Iversen L.L., Best J., Franks D.M., Hackney C.R., Latrubesse E.M., Tusting L.S., 2021, Sand, gravel, and UN Sustainable Development Goals: Conflicts, synergies, and pathways forward. One Earth, 4(8), 1095–1111.

Durán-Herrera A., Juárez C.A., Valdez P., Bentz D.P., 2011, Evaluation of sustainable high-volume fly ash concretes. Cement and Concrete Composites, 33(1), 39–45.

Fang B., Xu T., Shi S., 2016, Laboratory study on cement slurry formulation and its strength mechanism for semi-flexible pavement. Journal of Testing and Evaluation, 44(2), 907–913.

Gagg C.R., 2014, Cement and concrete as an engineering material: An historic appraisal and case study analysis. Engineering Failure Analysis, 40, 114–140.

Gerges N.N., Issa C.A., Fawaz S., 2015, Effect of construction joints on the splitting tensile strength of concrete. Case Studies in Construction Materials, 3, 83–91.

Habib M. Z., Alom M. M., Hoque M. M., 2017, Concrete production using recycled waste plastic as aggregate. Journal of Civil Engineering (IEB), 45(1), 11–17.

Hanifa M., Agarwal R., Sharma U., Thapliyal P.C., Singh L P., 2023, A review on CO_2 capture and sequestration in the construction industry: Emerging approaches and commercialised technologies. Journal of CO_2 Utilization, 67, 102292.

Irlan A.O., Parung H., Tjaronge M.W., Caronge M.A., 2025, Mechanical, environmental, and cost evaluation of concrete using recycled polypropylene. Case Studies in Chemical and Environmental Engineering, 12, 101255.

Janardhan P., Narayana H., Darshan N., 2024, Compressive strength studies of concrete with partial replacement of cement and fine aggregate with incinerated solid waste and recycled plastic waste, Materials Today: Proceedings, DOI: 10.1016/j.matpr.2023.03.252.

Kelechi S.E., Adamu M., Mohammed A., Obianyo I.I., Ibrahim Y.E., Alanazi H., 2022, Equivalent CO_2 emission and cost analysis of green self-compacting rubberized concrete, Sustainability, 14(1), 137.

Kurda R., de Brito J., Silvestre J.D., 2018, Combined economic and mechanical performance optimization of recycled aggregate concrete with high volume of fly ash. Applied Sciences, 8(7).

Ma Q., Guo R., Zhao Z., Lin Z., He K., 2015, Mechanical properties of concrete at high temperature: A review. Construction and Building Materials, 93, 371–383.

Martin J.W., 2006, Glasses and ceramics. Materials for Engineering, 133–158.

Moir G., 2003, Cements. Advanced Concrete Technology, 3–45.

Murugan S.S., 2020, Mechanical properties of materials: Definition, testing and application. International Journal of Modern Studies in Mechanical Engineering, 6(2), 28–38.

Musembe T.M., 2013, Laterized quarry dust and recycled concrete as alternative building materials, Jomo Kenyatta University of Agriculture and Technology.

Nagrockienė D., Girskas G., Skripkiūnas G., Daugėla A., 2015, Properties of concrete modified by amorphous alumina silicate. Engineering Structures and Technologies, 6(4), 178–183.

Ogunleye E., 2023, The effects of laterite type on compressive and flexural strengths of concrete utilizing laterite-sand fine aggregate. Global Journal of Engineering and Technology Advances, 16(2), 180–191.

Pal T., Pramanik S., Verma K. D., Naqvi S. Z., Manna P. K., Kar K. K., 2021, Fly ash-reinforced polypropylene composites, Handbook of Fly Ash, 569–591.

Patil S., Bhaskar R., Xavier J.R., Raja R., 2024, Experimental evaluation and statistical modeling of sustainable sisal fiber-reinforced fly ash-based lateritic concrete using response surface methodology. Journal of Building Engineering, 84, 108498.

Pešić N., Živanović S., Garcia R., Papastergiou P., 2016, Mechanical properties of concrete reinforced with recycled HDPE plastic fibres. Construction and Building Materials, 115, 362–370.

Purnell P., Dunster A., 2009, Recycling of concrete, Management. Recycling and Reuse of Waste Composites, 569–591.

Raja R., Vijayan P., 2021, Investigations on mechanical characteristics and microstructural behavior of laterized high strength concrete mix. Arabian Journal for Science and Engineering, 46(11), 10901–10916.

Rana K., Dumre G., Raj T., 2024, Transforming waste into strength: Evaluating properties of concrete with waste glass substitution. Cleaner Waste Systems, 9, 100179.

Ren G., Gao X., Wen X., Su A., 2024, Experimental study on the long-term performance of sisal fiber reinforced high-performance concrete subjected to drying-wetting cycles. Case Studies in Construction Materials, 21, e03911.

Rosa A.C., Hammad A.W.A., Boer D., Haddad A., 2023, Use of operational research techniques for concrete mix design: A systematic review. Heliyon, 9(4), e15362.

Shafieyzadeh M., 2013, Prediction of compressive strength of concretes containing silica fume and styrene-butadiene rubber (SBR) with a mathematical model. International Journal of Concrete Structures and Materials, 7(4), 295–301.

Xiao J., Ma Z., Sui T., Akbarnezhad A., Duan Z., 2018, Mechanical properties of concrete mixed with recycled powder produced from construction and demolition waste. Journal of Cleaner Production, 188, 720–731.

Xiong G., Al-Deen S., Guan X., Qin Q., Zhang C., 2024, Economic and environmental benefit analysis between crumb rubber concrete and ordinary Portland cement concrete. Sustainability, 16(11).

Yankelevsky D.Z., 2024, The uniaxial compressive strength of concrete: Revisited. Materials and Structures, 57(6), 144.

Yildizel S.A., Calis G., Tayeh B.A., 2020, Mechanical and durability properties of ground calcium carbonate-added roller-compacted concrete for pavement. Journal of Materials Research and Technology, 9(6), 13341–13351.