ISSN: 2754-4915

Journal of Material Sciences & Manufacturing Research

SCIENTIFIC Research and Community

Research Article

Open Access

A Comparative Study Investigating the Feasibility and Potential of Utilising Polymer, Demolition & Glass Waste as a Partial Replacement for Fine and Coarse Aggregate in Concrete

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ABSTRACT

The construction industry is a key CO_2 contributor. Contemporary research focuses on formulating cement replacement composites; however, less attention is deliberated to formulating fine/coarse aggregate replacement composites. The waste from different fields contributes enormously to adverse environmental effects, thus necessitating reuse/recycling. The demolition/reconstruction of old buildings/infrastructure is adding further to the waste contribution by the construction industry. The total quantum of fine/coarse aggregate in the construction industry is estimated to be around 20 billion tons, contributing around a billion tons of CO_2. Therefore, even partial replacement of virgin sand/coarse aggregates with various waste materials like glass, rubber, plastic, tyres, recycled concrete and others will economise the cost of manufacturing the concrete with reduced CO_2 footprints as eco-friendly materials. This study conducted a comparative analysis for investigation of the characteristic compressive and split tensile strength of concrete composites with partial replacement of virgin sand/coarse aggregate by 10-30% of Crushed Glass (CG), Crumb Rubber (CR), Recycled PET Bottles (RPB), Recycled Concrete Aggregate (RCA) and 5-10% of Shredded Tyres (ST). Generally, all the composites demonstrated par/ better strength with the control mix, achieving the target strength of C55/67 concrete. The composites with CG, RPB and RCA exhibited an improvement in compressive strength, attaining more than 70 MPa (high-performance concrete strength) and up to 10% improvement in split tensile, attaining 4.3 MPa. CR and 5-10% ST exhibited a slight decrease in compressive strengths. All the composites formulated in this study explicate their diverse uses for multipurpose infrastructural applications in the construction industry as improved, economical, eco-friendly waste absorbent composites.

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Received: November 13, 2022; **Accepted:** November 25, 2023; **Published:** January 20, 2024

Keywords: Eco-Friendly Composites, Fine/ Coarse Aggregate Replacement, Compressive Strength, Split Tensile Strength, Preservation of Natural Resources

Introduction

The construction industry is envisaged among the top global waste and carbon dioxide (CO_2) contributors. 80% of the construction sector's share is contributed by manufacturing/ transportation/ formulation of cement concrete alone. Fine and coarse aggregate are the essential ingredients of concrete and account for around 15-20% share of the construction industry's waste/ greenhouse gas emissions. Moreover, mining/extracting gravel/ sand or crushing rocks to get fine/ coarse aggregate depletes these naturally occurring resources faster, resulting in a scarcity of resources and environmental/ ecological impacts. The construction industry is estimated to produce around 5 billion tons of CO_2 globally, mainly contributed by cement concrete. Global cement production is approximately 4.1 billion tons per year; therefore, cement production alone accounts for more than 4 billion tons of CO_2, with around one ton of CO_2 emission per ton of cement. The quarrying, transportation and crushing/ extraction of around 20 billion tons of sand, gravel and aggregates for the formulation of cement concrete/ road construction account for about one billion tons of additional CO_2 emission per year. The global aggregate market size is estimated at around 500 billion USD. Concrete manufacturing makes up 70% of the global aggregate market share, highways/ airfield construction 18%, and 12% is the market share of all other industries/ uses, as illustrated in Figure 1. The USA, Canada and Mexico in North America, Brazil in South America, Germany and the UK in Europe, Gulf countries in the Middle East, and China and India in Pacific Asia are the major consumers of the aggregates due to significant ongoing construction/development works in these countries.

The mining, excavation, and crushing industry for producing fine and coarse aggregates is experiencing a surge in demand and financial benefits. However, this trend has led to illegal and uncontrolled production, resulting in a faster depletion of natural resources, non-conservation of these resources for future generations and damaging impacts on the environment [1-5]. The ecology and biodiversity of natural habitats are also disturbed and fauna and flora are adversely affected due to the loss of vegetation and reduced water levels after excavation [6-7]. Furthermore, this industry impacts the coastal and marine landscapes, induces variations in geographical and morphological patterns and degradation of stream beds' longitudinal and transverse gradients [8-10]. It also adversely affects beds and channel stability, resulting in erosion and stream flow variations [11-12]. The researchers have identified major repercussions of uncontrolled extraction/ mining/ quarrying/ crushing of sand and coarse aggregate on human health/ wellbeing, disturbed eco-system and depletion of natural resources [13]. The excessive mining/ extraction of sand/ gravel from rivers impacts the geological/ hydrological profile of rivers and may result in increased flooding, weaker channel structure, localised impact on the water table and may impact on the water quality/ sediment transportation [14]. The worst impact of uncontrolled mining/ extraction is the depletion of natural resources, especially in low-income developing countries where these activities are not properly regulated [15]. The desert sand, being very fine in particle size, cannot fulfil the purpose of fine aggregate usage in concrete; therefore, river sand extraction is depleting at a rapid rate as it takes millions of years to produce the alluvial/ fluvial deposits on the river delta, which is being extracted in a matter of years only badly impacting the flood plains and river deltas. The use of gravel/ crushed rocks as coarse aggregate is also depleting the gravel deposits/ mountain ranges at a faster rate than their reproduction, thus resulting in the obliteration/ extinction of natural resources [16-17].

Moreover, the construction industry is also a substantial contributor to construction waste in the form of demolished buildings and road resurfacing/ reconstruction. Other sectors also produce significant waste like glass, rubber, tyres, and polyethylene terephthalate (PET) plastic bottles [18]. The researchers have been endeavouring to formulate supplementary cementitious materials (SCMs) using different industrial/ agricultural waste materials/ ashes having pozzolanic qualities/ silica (SiO_2) as partial/ full cement replacement, objectively to reduce the cement consumption, formulation of environmentally friendly materials by lowering greenhouse gases footprints of the construction industry and to absorb the enormously produced industrial/ agricultural waste by incorporating into the cement concrete composites in the form of ashes/ fibres [19-23]. However, considering the vast market share/ quantum of aggregates and their CO_2 footprints, conducting concerted endeavours to evaluate the replacement of the fine/ coarse aggregate partially/entirely with different industrial waste materials is essential. Contemporary studies have conducted experimental studies to partially replace the aggregate with a dual-purpose option of absorbing a portion of around 2 billion tons/ year of solid waste going into sea/ landfill and to economically formulate eco-friendly concrete composites targeting improved mechanical properties by employing specific mixing ratios. The researchers have been using different percentages of cement replacement/ enhancement materials like pulverised fly ash, metakaolin, ground granulated blast furnace slag, palm ash, rice husk ash, the fibres like glass fibres, wheat straw, polypropylene fibres, steel fibres, and fine/ coarse aggregate replacements like crushed/ shredded glass, crumb rubber, crushed/ shredded PET bottles, shredded tyres and recycled concrete aggregates as economic/ eco-friendly considerations [24-40].

This study has focussed on the formulation and experimental/ comparative investigation of the performance of cement concrete by partially replacing fine aggregate with 10%, 20% and 30% glass, crumb rubber (CR) and shredded recycled PET bottles (RPB), and partially replacing coarse aggregate with 10%, 20% & 30% recycled concrete aggregate (RCA) and 5%, 7.5% & 10% shredded tyres (ST), to achieve target design mix characteristic strength of C55/ 67 (67 MPa). The compressive and split tensile strengths of all the composite mixes have been compared with the control mix and mutually with other composites to ascertain the best-performing composites/ mixes, replacement materials and optimum mixing ratios. The novelty of this research is to conduct extensive laboratory work for the determination of the feasibility/ utilization of various combinations of fine/ coarse aggregate replacements through comparison of composites of different materials and the PCC control mix. The composites produced in this study can be utilized in various construction categories ranging from nominal to high-strength grades of concrete, demonstrating enhanced strength, improved pore structure, environmental benefits, preservation of natural resources and befitting disposal of global waste. This study supports the use of alternative fine and coarse aggregate, especially derived from other industries' waste, to benefit the environment by avoiding the concentration of global waste/ enormous disposal effort. It will help preserve the natural resources for the next generations and prevent unnecessary mining/ quarrying/ extraction of sand/ gravel from water channels, thus safeguarding the natural habitats/ ecology/ biodiversity. The use of 30% alternative aggregates in concrete can prevent up to 30% emission of CO_2 contributed by around 20 billion tons of aggregate usage in the construction industry, emitting around one billion tons of CO_2, and will likely reduce an estimated 300 million tons of CO_2 emissions annually. Moreover, this study was aimed at the development/ formulation of high-strength concrete using alternative fine/ coarse aggregates targeting C50/60 (high strength threshold of 60+ MPa), which has been achieved.

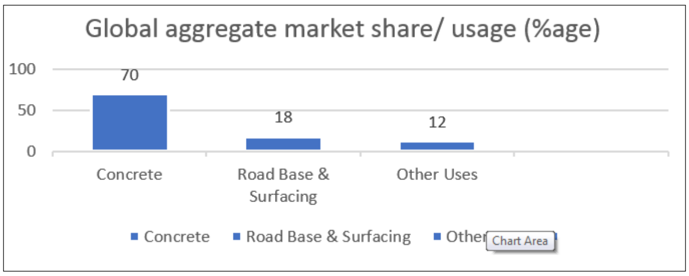

Figure 1: Percentage of Global Aggregate Market Share by Usage/ Application

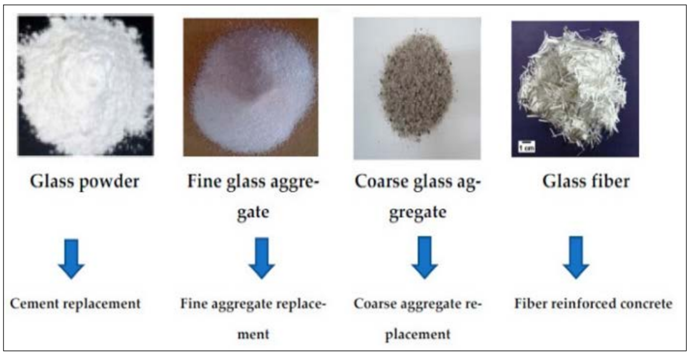

Figure 2: Different Uses of Waste Glass in Concrete [41]

Materials and Methodology

Materials

• Cement, Water, Plasticiser and Aggregates

The OPC white cement CEM1 52.5 has been used in conformance to BS EN 197-1, composing CaO (67.1%), SiO2 (25.2%) and Al_2O_3 (3.18%), which is an anhydrous material requiring a sufficient quantity of water for the hydration reaction to produce calcium-silicate-hydrates (C-S-H gel) responsible for the strength of cement concrete as shown in the equation below [42-43].

Regular tap water has been used in conformance with BS EN 1008:2002, with a water/cement ratio of 0.35 [44]. 0.2%-0.25% (of the cement mass) carboxylate polymer-based plasticiser has been used to obtain the workable consistency of the composites with a target slump S1. The angular/crushed/ shredded stone coarse aggregate passing a 20mm sieve and fine aggregate (river sand) passing a 4mm sieve have been used as virgin aggregates in conformance with BS EN 12620/2013 [45].

$2(3CaO.SiO_2) + 6H_2O \longrightarrow 3CaO.2SiO_2.3H_2O + 3Ca(OH)2$ + Heat (Nadir and Ahmed, 2022a)

• Crushed/ shredded Glass (CG)
The glass industry is estimated to produce more than one hundred million tons of glass annually, with only a 21% recycling rate of around 27 million tons [46]. The balance quantity of more than 70 million tons goes into the sea/ landfill without serving any beneficial use but adding to the world's solid waste. The glass generally contains around 70% SiO_2, 11% CaO, 10-12% Na_2O, BaO, PbO and 8-9% other elemental minerals/compounds. The crushed/ shredded/ fine glass has a density of 2380 kg/m^3, a specific gravity of 1.7, a hardness of 6-7 on the Mosh scale and a pH in water is less than 11. The chemical composition/ physical properties make it a suitable material for replacement as cement (glass powder), fine aggregate (fine glass passing 5mm sieve), coarse aggregate (crushed/ shredded glass passing 20mm sieve) and glass fibres as shown in Figure 2 for improvement of mechanical properties of concrete, as an SCM and as replacement material/ eco-friendly waste disposal in conformance with BS EN 12620-2009, and 8500-2 (www.concrete.org.uk, 2020) [41,45-49]. Using more than 20% fine glass powder (smaller than 75µm) as SCM in concrete induces an alkali-silica reaction (ASR) due to excess silica in the glass powder imparted during the OPC hydration process. Crushed glass was used as a partial sand replacement ibetween 1980-1990, but its use was discontinued/ reduced due to pronounced ASR reaction. It can result in the production of swollen $Si(OH)_4$. CaO gel creates cracks and weakens the concrete, as shown by the following chemical equation [50]. However, using crushed/ shredded glass as a partial replacement of fine and coarse aggregates has exhibited promising/ improved chemo-mechanical properties of concrete by reaching the strength threshold of high-strength concrete [51-53]. The ASR issue can be overcome by utilising a GGBS-cement blend with a minimum GGBS content of 30% [18].

$SiO_2 + 2Ca(OH)_2 \longrightarrow Si(OH)_4.2CaO$ [50].

• Crumb Rubber (CR) and Shredded Tyres (ST)
Rubber is a widely used natural/ synthetic material in numerous domestic/ commercial products/ packaging/ tyres. The tyre industry alone is estimated to produce around 1.5 trillion tyres annually, making it a significant recycling/ disposal issue globally [54]. The tyres are estimated to comprise approximately 20-34% natural rubber, 11-25% synthetic polymers, 24-26% fillers/ antioxidants, and 12-25% steel wires [55-56]. The tyres are generally crushed/ shredded/ grounded into rubber particles of different fine/ coarse grain sizes (0.5-20 mm) using a cracker, granular, or micro milling process. 0.5-4mm grains are used as crumb rubber for replacement of fine aggregate, and 5-20 mm shredded tyre grains can be used as coarse aggregate replacement [57]. The shredded/ ground tyres contain around 55% rubber polymers, 25-40% carbon black, 5% ash, and about 15% other chemicals/ fillers/ acetones exhibiting a density of around 480 kg/m^3, the specific gravity of 1.15, elasticity of 4-15 MPa and water absorption of up to 10%. The hydrophobic, porous, low-density and elastic crumb rubber/ crushed/ shredded tyres can result in consumption of water during the hydration process, air entrapment, low-density lightweight concrete, uneven distribution on mixing with natural aggregates, weak load-bearing zones in the concrete structure leading to the creation of abrupt failure initiation points when subjected to compressive loading. However, the characteristic elasticity may increase the tensile/ flexural strength of the composites [54,56-62]. These phenomena are pronounced especially in replacing virgin coarse aggregates with shredded tyre particles passing a 20mm sieve. Therefore, special care should be exercised for formulating fine aggregate composites with crumb rubber with up to 30% and coarse aggregate composites with up to 10%, as considered in this study. Islam et al. conducted a study illustrated in Figure 3, elaborated on how the tyres from vehicles generate waste which goes into landfill or burnt, causing pollution/ global warming/ reduction of valuable land; so if these tyres are converted into fine/ coarse recycled aggregates and are then used as composites with partial/ full replacement as normal/ lightweight concrete in domestic/ commercial construction can exhibit economic/ eco-friendly benefits along with improving the physio-chemical composition of OPC based composites resulting in enhanced strength and environment [55].

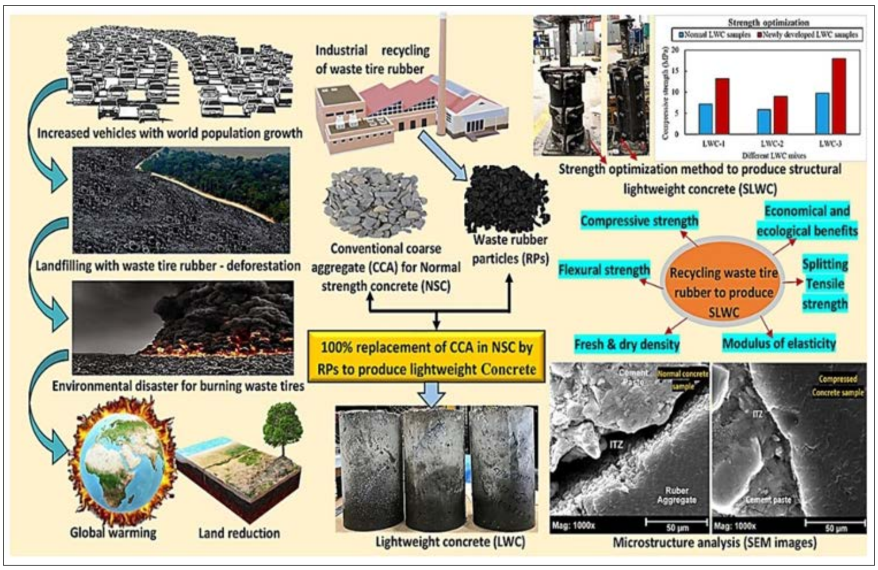

Figure 3: Use of Crumb Rubber/ Crushed/ Shredded Tyres as Fine/ Coarse Aggregate in Concrete Composites (55)

• Recycled PET Bottles (RPB)
Scientific inventions in organic chemistry introduced humankind to new materials based on polymers named plastic. Historically, around 10 billion tons of plastic have been manufactured, and the trend suggests the quantity will reach approximately 15 billion tons by 2050. Plastic recycling is estimated to be around 9%, disposal by incineration is about 12%, and the rest, 79%, is going into landfill/ sea/ environment around us with a remote possibility of biodegradation/ termination [63-67]. The world is producing around 15% Polyethylene terephthalate (PET) plastic as plastic bottles and packing material annually, manufacturing around 20000 PET bottles per second. The shredded plastic with a 1-5 mm grain size can be an excellent fine aggregate replacement due to its inherent elastic/non-water absorbent properties. The shredded PET fine aggregates exhibit an elasticity of around 2-3 GPa, a specific gravity of 1.1, and a 1.4 g/cm3 density. However, the lightweight/ low-density grains can reduce the density of the composite and uneven distribution/ morphology can decrease the intra-cement-aggregates bonding compared to the natural aggregate's bonding, leading to weaker zones/ failure points [19-20, 68-70].

• Recycled Concrete Aggregate (RCA)
OPC-based concrete has revolutionised the construction mechanics of modern infrastructure. Still, it also has a specific life restriction, necessitating the demolition/ reconstruction of structures after the expiry of their life. This reconstruction/ demolition has created an enormous waste disposal issue in the construction industry. It is already under intense criticism due to its coherent CO_2 footprints (responsible for 40% of CO_2 emissions and 35% of global waste) [71]. An estimated 300 million tons of recycled concrete/ pavement waste is produced annually in Europe alone, with India producing around 200 million tons and China and the USA about 500-600 million tons annually [72]. The researchers have endeavoured to absorb this gigantic waste into the formulation of new concrete composites and resurfacing/ paving materials using the old concrete as recycled aggregates with up to 40% in concrete and up to 75% in the road surfaces/ pavements, especially in 1990-2000 but were limited to low-strength utilisations due to inherent characteristic limitations of RCA [73-77]. The morphology of old concrete aggregates, higher water absorption, toughness index, marshal stability, vulnerability against chemical attacks and decreased flexural strength are the issues which necessitate the careful formulation of concrete composites using recycled aggregates.

Methodology
In this study, an endeavour has been made to conduct a comparative analysis for elucidating the characteristic compressive and split tensile strength of concrete composites containing 10-30% crushed/ shredded glass (CG), crumb rubber (CR), recycled PET bottles (RPB), recycled concrete aggregate (RCA) and 5-10% of shredded tyres (ST) as replacement of fine or coarse aggregates. The control mix has been prepared using OPC CEM1 52.5 with 100% virgin fine/ coarse aggregate without mixing replacement materials using a 1:1:3 ratio, targeting characteristic compressive strength class of C55/67 or M67 concrete [78-79]. The composites containing OPC, virgin sand, virgin coarse aggregate and crushed/ shredded glass (CG), crumb rubber (CR), and shredded recycled plastic PET bottles (RPB) as replacement materials of fine aggregates have been formulated with the composition as shown in Table 1. Recycled concrete aggregate (RCA) and shredded tyres (ST) have been used as replacement materials for coarse aggregates along with OPC and virgin sand/ coarse aggregates to formulate coarse aggregate composites, as shown in Table II. The mix ratio of 1:1:3 has been used with a water/cement (w/c) ratio of 0.35 along with 0.2-0.25% carboxylate polymer-based plasticiser to achieve a workable consistency with a target slump of up to 30 mm (S1) using standard cone and rod apparatus (Figure 4a) as per BS EN 8500 [48, 21]. 100mm cubes have been prepared/ water cured to test on 7, 28 and 91 days of curing for compressive strength assessment as per BS EN 12390-2:2019 on the standard compressive testing machine shown in Figure 4b [80, 21]. Cylinders of 300mm (L) long with 150mm dia (D) have been cast/ air cured for testing under a standard compressive testing machine exerting a compressive load of 400N/sec (P) to ascertain spilt tensile strength on 91 days using the formula "2P/πDL" as per BS EN 12390-6:2009 (Figure 4c). The slump test using the cone and rod method, cube testing for compressive strength and cylinder testing for assessment of split tensile strength conducted in the laboratory are illustrated in Figures 4 (a, b, c).

Figure 4a: Slump Testing [48].   **Figure 4b:** Cube Testing for   **Figure 4c:** Cylinder Testing for Split Tensile Strength [47]

Figure 4: Slump Testing **(4a)**, Cube Testing for Compressive Strength **(4b)**, Cylinder Testing for Split Tensile Strength **(4c)**.

Table I: Combination of Mixes with Partial Replacement of Fine Aggregate with CG, CR, RPB

Partial Replacement of Fine Aggregate with Glass, CR, RPB and Coarse Aggregate with RCA and CT					
Mix Material	**Replacement Material (kg)**	**Cement (kg)**	**Fine Aggregate Sand (kg)**	**Coarse aggregate (kg)**	**Slump (mm)**
Control	0	6.2	6.2	18.6	S1
CG 10%	0.6	6.2	5.6	18.6	S1
CG 20%	1.2	6.2	5	18.6	S1
CG 30%	1.8	6.2	4.4	18.6	S1
CR 10%	0.6	6.2	5.6	18.6	S1
CR 20%	1.2	6.2	5	18.6	S1
CR 30%	1.8	6.2	4.4	18.6	S1
RPB 10%	0.6	6.2	5.6	18.6	S1
RPB 20%	1.2	6.2	5	18.6	S1
RPB 30%	1.8	6.2	4.4	18.6	S1

Table 2: Combination of Mixes with Partial Replacement of Coarse Aggregate with RCA and ST

Partial Replacement of Fine Aggregate with Glass, CR, RPB and Coarse Aggregate with RCA and CT					
Mix Material	**Replacement Material (kg)**	**Cement (kg)**	**Fine Aggregate Sand (kg)**	**Coarse aggregate (kg)**	**Slump (mm)**
Control	0	6.2	6.2	18.6	S1
RCA 10%	1.8	6.2	6.2	16.8	S1
RCA 20%	3.6	6.2	6.2	15	S1
RCA 30%	5.4	6.2	6.2	13.2	S1
ST 5%	0.9	6.2	6.2	17.7	S1
ST 7.5%	1.4	6.2	6.2	17.2	S1
ST 10%	1.9	6.2	6.2	16.7	S1

Results

100mm cubes were tested at 7,28, and 91 days of water curing under a standard compressive testing machine (Figure 4b) by applying a 3KN/sec load and calculating compressive strength using the "load/area" formula [80]. The 150x300mm cylinders were tested at 91 days of air curing in the standard compressive loading machine (Figure 4c) by applying 9 KN/sec load "P" on the horizontal axis to determine the split tensile strength using the formula "2P/πDL" [21,47]. The standard cone and rod slump testing (Figure 4a) was conducted to achieve a workable consistency of concrete composites using a 0.35 w/c ratio and 0.2-0.25% plasticiser (by weight of OPC) (BSI, 2019a). The increased dosages of the replacement materials decreased the workability, thus necessitating the use of 0.2-0.25% plasticiser to obtain the self-compacting workability of the mixtures, in line with the results obtained by the other researchers [19-20,55, 58,51-53,68-70,73-77,81]. An average density of around 2350 kg/m for all the mixtures/ composites except those with 20-30% CR and 7-5-10% ST exhibited a slight reduction to 2250-2280 kg/m3. However, all the mixtures achieved an average concrete density between 2250-2400 kg/m3, fulfilling the objective of targeting the density range for standard concrete (2000-2500 kg/m3. All the mixes generally achieved the target compressive strength of C55/67 or M67 concrete at 91 days of curing, exhibiting an increasing trend with the increased age of curing. Generally, all the composites with fine aggregates replacement exhibited more than 70 MPa strength at 91 days except the composites containing 20% and 30% crumb rubber (CR) and 7.5% and 10% shredded tyres (ST), which exhibited a decreasing trend in compressive strength with increased dosage of aggregate replacement as expected. Nevertheless, still falls in the normal concrete strength range of C40/50 (50MPa) (required for the majority of the common concrete infrastructure/ structural applications) (Figures 5 and 6). Generally, all the composites with fine aggregate replacement exhibited improved split tensile strength, but the composites with coarse aggregate replacement demonstrated a reduction in the split tensile strength (Figure 7).

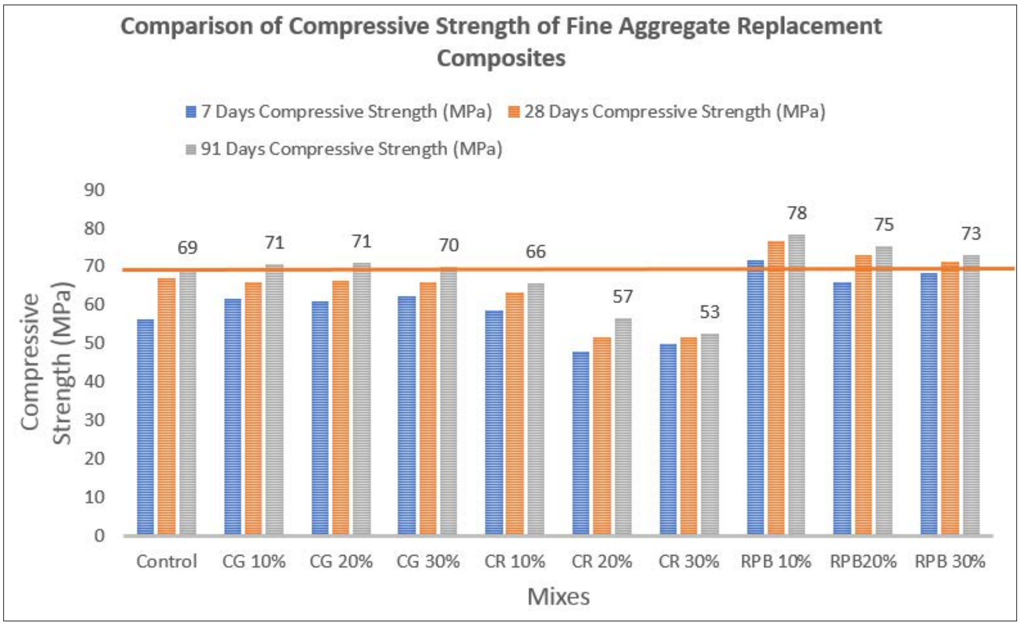

Figure 5: Comparison of Compressive Strength of Fine Aggregate Replaced Composites (aggregate size up to 5 mm; CG: Crushed Glass, CR: Crumb Rubber, RPB: Recycled Plastic Bottles).

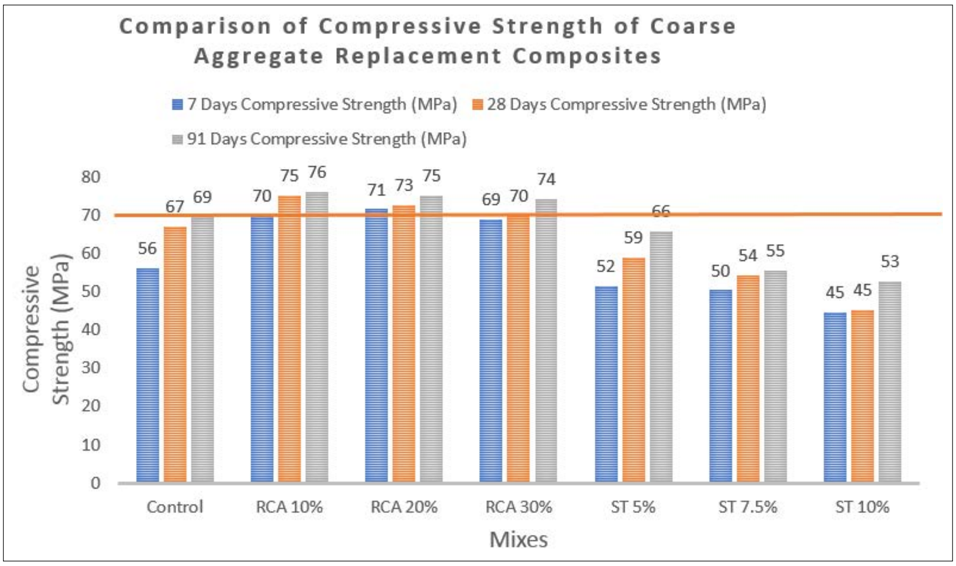

Figure 6: Comparison of Compressive Strength of Coarse Aggregate replaced Composites (aggregate size up to 20mm; RCA: Recycled Concrete Aggregate, ST: Shredded Tyres)

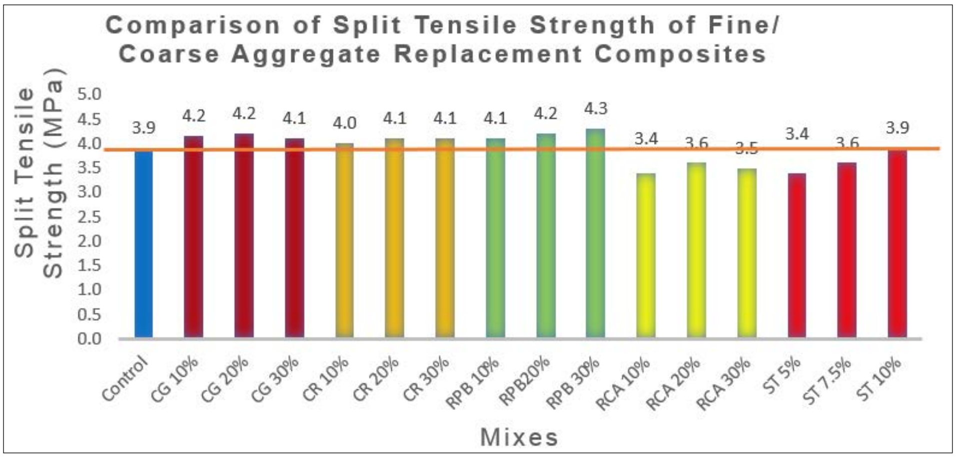

Figure 7: Comparison of Split Tensile Strength of Fine/ Coarse Aggregate Replacement Composites

Discussion

Contemporary studies persistently focus on formulating partial/ full cement replacement composites; however, less attention is paid to formulating fine/coarse aggregate composites. The waste from different domestic/ commercial fields and demolition/ reconstruction of old buildings/ infrastructure contribute enormously to increasing pollution and global warming. The total annual usage of fine/ coarse aggregate in the construction industry is estimated to be around 20 billion tons, contributing around a billion tons of CO_2. Therefore, even partial replacement of virgin sand/coarse aggregates can produce economical/ greener concrete to help conserve the raw materials for future generations. The succeeding sections elaborate on the investigation of the improvement of compressive/ tensile strength of composites containing partial replacement of fine/ coarse aggregate in comparison to the control mix with cement and virgin aggregates. Generally, all the composites demonstrated par/ better strength than the control mix (without any replacements), achieving the target strength of C55/67 or M67 concrete. The composites with 10-30% CG, RPB and RCA exhibited up to 3-13% improvement in compressive strength, attaining more than 70 MPa (well above the high strength concrete limit) and up to 10% improvement in split tensile, attaining 4.3 MPa. 10-30% CR and 5-10% ST exhibited a uniform decrease of 6-23% compressive strength up to 53-65 MPa, still attaining considerably high concrete strength (most concrete structures require a strength range of 30-50 MPa).

Comparison of Compressive/ Split Tensile Strengths of Fine Aggregate Replacement Composites

The composites containing crushed glass (CG), crumb rubber (CR) and shredded recycled PET bottles (RPB) as a partial fine aggregate replacement were analysed by comparing their characteristic compressive strength with the control mix and with each other. The composites with 10, 20 and 30% fine aggregate replacement demonstrated a slight increase in compressive strength than the control mix at 91 days of curing (Figure 5). The composites with RPB and CG performed better than the control mix and crumb rubber composites (Figure 5), as investigated/ supported by contemporary studies [51-53]. As highlighted earlier, crushed glass was previously utilised as a partial sand replacement in concrete back in the 1980s – 1990s, however, this led to the subsequent development of ASR in the structures; consequently, the utilization of crushed glass was abandoned. However, there is still potential to utilise crushed glass as a partial fine aggregate in ASR resistant concrete containing a minimum of 30% GGBS as a partial cement replacement [18]. The composites with 10-30% crumb rubber demonstrated a 4 to 23% reduction in compressive strength compared to the control mix (Figure 5) and lesser than all other composites containing crushed glass or recycled PET bottles but still conforming to C40/ 50 concrete (Figure 5). The composites with shredded recycled PET bottles performed the best and reached the threshold of high-performance concrete (≥70MPa) with a 6-13% increase in compressive strength. 10% RPB exhibited 78 MPa strength, attaining a 13% increase; however, a gradual decrease was observed with an increased dosage of RPB replacement with virgin sand, while 20% and 30% RPB composites attained 75 MPa and 71 MPa, respectively. They were still achieving more strength than the control mix and achieved the high-strength/ high-performance concrete range (Figure 5), as suggested/ demonstrated in other studies [19-20,55,69,74]. All the composites with 10-30% CG, CR and RPB demonstrated up to 10% enhancement in split tensile strength compared to the control mix/ coarse aggregate composites with RCA/ ST due to their inherent increased elasticity, better intra-ingredients bonding, reduced water absorption and better flexibility of the CG and RPB than the virgin sand in line with the findings of the contemporary studies (Figure 7).

Comparison of Compressive/ Split Tensile Strengths of Coarse Aggregate Replacement Composites

The composites replacing coarse aggregate were formulated using 10,20,30% recycled concrete aggregate (RCA), and 5,7.5, and 10% shredded tyres (ST). The dosage of ST was kept up to 10% (due to its lower density compared to the density of the virgin coarse aggregate) to achieve the normal concrete density range of 2000-2500 kg/m^3. The cubes were tested at 7, 28 and 91 days, and compressive strength was compared with the control mix and other composites. The composites containing the 10-30% RCA performed better than the control mix and ST composites by achieving high strength/high-performance concrete strength of 74-76 MPa (an increase of 7-10% compressive strength) at 91 days of curing, as shown in Figure 6. The composites with ST 5-10% demonstrated a gradual decrease of up to 23% in strength. They were observed as the least performing replacement material for the virgin coarse aggregate (yet achieving more than 53 MPa strength of normal strength concrete range), as expected due to their hydrophobic qualities, decreased intra-ingredients bonding in the concrete composites with ST or CR and creation of weaker zones within the concrete structure because of the variation in toughness/ elasticity modulus of virgin aggregates and the replacement aggregates. The split tensile strength of all the coarse aggregate replacement composites was observed to be less than the control mix, and a decreasing trend was noticed with increased replacement dosages (Figure 7). The decrease in tensile strength is not a very important factor as concrete is not utilised in construction applications predominantly for its tensile strength characteristic. When a structure is subject to tensile loading, it requires strengthening with steel reinforcement. The decreased tensile strength of these composites is attributed to their characteristic rigidity/ toughness/ water absorption and the creation of weaker failure zones within the concrete structure because of the morphological variation and reduced modulus of elasticity as compared to the virgin coarse aggregates.

Conclusion

The composites with 10-30% fine aggregate replacement and 10-30% coarse aggregate replacement with RCA were observed to perform the best of all the mixes, demonstrating up to 70-78 MPa strength (13% increase). In contrast, composites containing 30% CR and 10% ST demonstrated a slight decrease in strength; however, they still achieved more than 50 MPa, sufficient to be used extensively in all normal construction/ structural applications. The composites having ST as coarse aggregate replacement demonstrated reduced strength parameters compared to the control mix and the fine aggregate composites, emphasising a more careful selection of materials with optimum dosage for the coarse aggregate replacement if used for high strength requirements. All the composites were observed achieving more than 50-70 MPa strength, proposing possible use with 10-30% reduced virgin aggregate consumption, with 10-30% reduced CO_2 emissions, preservation of natural resources, protection of river delta from hydrogeological variations and economic use/ recycling of the waste materials for high strength concrete requirements.

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