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Analytical framework for value added utilization of glass waste in concrete: Mechanical and environmental performance

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ABSTRACT

This work was designed to incorporate glass waste as partial replacement of coarse aggregate in concrete through optimization of its amount by assessment of mechanical and environmental performances. Fresh and hardened properties of glass waste concrete were evaluated and compared with the conventional concrete. Moreover, compressive strength was evaluated experimentally as well as analytically at different ages. While, environmental performance was evaluated with an assessment of CO_2 footprint and volume utilization of raw materials for both types of concrete; conventional and glass waste concrete. Consequently, a sustainable concrete was selected that possesses high workability and mechanical performance, minimum CO_2 footprint and least utilization of conventional natural raw materials. For optimization, corresponding values of designed parameters were translated into a framework for glass waste management by application of analytical hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS). Similar prioritization for all types of mixtures was achieved through proposed framework by applying such multi criteria decision making techniques. Proposed framework may further be used for adjusting the priority weights for each criterion according to the requirement as well as for extended evaluation of additional criteria.

1. Introduction

Waste generation from various industries is a big threat to the environment and society. Every industry produces large amount of waste that pollutes either the air, water, or land and is posing a serious threat to human health as well. Combustion of waste material and landfilling were the only solutions for the waste management in the past, but increased awareness of sustainable environment by several authorities and non-governmental organizations (NGOs) has rendered it as ineffective and detrimental to the environment. The current focus of all manufacturers is to recycle and reuse the waste materials, instead of dumping.

Recent studies show that concrete industry has become the main consumer of many industrial wastes (De Brito and Saikia, 2012; Gu and Ozbakkaloglu, 2016; Siddique, 2007). Authors of this study have carried out a series of work to incorporate the construction and industrial wastes in concrete for sustainable design, effective waste management, conservation of natural resources and conservation of energy (Rashid and Balouch, 2017; Rashid and Nazir, 2017; Rashid and Rashid, 2017; Rashid et al., 2017). Likewise, many researchers had utilized various construction and demolition wastes in concrete for conservation of natural resources and to produce recycled sustainable concrete. De Brito and Saikia, 2012 summarized the work of many authors and that compilation provides the efficient utilization of industrial waste materials in concrete. Siddique, 2007 composed a comprehensive summary that reports the properties of concrete influenced by various industrial wastes. Both compilations concludes that three constituents of concrete; cement, fine and coarse aggregate can be replaced partially or fully by several waste materials for its effective management (De Brito and Saikia, 2012; Siddique, 2007).

Utilization of glass in manufacturing of various goods and products for construction and various industries is on the rise due to a rapid growth in infrastructure development, industrialization for improvement in standard of living (Park et al., 2004). Modernization of buildings has given rise to a trend of utilization of huge quantities of glass in building facades. Each year a large number of such buildings are completing their intended life and adds more glass in the waste stream. Other industries like; electronics and

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packaging are also generating major quantities of glass waste. Yearly volume of waste generated around the world as estimated by United Nations is 200 million tons out of which 7% is glass waste (Topcu and Canbaz, 2004). With the increase in glass utilization, waste generation issues have also risen which require serious mitigation policies.

One way to manage the large quantity of glass waste being collected every year is the landfilling. Almost 74% of the collected glass waste was disposed in landfills even in the USA, which is among the top developed countries (Afshinnia and Rangaraju, 2016). For Hong Kong (developing country), 96.7% of glass waste was sent to landfills for direct dumping ((Ling et al., 2013) (Table 1)). Various environmental problems are encountered as glass waste is abandoned and only sent to landfill sites (Ismail and Al-Hashmi, 2009). The other way of management of glass waste is to recycle and reuse in the manufacturing of glass products. Attempts are being made to increase the rate of recycling ((Jani and Hogland, 2014) (Table 1)) but the main barrier is the different colors of the glass, variation in chemical composition, amount of dirt and different toxic elements attached to the waste glass (Bignozzi et al., 2015; Bursi et al., 2017; D'Amore et al., 2017; Kim and Kim, 2018; Yao et al., 2018). The effective way to reuse the glass waste is just by cleaning and crushing it to different sizes and use it as building material that may be the most viable and eco-friendly solution (Afshinnia and Rangaraju, 2016).

Several studies have been carried out in past that incorporated glass waste in concrete (Jani and Hogland, 2014; Mohajerani et al., 2017). One of the advantages of glass concrete is its thermal stability at a temperature range of −20 to 60 °C due to low thermal conductivity and high specific heat as compared to the conventional stone or crushed aggregate (Poutos et al., 2008). Particle size of the glass waste highly influences the performance of a glass incorporated concrete (Corinaldesi et al., 2005; Dhir et al., 2009; Federico and Chidiac, 2009; Lam et al., 2007; Taha and Nounu, 2008). In powder form it can provide pozzolonic properties due to which it has been used as the partial replacement of cement. Generally, 80% of the volume of concrete is occupied by cumulative fine and coarse aggregates (Li, 2011) and replacement of conventional aggregates by glass waste may results into significant conservation of the non-renewable natural resources that is also a big concern for environmental sustainability. Due to significant advantages glass waste can be utilized in concrete without compromising the desired performance.

Carbon dioxide (CO_2) is another big threat to the environment and its emission must not be elevated during the utilization of glass waste in concrete, instead of using virgin raw materials. Carbon dioxide (CO_2) footprint has been assessed in various studies which concludes that about 80% CO_2 was emitted from cement production and nearly 13–20% CO_2 was emitted from coarse aggregate in the life cycle of concrete (Flower and Sanjayan, 2007). Quantification of CO_2 emission is an important task and several methods (input base, life cycle assessment, etc.) are available to measure it accurately and precisely (Shen et al., 2015). CO_2 emission can be calculated by calcination of raw materials, fuel and electricity used. In case of coarse aggregate, there will be no calcination only crushers are required to get the desired grade of aggregate. Different types of crushers with different capacities are used and operated by electricity. For glass waste aggregate again crusher is required to get the desired size. So electricity is the main contributor to calculate CO_2 footprint therefore it must be assessed in depth.

Table 1
Properties of conventional coarse aggregate and glass waste aggregate.

Properties	Conventional coarse aggregate	Glass waste aggregate	Standard
Shape	Rounded	Elongated	ASTM C-33
Maximum Size (mm)	20	20	ASTM C-33
Fineness Modulus	6.61	7.86	ASTM C-136
Specific Gravity	2.650	2.500	ASTM C 127
Impact Value (%)	13	22	BS 812-112
Crushing Value (%)	22	31	BS-812-110
Rodded Bulk Density (kg/m^3)	1596	1568	ASTM, C 29
Elongation Index (%)	20.15	42	BS-812-105.1
Flakiness Index (%)	22.93	100	BS-812-105.2

A missing parameter up till now is the integration of mechanical performance along with the environmental impacts of glass-incorporated concrete. Also, a framework is missing in which any user can put the target workability and mechanical performance to achieve a particular amount of glass waste to be incorporated in a specific mixture. Such framework must have an option to incorporate environmental impacts along with the mechanical performance.

With such background, experiments and analytical work were carried out by using glass waste as partial replacement of the conventional coarse aggregate to assess the following; (1) Fresh and hardened properties, (2) Consumption of natural resources in terms of volume of raw materials and (3) CO_2 emission, for both types of concrete. Finally, analytical framework was proposed for selection of sustainable concrete with glass waste by incorporating workability, density, compressive strength, CO_2 footprint and utilization of raw materials.

2. Methodology

In order to evaluate the efficient utilization of glass waste, experimental and analytical work was conducted. In experimental set-up, different quantities of glass waste were added in various concrete by partially replacing coarse aggregate and their fresh and hardened properties were evaluated. Analytically, sustainable concrete was selected on the basis of the results of multi criteria decision making (MCDM) techniques.

2.1. Materials and specimen preparation

Ordinary Portland cement of ASTM type-I was used as a binder for the preparation of specimens, with specific gravity 3.13. The river sand used as fine aggregate was locally available with specific gravity 2.67 and fineness modulus 1.87. Coarse aggregate was extracted from Margalla hills of Pakistan and its specific gravity was 2.65 and fineness modulus was 6.61. Glass waste (GW) was used as partial replacement of coarse aggregate. GW was obtained from the waste generated by local glass market where large quantity of glass waste was accumulated due to poor quality, mishandling, transportation, and damaging during placing, or may be due to some other reasons. Large quantity of glass waste was green in color while the rest was transparent and silver colored as shown in Fig. 1. The properties of glass were compared with that of coarse aggregate as mentioned in Table 1.

Concrete was proportioned by following ACI guidelines (ACI 211.1-91). Several trails were carried out to obtain water to cement ratio of 0.55 for a target strength of 21 MPa. Four types of mixtures were prepared. The first mixture was the conventional concrete which was prepared for reference purpose, in which amount of GW was zero and it is narrated as control specimen (CC) in this work. Other three types of mixtures were prepared by replacing normal coarse aggregate with GW by an amount of 10, 20 and 30%, respectively, by weight. The proportions of mixture for one cubic meter of concrete are presented in Table 2. After mixing of respective constituents, all types of concrete were poured into steel