Sustainable Concrete with Substitute Materials: A Review

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1 Introduction

Concrete being versatile and the most abundant construction material, the consumption of concrete in India is increasing rapidly each year. In the year 2009, the concrete consumption was 193 MMT which increased to 398 MMT in 2017. Also, cement being the main core ingredient of concrete, production of cement is the third biggest reason for man-made CO2 discharges. Cement represents 83% of aggregate energy use in the generation of non-metallic minerals and 94% of CO2 emanations. In India, the cement capacity is estimated to be 270 MT in 2017 with 5–6% increase in production each year. The country's per capita estimated consumption stands at around 225 kg.

Production of cement emits greenhouse gases both by limestone calcination and burning of fossil fuels which is very harmful for health and environment. The main environmental issues related to the production of cement are the consumption of raw materials and energy use as well as greenhouse gas (GHG) emissions in the air. Considerable research is being done to replace cement, may be partially.

The amount of waste materials also may amount to millions of tons annually. In India, the quantity of solid waste is 960 million tons created every year as by items amid mechanical, mining, city, horticulture, and different procedures, 350 million tons is natural waste from farming source and rest 290 million tons is inorganic misuse of modern and mining segments. Production of sustainable concrete utilizing waste materials is the contemporary trend of the architecture, engineering, and construction industry.

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Disaster resilience is another area of strategic importance in which the buildings/structures should be able to resist the impact of different hazards like earthquakes, cyclones, or floods. Heavy self-loads are one of the limitations for construction of tall buildings especially in earthquake-prone areas. If somehow structures are made lighter, cost of the foundation can also be lowered down. Structural lightweight concrete has an in-place density is 1440–1840 kg/m^3 as compared to 1240–2400 kg/m^3 of conventional concrete [1]. Concrete can be made lighter by using lightweight coarse aggregate since coarse aggregates form the major portion of concrete weight. The use of lightweight aggregate concrete (LWAC) started in earlier Indus valley civilizations. Today, lightweight aggregates are delivered in an extensive unit weights from 50 kg/m^3 for expanded polystyrene to 1000 kg/m^3 for clinkers. The mechanical properties of concrete and its durability parameters can be varied widely using chemical admixtures. Technological advancements in this area have resulted in the formulation of many chemicals which gave higher strengths or any other modification in concrete behavior. The personnel handling the chemicals at large scale has to follow the instructions but more on paper than actual practice. Moreover, the fumes from chemicals affect the personnel's health. Thus, a need was long felt to research the age old extracts from fruits which can be used to modify concrete's properties. This paper besides reviewing the research on sustainable lightweight concrete also explores the use of herbal admixtures derived from common fruits in concrete.

2 Literature Review

2.1 Materials Used as Partial Replacement of Cement

Nagaswaram et al. [2] carried out investigation to replace cement with fly ash and fine aggregate with thermocol in lightweight M25 concrete. Concrete mixes were designed by replacing cement with 35% and 40% fly ash and fine aggregate with 0.2% and 0.3% thermocol. Results revealed that for combination of 35% fly ash and 0.2% thermocol, the 28 days compressive strength of concrete was 7% and for combination 40% fly ash and 0.3% thermocol 10% higher than the normal mix. Also, improvement in workability of concrete mix was obtained due to spherical particles of fly ash and thermocol.

Abbas et al. [3] studied the effect of replacement of cement by 10, 20 and 30% of brick powder, glass powder, and tile powder. From experimental investigations, it was concluded that concrete having 10% brick powder, the compressive strength at 7, 28, and 90 days incremented by about 6%, 4.7%, and 2.0% and flexural strength by about 2, 1.6, and 3.6% when compared to normal concrete. For samples of concrete prepared by replacement with 10% waste glass powder, the compressive strength increased by about 7.2, 5.6, and 2.0% and with 20% replacement, by 8, 6.3, and

4% at 7, 28, and 90 days. However, the concrete mixes prepared by tile powder substitution in different percentages declined the strength parameters.

Leterier et al. [4] performed an investigation on partially replacing cement by waste brick powder in different proportions of 5%, 10%, and 15% in concrete specimens. The strength values after 28 days exhibited almost 9% rise than reference concrete.

Tan et al. [5] investigated capability of using ground eggshell in concrete. Tests were carried by replacing 5–20% of cement with eggshell powder and it was observed that the eggshell concrete achieved higher early strength due to accelerated hydration process. However, the durability of concrete decreased with powdered egg shell and an optimum percentage of 15% was obtained to get 48.36 MPa compressive strength and 10.1 MPa flexural strength at 28 days.

Wattanapornproma and Stitmannaithum [6] studied the properties of concrete at w/c ratio of 0.40, 0.50, or 0.67 by replacing cement with fly ash as 10%, 20%, 10%, 20% powdered glass and 10% silica fume. The results indicated that 10% of silica fume as partial replacement of cement exhibited best results with highest strength of 750 kSc after 28 days and lowest drying shrinkage of 310 microstrain after 75 days at W/B 0.44 followed by 10% glass powder.

Yerramala [7] studied the effect of replacing cement with 5–15% eggshell powder (EPS). From experimental data, it was observed that on replacement cement with 5% EPS, the compressive strength of concrete mix increased and was better than the control concrete. On further increase of EPS to 10%, the compressive strength declined. On the other hand, on substituting cement with 10% EPS, the split cylinder tensile strength was comparable to normal concrete and decreased with further increase in EPS content up to 15%.

Sharma et al. [8] studied the strength parameters and absorption capacity test of M35 grade with partial substitution of cement with brick kiln dust. The brick kiln dust was used in varying percentage as 0, 5, 10, 15, 20, 25, and 30% with superplasticizer admixture as maximum 2% by weight of cement. It was concluded from experimental results that the compressive strength of blocks increased by the use of brick kiln dust from 5 to 15% but above 15% the strength decreased. It was strictly observed that the water absorption percentage was increased as the number of days increased.

Aliabdo et al. [9] investigated the reuse of marble dust as cement replacement in concrete. The cement is replaced with 0.0, 5.0, 7.5, 10.0, and 15.0% of marble dust with low w/p ratios of 0.5 and below. Results revealed that with 0.50 w/p ratio, there is reduction in compressive strength of mix due to marble dust after 28 days, whereas with 0.40 w/p ratio, the gain in strength was significant up to 10% substitution. The strength in tension was maximum with 7.5% marble dust with 0.50 w/p ratio for all curing ages, and it gave increasing results with 0.40 w/p ratio.

Vishaliny et al. [10] investigated addition of finely powdered waste glass on compressive, split tensile, and flexural strength of concrete. Finely powdered glass with particles of size less than 75 μm was partially replaced in percentages as 10, 20, 30, and 40%. The compressive, split tensile, and flexural strength of normal concrete at 28 days was found to 31.1 N/mm^2, 2.27 N/mm^2, and 3.25 N/mm^2. Increase in compressive stress was 19.6%, 25.3%, and 33.7% after addition of glass powder as 20%, 30%, and 40% as substitutes.

Kamaruddin et al. [11] experimented the effect of clay brick powder in place of cement on properties of M30 concrete with w/c ratio of 0.6. Cement was replaced in various percentages such as 10%, 20%, and 30% and samples were observed at 7, 28, 60, 90, and 120 days. From results, it was noticed that the workability declined with rising ground clay bricks contents. The strength values improved by 18.5%, 13.16%, 5.1% for 10%, 20%, and 30% substitutions, respectively, in comparison to the controlled specimen.

From the above review, it was observed that brick powder, waste glass powder, egg shell powder, and marble dust provided technological and environmental benefits by effectively replacing cement in the concrete.

2.2 Alternative Eco-Friendly Admixtures

Admixtures are added to the concrete mix to improve its green as well as set properties. Nowadays, admixtures available in the market are chemicals added in the percentages of 2–4%, which are expensive and also pollute the environment. However, literature revealed that there are some natural admixtures such as Arabic gum, black gram flour, broiler hen eggs, cassava starch, corn starch, egg shell powder, gram flour (Besan), ghee, kadukkai, maize starch, okra, sugar, and triphla used in ancient times which when added to concrete had capability to enhance its binding properties, compressive strength, and workability.

Hazarika et al. [12] investigated the effect of substituting water with aqueous extract of okra as bio-admixture in production of concrete. The aqueous extract of okra was prepared by mixing 1 part of okra pod and seeds with 10–50 part of water. Then this aqueous solution was mixed with cement and aggregates to cast concrete samples (BA110, BA120, and BA140) at w/c of 0.53. Results revealed that the slump of fresh concrete reduced on addition of okra bio-admixture in comparison to reference concrete mix. However, the compressive strength was found to be on higher side for sample BA140, approximately same for sample BA120 and on lower side for sample BA110.

Babu and Neeraja [13] experimented on effect of addition of broiler hen eggs as natural admixture (NAD) on properties of M25 conventional and Class F fly ash blended concrete prepared by substituting cement with 25, 35, 45, and 55% fly ash. Broiler egg was first mixed with water and then put in both control and fly ash mixes in various proportions ranging from 0.25 to 0.75% to the weight the binder. The liquid (water + NAD)/binder ratio was maintained as 0.5. Various tests were conducted to determine the initial setting time, workability, and compressive strength. Slump loss decreased with the increase of NAD dosage to binder mixes. The optimum compressive strength for conventional as well as blended concrete for all ages was obtained at 0.25% dosage of NAD. Concrete mixes with 35% fly ash and 0.25% NAD exhibited highest strength value and concluded as optimum mix.

Mohamed et al. [14] analyzed the effect of Arabic gum biopolymer (AGB) on the strength and permeability of concrete mix. Samples of concrete were prepared by mixing AGB in the range of 0.1% and 1.1%. Results showed that the permeability of concrete mix decreased by 16% for an optimal AGB of 0.9% by weight. Flexural and tensile strengths increased with the increase of AGB content up to 0.7% and values obtained 4.21 MPa and 2.38 MPa, respectively.

Patel and Deo [15] studied the effect of natural organic materials such as gram flour, ghee, and triphala as an admixture in concrete. Both fresh and hardened properties, and cost analysis per N/mm^2 were determined and compared with conventional concrete. The admixtures were added to concrete mix in 0.5, 1, and 0.5% by weight of cement and mix was prepared at 0.40 and 0.45 w/c ratio. It was concluded that on adding gram flour and triphala in concrete for both w/c ratio, the workability of mix increased. However, the addition of ghee did not show any effect on the workability. Increase in strength of mix was observed on addition of gram flour only. Cost per N/mm^2 was found to be lower for concrete mixed with 1% gram flour at 0.45 w/c ratio.

Suhad et al. [16] studied addition of corn starch in different proportions as admixture in concrete. The percentage of corn starch was taken as 1.0, 3.0, and 5.0%. Results revealed that the density of concrete at 28 days after addition of 1, 3, and 5% corn starch increased by 4%, 3%, and 3%, respectively. The compressive strength of concrete was also found to be increased by 18%, 17%, and 10% in comparison to normal concrete. From experimental results it was observed that the optimum percentage of corn starch was 1% after that the density and compressive strength of concrete considerably reduced.

Kumar et al. [17] performed detailed experiment by using "Terminalia chebula" (Kadukkai) and chicken eggshell as an admixture in M20 plain cement concrete (1:1.5:3) with 0.4 w/c ratio. Two types of concrete mixes were prepared by adding (i) 2.5–7.5% kadukkai, (ii) 5% kadukkai along with 5–15% eggshell powder. It is observed that inclusion of Kadukkai and eggshell helps in improving properties of concrete. 5% addition of kadukkai to concrete mix showed maximum compressive, tensile, and flexural strength with value of 36.59 N/mm^2, 3.35 N/mm^2, and 5.75 N/mm^2.

Akindahunsi et al. [18] carried out experiments by adding 0.5, 1.0, 1.5, and 2.0% cassava and maize starch as admixture. The setting time was delayed and durability properties were improved on addition of starches to the mix. Comparison of cassava and maize starch revealed that cassava starch concrete mix showed less slump and higher viscosity in comparison to maize starch mix.

Shilu and Xavier [19] focused on the effect of starch admixtures namely tapioca and maize on strength characters of concrete. Various percentages of tapioca in concrete ranging from 0.5 to 2.5% with constant percentage of 1.5% maize was used as admixture. The optimum percentage of admixture was found to be 2% tapioca and 1.5% maize which enhanced the properties of concrete. The strengths of concrete with 2% tapioca and 1.5% maize in concrete were 40.515 MPa (compressive), 3.862 MPa (split tensile), and 5.83 MPa (flexural).

Abalaka [20] made a comparative study by adding 0–1% (by weight of cement) white sugar and cassava starch as admixture to M35 concrete. Results revealed that cassava and sugar showed similar effects in concrete. The optimum dose at which concrete mix gained maximum compressive strength value of 42.59 and 42.36 N/mm^2 at 28 days curing was 0.05% for cassava and 0.06% for sugar, respectively.

Chandra and Aavik [21] evaluated use of black gram as admixture on properties of M25 concrete. Concrete cube samples were prepared by adding 1.5% (by weight of cement) black gram and mix of black gram and oil emulsion. The compressive strength achieved was 19.0 MPa for black gram mix and 22.5 MPa for mix of black gram and oil emulsion.

2.3 Materials Used as Partial Replacement of Coarse Aggregates

Patel et al. [22] performed experiments by replacing coarse aggregates with styrofoam for M30 concrete. 0%, 20%, 40%, 60%, 80%, and 100% styrofoam was used to replace coarse aggregates. The test results showed that with the increase in proportion of styrofoam in the mix, the strength of concrete decreased. At 100% replacement of coarse aggregates by styrofoam, the strength in compression and mass of the concrete was observed to be 23.4% and 42.85% less than the normal concrete, respectively.

Karanth et al. [23] attempted to achieve M20 grade of lightweight concrete by replacing coarse aggregate with cinder (20%, 40%, 60%, 80%, and 100%) and fine aggregate with fly ash granules (100%). Steel fibers of length 25 mm and diameter 0.45 mm were also added at a ratio of 1% by weight of cement in concrete to enhance the tensile strength of the concrete. Substitution of natural coarse aggregates with 100% cinder resulted in reduction of density of mix by 18.13% and strength by 48%. Also, substitution of fine aggregate with fly ash was found not found to effective as the strength of concrete reduced by 25% in comparison to conventional concrete.

Shinde et al. [24] revealed that for M 20 grade of concrete prepared with 0%, 10%, 15%, 20% substitution of coarse aggregate by coconut shell, the maximum compressive strength attained was 31.75 N/mm^2 for 0% substitution while the minimum compressive strength attained was 9.75 N/mm^2 for 20% substitution. Also, these values were less than the target mean strength 20 N/mm^2. The concrete 10% substitution of coconut shell was same as concrete at 0% substitution. So, the 10% was suitable for sulfate attack. With increasing the percentage of coconut shell in concrete reduces its strength but 10% substitution was optimum percentage.

Gawale et al. [25] used expanded polystyrene (EPS) in granular foam to replace natural aggregates and found that the unit weight of concrete reduced from 1350 to 950 kg/m^3. Also, alluring effect on strength of concrete was observed on using EPS dots. On the basis of results, it was recommended that such concrete could be used in casting non-structural elements such as partition wall, foot path, parapet wall, and bed concrete.

Mulla and Shelake [26] compared the results of M20 concrete prepared by using expanded polystyrene beads and conventional aggregates. Results revealed that the concrete with expanded polystyrene (EPS) beads had low compressive strength in comparison to conventional concrete. However, the increase in workability was observed with the increase in expanded polystyrene (EPS) beads in concrete.

Mishra and Mishra [27] studied the effect of partial substitution of natural coarse aggregates by recycled plastic aggregates. Various percentages of plastic aggregates ranging from 10 to 40% were used in concrete. The optimum percentage of admixture was found to be 20% with compressive strength of 85.69% higher than conventional concrete.

Kumar and Prakash [28] studied the properties of structural light weight M20 grade of concrete which was produced by replacing coarse aggregate by blending lightweight aggregates such as Cinder and Leca in various percentage proportions like 0:100, 10:90, 20:80; 30:70; 40:60, 50:50 and vice versa by volume of concrete. From experimental results, it was observed that by using 60% of cinder and 40% of Leca for substitution of aggregate made a good lightweight structural concrete and had achieved an average compressive strength of 28.89 N/mm^2 and split tensile strength of 1.67 N/mm^2. The achieved density of normal concrete was 2651 kg/mm^3 which was obviously higher than lightweight aggregate concrete as its density varied from 1750 to 1850 kg/mm^3.

Kakade and Dhawale [29] analyzed the physical and mechanical properties of M20 concrete in which pounded, granular coconut shells were utilized as semi-substitution of coarse aggregates in various fractions. The specimens were casted with 0%, 25%, and 50% substitution with consistent water cement proportion of 0.46%. Following 28 days of curing, the compressive strength of cubes was observed to be 21.31 MPa and 14.88 MPa at 25% and 50%. The unit weight was observed to be in range between 1975–2111 kg/m^3 and 1880–1930 kg/m^3 which reflects a weight reduction of 15% and 25% for 25% and 50% replacements, respectively.

Lalitha and Raju [30] conducted experimental studies for M30 grade concrete in which sea shells and coconut shells were used. The compressive strength of concrete were found as after 3 days at 0%, 10 (5% + 5%), 20 (10% + 10%), 40 (20% + 20%), 60 (30% + 30%) were 18.23, 18.12, 8.46, 7.86, 4.67 MPa and for 7 days 28.77, 28.32, 18.78, 13.44, 7.89 MPa and for 28 days 38.67, 37.42, 28.9, 18.53, 10.43 MPa. It was noticed that the optimum percentage for replacement of coarse aggregate by sea shells and coconut shells was 10% and increased percentages of sea shells and coconut shell show lesser strengths.

Sobuz et al. [31] in addition to strength parameters investigated cost analysis of concrete produced by using oil palm shells(OPS) in the mix proportions of 1:1.65:2.45, 1:2.5:3.3, and 1:3.3:4.2 with corresponding w/c ratios of 0.45, 0.6, and 0.75, respectively. With acceptable strength ranges, the research highlighted a cost reduction of up to 15%.

Ahmed and Raju [32] replaced recycled plastic as coarse aggregates and investigated workability, compressive, and tensile strength. Their study concluded that plastics can be used in concrete up to 10% as partial replacement of coarse aggregate with water cement ratio of 0.4, 0.45, 0.5, etc., as it reduces the workability of concrete, reduces tensile and compressive strength, and also lowers the density in concrete for a given w/c ratio.

Ramesan et al. [33] tried using polyethylene as substitute for coarse aggregates up to 40% and investigated workability, strength characteristics of RCC and PCC beams. They found that workability increased by 50%, compressive strength by 9.4%, and splitting tensile strength by 39% with reference to usual concrete. The ultimate load for the beams and consequently, the flexural strength showed an increase and they concluded an optimum percentage of replacement as 30%.

Similar investigation was carried out by Tamut et al. [34] with expanded polystyrene (EPS) beads. It was observed that thought the workability increased with increasing percentages of EPS beads due to ball bearing effect, but there was a decrease in the strength of cubes casted with EPS substitutes.

Shah and Patel [35] emphasized the use of lightweight concrete with EPS beads in partition walls, panels and other non-load bearing elements of the buildings as they provide good thermal insulations, durability, and required compressive strength. Cost analysis on such concrete was done in relation to decreasing strength, and cost of one concrete block of standard size (150 × 150 × 150 mm^3) was calculated as Rs. 15.73.

Asokan et al. [36] adopted EPS mix proportioning of concrete mix as 1: 1.75: 1.92 with w/c as 0.45 and concluded the same results of increased workability and reduced strength.

Kuhail [37] coined polyconcrete with polystyrene, sand, and differing w/c ratios from 0.3 to 0.45 and cement from 238 to 600 kg/m^3. The research achieved strengths of up to 200 kg/cm^2 with a low density and high workability at a very low water/cement ratio of 0.35. Applications included non-structural components thermal and sound insulation slabs, frost resistance slabs, screed and roof slopes and precast lightweight components and lightweight blocks.

The experimental research studies mentioned above show replacements by coconut shells, sea shells, palm oil shells, recycled plastics and EPS beads. All the researchers conclude obvious lesser costs with replacements, reduction in weight and also, reduction in strength parameters with increased percentages of substitutes. The strength estimations of concrete blended with plastic waste generally decline as compared to the conventional concrete mixes with increasing waste plastic proportion at all curing stages. This may be because of reduction in the adhesion between the materials. What is more is the hydrophobic characteristic of plastic waste which may confine cement hydration. The flexural strength and tensile strengths too show a decline in the values which impair the use of these mixes in structural concrete. Thus, the applications have been given as non-structural, mostly in partition walls but with good sound and thermal insulation. However, good workability has been observed with EPS beads at considerable lower water cement ratios.

3 Conclusion

This paper covers review on concrete variations having either partial replacement of cement or coarse/fine aggregates and use of herbal admixtures ranging from material aspects to applications in the field. Paradigm shift of construction industry to sustainability and the simultaneous lack of research data have posed limitations on the use of such concretes. The late 2000 to early 2019 saw intense research in this area to compare mainly the strength parameters of concrete variations to conventional concrete. The compressive, tensile, and flexural strengths are comparable to target strengths for optimum percentage of replacements as found in different research works and thus will not considerably affect concrete applications. Consequently this survey suggests the manufacture of concrete utilizing various wastes given the work cost acquired in the extraction of waste or using herbal admixtures do not exceed the cost for conventional concrete. This review is likely to help and encourage the stakeholders to rational usage and long term performance of concrete made out of these replacements. Further studies can be done on money related examination of reused concrete and potential natural advantages of sustainable concrete.

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