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Review on Sustainable Concrete: Alternatives to Cement, Gravel, and Sand

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Abstract: Concrete is the most widely construction material in the world due its easy formation and availability of raw materials. The disadvantage of its use was cement since it responsible of most CO2 emissions in world. Besides that, due to rapid publication growth, the waste materials generated by humans, such as plastic, glass, and non-biodegradable materials, harm the environment, so most research has involved incorporating waste materials in concrete to create an eco-friendly concrete. In this research, some studies that replaced cement with silica fume, palm ash, and fly ash, sand with glass powder and PET, gravel with crushed concrete and rubber were reviewed.

1.1 Introduction

Due to the development of urban and publication growth, waste materials that are not disposed of and harm the environment increase. To save our plant, researchers had studied many methods to get rid of this waste. One of the most common methods used these materials as an alternative partial replacement for main concrete components to double the benefit, by getting rid of waste and minimizing cement used, and keeping earth resources(sand and gravel). For example, tons of tires were thrown each year; these tires were used as partial gravel replacement in concrete and used in construction under dynamic load. At the same time, plant waste such as palm kernel, palm ash, rice husk, and egg shells are used as cement replacements. Some research on waste materials in concrete was reviewed in this paper.

1.1.1 Fly ash

Fly ash is a byproduct of coal combustion in thermal power plants. This fine, glassy material constitutes 15-35% of commonly used pozzolanic materials in concrete. Research has investigated various replacement levels of fly ash, focusing on its effects on properties such as compressive strength and workability to enhance concrete performance while reducing environmental impacts. Some of these studies are listed in **Table 1**.

Table 1 Some researches on fly ash.

Author and year	Replacement percentage of fly ash	conclusions
Agrawal & Gaur, 2019[1]	10%,20%,30%	By studying the mix design of concrete with a grade of 50, it was concluded that when fly ash was used, the quantity of cementations materials increased while the amount of cement decreased. Additionally, the amount of sand was

		reduced, and the quantity of gravel remained the same as that in ordinary mixes. Furthermore, the amount of water used was also reduced when fly ash was incorporated.
Fořt et al. ,2020 [2]	From 0% up to 70% with steady increasing of 10%.	20% of cement can be replaced by fly ash without affecting any of the mechanical properties, and 30% requires further study by testing the concrete at later ages due to the delay in pozzolanic reactivity.
Antoni et al.,2021[3]	0-100%	Two factors affected the mechanical properties: the source of fly ash, even if it was from a plant, and the types of plants used, along with the percentage of replacement.
Akin and Alithawi ,2022[4]	10%,20%,30%	The study utilized three different mixing methods. For all replacement percentages, workability improved compared to the control mix (0% fly ash). The compressive strength increased with 10% fly ash but began to decline as the replacement level increased. The study also examined the freeze-thaw resistance of concrete and found that concrete containing fly ash exhibited better durability under these conditions.
Jiang ,2023[5]	/	Examine the role of fly ash in concrete, focusing on strength, workability, hydration, advantages, disadvantages, and applications.

1.1.2 Palm ash

Palm ash is a material created from the burning of palm waste, such as fronds. This ash, which is produced by burning various palm parts at temperatures typically ranging from 500 to 800 °C, can be processed and finely ground to serve as a pozzolanic material in concrete.

It contains a high percentage of silica oxides (SiO_2), along with some alumina and iron. These properties make it a pozzolanic material that can react with the calcium hydroxide produced during cement hydration, leading to the formation of additional cementations compounds known as calcium silicate hydrates (C-S-H).

Number of study on using palm ash in concrete was listed in **Table2**.

Table 2 Some studies on concrete with palm ash.

Author and year	Replacement percentage of palm ash	conclusions
Okhio et al, 2020 [6]	10% to 100%	This research critically examines the utilization of palm ash as reported in previous studies and demonstrates that palm ash enhances concrete durability, particularly when grounded with very fine particles.

Ofuyatan et al., 2021[7]	10% up to 50% with10% for each step	Lightweight concrete was studied by testing its compressive strength, splitting tensile strength, and flexural strength. The results indicated that the maximum replacement percentage that did not affect the strength was 20%.
Ismail et al.,2022[8]	20% &40%	Concrete containing 40% palm ash exhibited a compressive strength that was 11% inferior to that of concrete devoid of fly ash at the 7-day However, at the 28-day interval, its compressive strength surpassed that of the control concrete by 6%, and it demonstrated an 8% increase at the 180-day assessment.
Razeman et al.,2023 [9]	10%,20% and 30%	Upon the examination of numerous studies, it was determined that a replacement ratio of 20% represents the most advantageous substitution level based on the weight of the cement.

1.1.3 Ground Granulated Blast-Furnaces (GGBS).

It is a remarkable byproduct of the iron and steel industry. It is ingeniously produced during the smelting of iron ore in blast furnaces, where molten slag is rapidly cooled with water (granulated) and subsequently dried and finely ground into a powder that strikingly resembles cement. GGBS functions as a remarkable partial replacement for Portland cement was used in many researches some of these studies were listed in **Table3**.

Table 3 Some studies on concrete with GGBS.

Author and year	Replacement percentage of GGBS	conclusions
Vijayalakshmi et al., 2020[10]	0%,15%,30% and 45%	As the proportion of the replacement material escalates, the overall strength diminishes.
Singh et al., 2022[11]	0% to 50% with 10% step	Two types of concrete with two strength (25MPa and 40MPa), M25 and M40, were evaluated for their compressive and flexural strength. The compressive strength remained constant at a 10% replacement and started to rise until it peaked at a 40% replacement, after which the strength declined. In both concrete types
Mat Dom et al.2022[12]	0% up to 80%	Several researches were reviewed and demonstrated that the best replacement percentage was 30% to 60% and beyond the 70% replacement there is a notable decrees in strength.

1.1.4 Silica fume

It is a very fine pozzolanic material resulting as a byproduct from the production of metallic silicon or ferrosilicon in electric furnaces. They are in the form of very fine spherical particles (with a diameter of less than 1 micron, which is about 1/100 the size of a cement particle).Contains a very high percentage of silica (SiO_2) — usually more than 90–95%. It was extremely used as cement replacement, some of the studies were listed in **Table4.**

Table 4 Some studies on concrete with silica fume

Author and year	Replacement percentage of silica fume	conclusions
Abera and Raj ,2021[13],	3%to 11% in 2% step	The incorporation of as much as 9% silica fume in place of cement has been shown to enhance compressive, split tensile, and flexural strengths after 28 days of curing. However, beyond this percentage, the workability decreased, and the mixes became hard to handle.
Abed et al. 2023[14],	7% to 33.11%	11.9% was the better replacement ratio that improved compressive strength, density.
Luthfiana et al. 2024[15],	0% to 20%	The results indicated that 10% silica fume raised compressive strength by 56% and beyond this replacement, the strength diminished

1.1.5 Different replacement materials

Nasrudin et al., 2022[16], used coal bottom ash, slag, wasted ceramic powder, and wasted glass powder as partial cement replacement to introduce an eco-friendly concrete. Wasted ceramic powder was also study by **Ghonaim & Morsy, 2023,[17],** in a replacement percentage ranged between 0% to 30%. The results indicated that ceramic powder can be used in concrete up to 30% by cement weight and retain the concrete with 30MPa.

Some researchers go with using plant waste such as coconut shell, egg shell, and rice husk, concluding that all of these materials can be used in concrete but shouldn't exceed a 15% range of replacement **Aryal and Ghimire (2023)[18], (Ayoade, 2024)[20], Mushtaq et al., 2024)[21]**.

In 2024, **Mohammed et al [21]** studied the possibility of using wasted brick powder as cement replacement with different percentage levels and compared it with the same concrete with the same replacement percentage of fly ash, then combined the two materials and concluded that the best results were obtained from using 12.5% of fly ash and 12.5% wasted brick powder.

1.1.6 Gravel replacement

Replacing gravel may involve using alternative materials or methods to enhance performance, lower costs, or promote environmental sustainability.

While there are many benefits to replacing gravel across different applications, it is crucial to consider the specific requirements and constraints of each situation.

1.2.1 Crushed concrete

An increasing number of construction projects are choosing crushed concrete over traditional gravel in their concrete mixes, and this shift is not merely a trend; it's a necessary evolution in the industry! The environmental and economic benefits are significant. Research definitively shows that crushed concrete can effectively replace natural aggregates in concrete formulations without compromising quality—often enhancing specific characteristics of the end product Some of the research conducted in the last five years was reviewed, including the following:

Kočí et al.2020[22], conducted a study evaluating the environmental impact of substituting coarse aggregate in concrete with crushed concrete pavements. The study examined two scenarios: a 50% replacement and a full 100% replacement of natural aggregate. The results suggest that replacing coarse aggregates with recycled concrete pavements could significantly reduce environmental impacts, and therefore it warrants further research (show fig1).

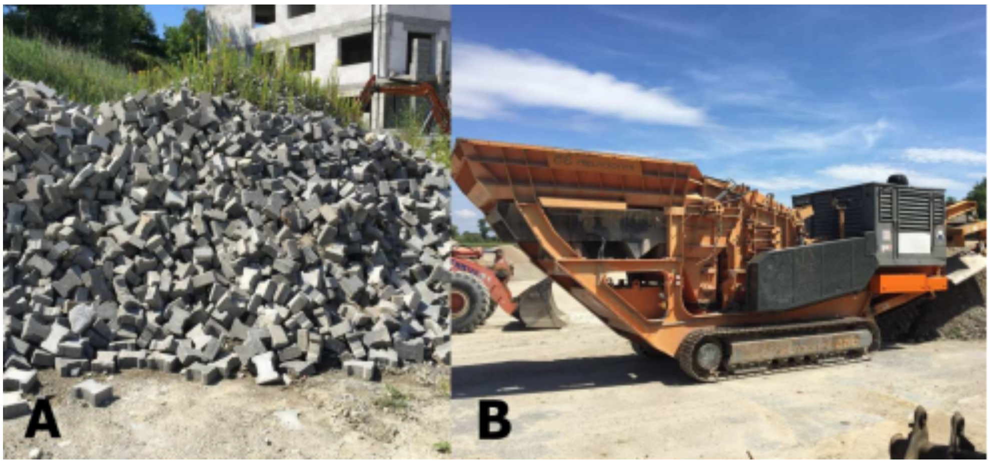

Figure 1Wasted concrete blocks and treatment procedure[22].

Oliveira et al. ,2020[23], examined the possibility of replacing 50% to 100% of natural aggregate with recycled aggregate derived from old structures to reduce concrete waste and benefit the environment, as shown in Fig2. To evaluate this, a concrete sample with 0% recycled aggregate was cast as a control. It cannot be used in a structural member

Figure 2 Reused wasted construction concrete as aggregate in concrete[23].

In 2022, a study **by Das et al [24]**. found results that were contrary to those reported in reference [23]. This study involved four replacement levels: 25%, 50%, 75%, and 100%, in addition to a control mix with 0% replacement of crushed concrete obtained from testing cubes in a construction laboratory and precast columns. The results indicated that recycled aggregate can be used up to 50%.

1.2.2 Rubber

The use of rubber as a substitute for gravel in conventional concrete has gained attention as a sustainable solution to environmental challenges. This innovative approach aids effective waste management without affecting its strength, and it can be used to study the possibility of enhancing concrete's durability, impact resistance, and elasticity. Some of the latest research will be reviewed here. In 2008, 1 billion end-of-life tires were produced globally, so **Aravind and Raj, 2022[25]** proposed using tire rubber as a partial replacement for cement. The results indicated that compressive, splitting, and flexural strengths decreased as the replacement percentage increased. Still, it can be used in concrete up to 15% and retains the traditional strength of regular concrete. It can be used beyond its replacement level, but with a suggestion of increasing cement or replacing some of the cement percentage with finer silica materials.

To minimize strength loss when using rubber **Ahmed et al. 2022 [26]** investigated treating it by soaking in 0.1 molar NaOH for 20 minutes. In cement for 20 minutes, before use, to enhance the bond between mortar and aggregate. 0%, 5%, 10%, and 15% replacement ratios were studied in M20-treated and untreated rubber; the best results were obtained with 5% treated rubber, with concrete restoring 93% of its compressive strength, while in splitting and flexural tests,5% and 15% replacement percentages increased compared with conventional concrete.

He et al. 2023[27] reviewed studies using concrete with different rubber replacement percentages and demonstrated that compressive strength decreased with increasing rubber content, as shown in Fig. 3. Despite this disadvantage, it has the advantage of improving concrete ductility and increasing the plastic deformation, which makes it more suitable to resist dynamic loads

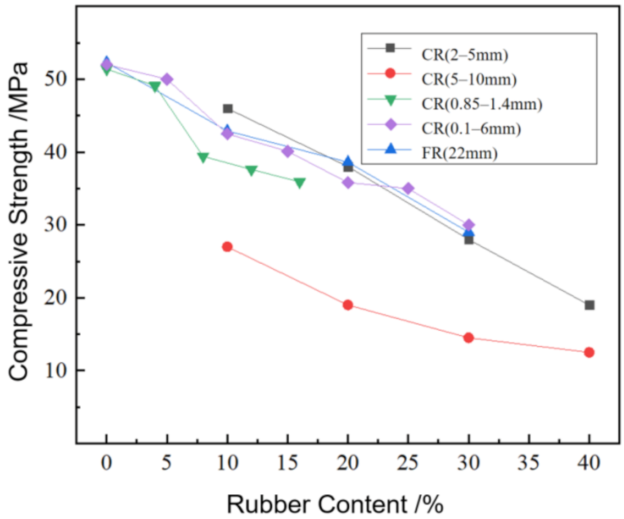

Figure 3 Replacement percentage Vs. compressive strength[27]

1.2.3 Deferent replacement materials

Al-Kaabi et al. 2020[28] use a plastic drinking bottle as a partial replacement for gravel. The replacement level was between 2.5% to 10% by weight of gravel. The compressive strength decreases by 12% to 47% as the replacement percentage increases.

Irawan and Khatulistiani ,2021 [29] used coconut shells with replacement percentages ranging from 0% to 30%; the optimal replacement percentage was 10%.

Maikano and Akanbi 2024, [30] used palm kernel shell and quarry dust as partial replacements for gravel. The best results were obtained with 5% kernel palm and 20% quarry dust. At the same time, **Ha et al. 2024[31]** used see shells with replacement percentages of 3% to 10% and found that the optimal replacement percentage was 3%.

1.2 Sand replacement

1.3.1 Glass powder

Natural sand typically contains salt, which can be detrimental in certain applications. Glass powder presents an eco-friendly alternative. Recent studies have explored its impact on the mechanical properties of concrete. These investigations have thoroughly examined the use of glass powder as a partial substitute for cement, gravel, and sand in ordinary concrete, highlighting its potential to improve both environmental sustainability and the mechanical properties of concrete. This research specifically reviewed the effects of replacing sand with glass powder.

Mishra et al. 2020[32] studied the effect of sand replacement levels ranging from 0% to 40%. The waste glass was collected from shops, then crushed and used in concrete. The best replacement level was 15%. **Pampana et al. 2023[33],** study the same replacement level but demonstrated that glass powder can be replace up to 30% from sand and it's the same replacement ratio concluded by by **Zebilila et al., 2024[34]**. Study done by **Belal,2024[35],** on optimal replacement percentage within the range 0%to 30% in terms of compressive strength and some of the mechanical properties. The results indicated that using 20% would maintain 96% of the control strength at 28 days.

1.3.2 PET

The use of polyethylene terephthalate (PET), which is derived from water bottles and is widely used as a replacement for sand in ordinary concrete, has been investigated as a sustainable approach to eco-friendly concrete. However, incorporating PET into concrete may influence its physical and mechanical properties. Some of the research that investigated it is listed.

Almeshal et al., 2020[36] collected wasted plastic bottles and cleaned them, shredded and ground them to a 4-0.075 mm grading as it shown in Fig4. And used it in concrete as a sand replacement at levels ranging from 0% to 50%, with a 10% increment per mix. The results indicated that the workability of concrete with PET was reduced due to its irregular particle shape. The compressive strength also decreased with PET increase until it reached a maximum decrease by 60% when 50% PET was used. However, PET can be used in concrete with a 5-10% replacement level as it doesn't have a notable effect on strength.

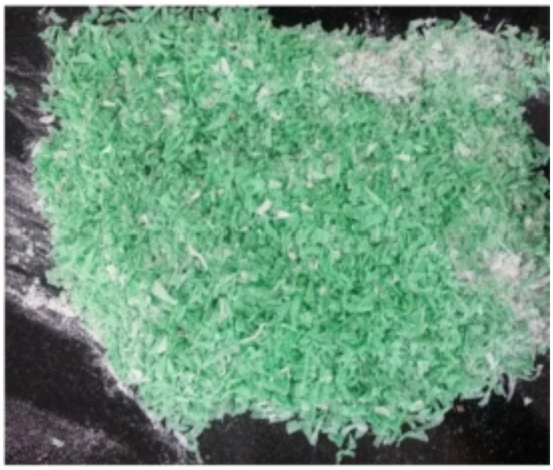

Figure 4 Crushed plastic bottle[37].

Correa et al. 2021[37] conducted a study examining the use of PET in structural members. The replacement percentage used was 10% by volume of sand, and it caused a 20% decrease in compressive strength, but mainly, using PET raised the resistance to chloride penetration by 15%. This percentage was also used by Sancak and Özyurt (2024) [38], after testing three replacement levels of 10%, 20%, and 30% by sand volume in concrete

Supit et al., 2022 [39] studied the replacement percentage of sand BY PET up to 30% but the best rate was 5% by weight of sand that can be used in concrete paving blocks.

Dawood & Sabar, 2025,[40] study the potential of using high replacement percentages of PET (30% and 50%) in lightweight concrete due to its benefits as a light material. The concrete mixture was reinforced with 1.5% polypropylene fibers. The 50% replacement percentage gave an acceptable density and compressive strength of 25MPa, which is acceptable too.

1.4 Conclusions

Wasted materials can be used in concrete to improve strength, such as GGBS. And can be used up to 30% without affecting the concrete's strength—other wasted plant materials can be used as cement replacements up to 15%. Rubber and PET can be used as a replacement for gravel and sand, respectively, up to 10% with a slight effect on strength. Crushed concrete can be used up to 50% as recycled aggregate in concrete.

1.5 Reference

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