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COMPARATIVE STUDY OF ECO–FRIENDLY CONCRETES PRODUCED USING RECYCLED MATERIALS AND INDUSTRIAL WASTE

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Abstract: This paper presents a comparative study on the properties of eco–friendly concretes produced using recycled materials and industrial waste, including recycled aggregates, plastic and PET fibres, sawdust, rubber granules, glass waste, and pozzolanic additives such as fly ash and slag. The literature analysis highlighted the impact of various recycled materials on the mechanical, physical, and durability properties of concrete, including compressive and flexural strength, modulus of elasticity, density, workability, and resistance to freeze–thaw cycles. The studies reviewed showed that, although eco–friendly concretes generally exhibit slightly lower properties than conventional ones, adjusting the proportions of recycled materials and pre–treating aggregates can achieve comparable performance. The use of nano–materials, PET fibres, and industrial waste reduces the consumption of natural raw materials and contributes to the sustainability and durability of constructions. The results emphasize the importance of optimizing mix design and quality control to fully exploit the potential of eco–friendly concrete in the construction industry.
Keywords: eco–friendly concrete; recycled aggregates; industrial waste; PET fibres; mechanical properties

INTRODUCTION

Concrete is a product made by mixing cement, aggregates, and water, and it is the second most used material on the planet after water.[1] The production of concrete consumes significant amounts of fossil fuels, which are closely linked to global warming. Cement manufacturing generates substantial carbon emissions; therefore, concrete can be considered an unsustainable material.[2]

The number of civil and engineering constructions is increasing significantly, especially due to the global population growth, which proportionally raises the demand for concrete and leads to higher CO_2 emissions. For this reason, there is a growing interest in eco–friendly concrete, including ecological mortars, with continuous efforts to improve its performance.

The concept of eco–friendly concrete, or eco–concrete, is still in its early stages and aims to use less energy and generate lower CO_2 emissions by producing concrete based on environmentally friendly materials. Among the components of concrete, aggregates are considered the most important raw materials, while the bond between cement and aggregates determines the upper limit of the concrete's strength.[3]

In the production of eco–friendly concrete, three major objectives are pursued: reduction of emissions, reduction of natural resource use, and utilization of waste.[4] By incorporating waste into the concrete manufacturing process, all three objectives are fully achieved. Considering the billions of tons of construction and demolition waste generated globally, it has been widely accepted that these materials should be recovered and reused through ecological methods rather than disposed of in landfills.

One commonly accepted method for valorizing construction and demolition waste is its use as a source of aggregates: solid wastes such as concrete and brick debris are successively crushed, ground, and sieved to produce recycled aggregates.[5] Eco–friendly concrete can be used in residential and non–residential civil constructions, industrial buildings (warehouses, factories), engineering structures (bridges, viaducts), special water transport constructions (canals, ports), industrial special constructions (silos, wastewater treatment plants), and hydro–technical structures (dams). Furthermore, using construction waste in the concrete production process helps reduce the amount of waste sent to landfills.

The advantages of eco–friendly concrete include versatility across different applications, year–round usability with appropriate measures, superior resistance to chemical attacks, reduced risk of cracking, and a contribution to the reduction of CO_2 emissions.[6]

MATERIALS AND METHODS USED

This study is based on a systematic and comparative analysis of the scientific literature regarding eco–friendly concretes produced from recycled materials and industrial waste. The materials examined include recycled aggregates from construction and demolition waste, plastic and PET fibres, rubber granules and powders, finely ground glass waste, sawdust and other wood residues, as well as pozzolanic additives such as fly ash.

The methodology consisted of the identification, selection, and analysis of articles published in journals indexed in recognized databases (e.g., Web of Science, Scopus, etc.) during the period 2010–2022. Only experimental studies reporting measured values of concrete properties were selected, including density, compressive strength, modulus of elasticity, water absorption, porosity, and freeze–thaw durability.

The comparative analysis was carried out by extracting and comparing relevant data on concrete performance according to the type of recycled materials and their replacement proportions. The studies were classified based on the category of materials used and the reported effects on physical, mechanical, and durability properties. Additionally, methods for pre–treatment of recycled materials were analysed, such as aggregate pre–saturation, fine grinding of glass, or surface modification of plastics through physical and chemical treatments.

RESULTS AND DISCUSSION

Classification of Eco–Friendly Concretes Based on Composition

Researchers have tested several eco–friendly concrete mixtures by partially replacing raw or auxiliary materials with wastes such as graphene, glass waste, sawdust, rubber granules, construction waste, and others.

Graphene Concrete – For the preparation of concrete with graphene oxides, researchers used nano–engineering techniques to suspend a layer of graphene in the water used for mixing concrete. The resulting material can be used directly in construction, reducing the amount of concrete normally required and consequently lowering greenhouse gas emissions. According to scientists, graphene reduces the required material for concrete preparation by approximately 50%.[7] One of the advantages of using graphene oxide, compared to other nanoparticles, is that its oxygen functionalities can be easily dispersed in an aqueous medium. It has been demonstrated that the impermeability and durability of concrete increase with graphene oxide. The required dose of graphene oxide is lower compared to other nano–materials to achieve performance enhancement.[8]

Concrete with Recycled Aggregates – Construction and demolition waste, depending on quality, can be used in various civil engineering works, contributing significantly to economic and environmental sustainability.[9] The inferior properties of concrete with recycled aggregates represent a major obstacle to replacing natural aggregates with recycled ones.[10] Incorporating a significant amount of recycled aggregate waste (15%) into concrete can improve its compressive strength, pore structure, and long–term durability.[11]

PVC Concrete – The advantages of using plastic waste (PVC) in mortar production include durability, reduced weight, and low biodegradability. Rubber can be used in mortar/concrete production due to its essential characteristics such as low density, high elasticity, and energy absorption. Rubberized concrete is highly resistant to aggressive environments and can be implemented in areas susceptible to acid attacks.[12]

Concrete with Fly Ash – Eco–friendly concrete using fly ash as a partial cement replacement is a well–studied and regulated alternative. The replacement percentage of cement with this industrial by–product is relatively low, up to 30%. Under these conditions, the concrete industry has consumed between 7% and 25% of stored fly ash, an insufficient quantity considering the large existing amounts.[4] Using a high volume of cement–based supplements (fly ash, slag) is recommended to improve workability, strength, or viscosity.[13] Fly ash in concrete improves rheological properties, reduces cracking due to lower heat of hydration, and enhances workability, volume stability, and sulphate resistance to varying degrees.[14] The utilization rate of fly ash varies widely, from 3% to 60%, with an average use of only 16%.[15] Research by W. Shen and colleagues observed that compressive and flexural strength of eco–concrete with fly ash decreases with increasing fly ash content, especially when exceeding 30%.[16]

Concrete with Oyster Shell Waste – Artificial reefs are important marine structures for ecological restoration, offering significant economic and environmental benefits.[17] Concrete is the most used material for artificial reefs due to its moldability and non–toxicity.[18] Research by J. Kong et al. found that recycled aggregates can completely replace natural aggregates in eco–concrete for better mechanical properties, but the replacement rate of oyster shell waste should not exceed 20%. Sulphate resistance decreased by 16.2% when oyster shell and recycled aggregate contents reached 40% and 100%, respectively. The eco–concrete exhibited a minimum 28–day pH value of 8.52, with the oyster shell waste being the main influencing factor.[19]

Concrete with PET Bottle Fibres – According to Mehta and Monteiro, the properties of fibre–reinforced concrete depend on fibre type, quantity, and dimensions; thus, no ideal fibre concept or usage standard currently exists.[20] To address structural issues such as shrinkage or hydraulic cracks, concrete properties were modified by adding polymer fibres. According to Pelisser et al., PET fibre volumes above 0.30% of total concrete volume cause homogeneity and workability issues.[21]

Figure 1 presents eco–friendly concrete blocks incorporating various recycled materials and industrial by–products (recycled concrete aggregates, PET fibres, crumb rubber, waste glass, fly ash, and slag), illustrating the characteristic heterogeneous texture typical of sustainable concrete mixtures.

Figure 1. Eco–friendly concrete blocks produced with recycled concrete aggregates, waste PET fibers, crumb rubber, recycled glass cullet, and supplementary cementitious materials

Introducing PET fibres into concrete increases compressive (C_n) and tensile (T_n) strength.[22] Gu and Ozbakkaloglu reports that PET fibres absorb additional stress from cracks, exhibiting higher tensile strength than reference concrete due to increased fibre length, as the fibres "stitch" cracks.[23] The load–bearing capacity of eco–concrete with PET fibres is higher than conventional concrete because the fibres improve mechanical properties in terms of compression, tension, and bending.[22]

Properties Influenced in Eco–Friendly Concrete with Recycled Aggregates

Many researchers have demonstrated the potential to produce concrete with recycled aggregates whose mechanical properties and durability can be satisfactory. However, recycled aggregates generally exhibit lower quality compared to natural aggregates, with water absorption being their main disadvantage. When used untreated in a concrete mix, recycled aggregates absorb part of the water initially calculated for cement hydration, which negatively affects certain concrete properties.[24] Recycled aggregates require more water for the same workability than conventional concrete; their density, compressive strength, and modulus of elasticity are relatively lower than those of standard concrete. For a given water/cement ratio, permeability, carbonation rate, and the risk of reinforcement corrosion are higher.[25]

Concrete Moisture – The main difference between natural and recycled aggregates is the presence of cement particles adhered to recycled aggregates. The old cement mortar is characterized by a porous structure and a greater number of micro cracks; therefore, using recycled aggregates as an alternative to natural ones typically leads to lower mechanical performance and reduced durability.[26] Additionally, the presence of old mortar causes recycled aggregates to exhibit water absorption 2.3 to 4.6 times higher than natural aggregates.[27]

Previous studies suggest that recycled aggregates at different moisture states may exhibit varying water desorption characteristics at certain ages.[28] Considering the significant effects of recycled aggregate moisture on concrete workability, some researchers proposed that workability could be improved by adjusting the moisture content of recycled aggregates before casting. Two commonly reported methods include pre–saturation (pre–wetting) of aggregates and mixing water compensation. Pre–saturation involves soaking the aggregates in water before mixing to achieve partially or fully saturated recycled aggregates.[29] Pre–saturation can reduce drying shrinkage and autogenously shrinkage of concrete by inducing internal curing effects. However, it may reduce the concrete's resistance to freeze–thaw cycles.[30]

For the alternative method, mixing water compensation, additional water is added to the concrete mix to offset the water absorbed by dry or partially saturated recycled aggregates, improving workability. Ferreira et al. compared the effects of these two methods on the workability of concrete with recycled aggregates. Dry recycled aggregates absorb water quickly; the saturation degree can reach 90% in just 5 minutes, after which water absorption slows, stabilizing after 20 minutes of soaking. Ferreira et al. recommended that 5 minutes is sufficient for pre–saturation. Differences between the methods are negligible, so both can improve the functionality of recycled aggregate concrete.[31,32]

Compressive Strength – Compressive strength is widely used as a fundamental indicator of concrete mechanical properties. Concrete with recycled aggregates shows lower compressive strength compared to natural aggregate concrete when more than 30% of natural aggregates are replaced.[33] Zhao et al. analysed the mechanical properties of concrete prepared with pre–treated recycled aggregates at different saturation levels and compared water control schemes. Three duplicate 100 mm concrete cubes were cast for each group and cured in wet conditions for 3, 28, and 90 days. They reported that the compressive strength of concrete with recycled aggregates was lower than that with dry natural aggregates (water content 82.5%).[34]

Flexural Strength – Previous studies confirmed that the flexural strength of concrete with recycled aggregates is lower than that of natural aggregate concrete.[35,36] Tourkia et al. found that flexural strength of recycled aggregate concrete was 8.4% to 21.2% higher than that of dry aggregate concrete.[32]

Density – The density of unsaturated recycled aggregate concrete is lower than that of natural aggregate concrete. For the same water/cement ratio, density decreases with the incorporation of recycled aggregates. A 20% replacement with recycled aggregates reduces density by approximately 5% compared to natural aggregate concrete.[37]

Durability – Several studies confirmed that concrete with recycled aggregates exhibits lower resistance to penetration of harmful substances (e.g., chloride ions, sulphate ions, water in alkali–aggregate reactions, and freeze–thaw actions) compared to concrete with natural aggregates.[38] Barra de Oliveira and Vazquez studied the performance of recycled aggregate concrete under freeze–thaw cycles at different moisture states (0%, 88.1%, 89.5%, and 100% saturation). They found that fully saturated recycled aggregate concrete exhibited the lowest freeze–thaw resistance, while partially saturated aggregates improved resistance compared to dry or fully saturated aggregates.[39]

Elasticity – The elasticity of recycled aggregate concrete is reported to be 15% to 45% lower than natural aggregate concrete, primarily due to weak aggregate strength and the porous nature of old mortar.[40] Pickel compared the modulus of elasticity according to ASTM C469/C469M–10 after 28 and 91 days of curing. Results indicated that moisture content effects on elasticity were similar to those on compressive strength; concrete with SSD aggregates exhibited the highest modulus among three RAC groups.[41]

Ferreira et al. compared the modulus of elasticity of recycled aggregate concrete using partially saturated aggregates (soaked for 5 minutes before casting) and dry aggregates with mixing water compensation. Results showed that water compensation can lead to higher elastic modulus compared to pre–wetting for aggregate replacement ratios below 50%.[31]

The quality of recycled aggregate concrete depends on the characteristics of the original aggregate and the condition of demolished concrete. Some researchers reported that using recycled aggregates degrades concrete properties, while others successfully produced recycled aggregate concrete with performance similar to conventional concrete.[42,43]

CONCLUSIONS

Analysis of the specialized literature shows that ecological concretes constitute a diverse category of materials with significant potential to reduce environmental impact. However, their performance depends directly on the nature of the recycled materials used and the manner in which they are integrated into the ecological concrete composition. The use of nano–materials, such as graphene oxide, demonstrates a superior capacity to enhance mechanical and durability properties due to efficient dispersion in aqueous media and beneficial structural effects on the cement matrix. Additionally, the incorporation of plastics, PET fibres, or rubber granules generally increases ductility and crack resistance, providing notable advantages in aggressive environments, although limitations related to workability and homogeneity may arise at high dosages.

Concretes produced with recycled aggregates remain the most studied category, yet their performance is strongly influenced by the porosity and high moisture content of the adhered waste. Properties such as density, compressive strength, modulus of elasticity, and durability are, in most studies, lower than those of conventional concretes, particularly at replacement rates of natural aggregates above 30%. Adjusting the moisture state of recycled aggregates, through controlled pre–saturation or mixing water compensation, can significantly improve workability and, in some cases, mechanical performance. Nevertheless, freeze–thaw behavior remains sensitive to saturation level, and excessive pre–wetting may compromise durability.

The integration of industrial waste, such as fly ash or slag, is well documented and provides tangible benefits regarding workability, volumetric stability, and reduced cracking during initial hydration. However, increasing the fly ash proportion beyond 30% negatively affects mechanical strength, emphasizing the need for an optimal balance between performance and sustainability. Positive results reported for concretes incorporating glass waste, oyster shells, or other alternative materials indicate that these resources can contribute to reducing natural aggregate consumption, although strict control of particle size, proportions, and interactions with the cement matrix is required.

The literature demonstrates that ecological concretes can achieve performance comparable to traditional concretes when recycled materials are properly selected, processed, and dosed. However, high variability in waste, lack of uniform standards, and the sensitivity of certain properties to moisture and internal structure remain significant challenges. Therefore, future research should focus on optimizing recycled material pre–treatment, advanced composition modelling, and developing dedicated standards for ecological concrete, enabling the widespread use of these materials as a safe and feasible option for sustainable construction.

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