# Compressive Strength of Concrete Using Construction Demolition Waste, Glass Waste, Superplasticizer and Fiber

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## ABSTRACT

This experimental study highlights the results of compressive strength tests performed on different specimens of concrete consisting of construction demolition waste and/or glass waste with or without superplasticizer and fiber. The 28-day compressive strength of concrete increases on the use of construction and demolition waste aggregates compared to that of control specimen. When fine aggregate is replaced with glass waste to the extent of 30%, an increase in compressive strength is observed. Utilization of construction and demolition waste aggregates and glass waste replacing fine aggregate yields improved compressive strength. The replacement of fine aggregate with glass waste including the use of superplasticizer and fiber tends to increase compressive strength. However, if construction and demolition waste aggregates and waste glass replacing fine aggregate including superplasticizer and fiber are used, the compressive strength achieved is less. The construction demolition waste and/or glass waste can be used in concrete yielding improved compressive strength, thereby solving the problem of disposal as well as preserving the environment.

**KEYWORDS:** Construction demolition waste, Glass waste, Superplasticizer, Fiber, Compressive strength, Reuse of waste.

## INTRODUCTION

The fast pace of infrastructure development worldwide has led to the demolition of a large number of obsolete concrete and masonry structures resulting in the generation of tremendous quantities of construction demolition waste consisting of concrete, broken glass, brick, wood, steel and waste of miscellaneous types, like marble, ceramic tile, stone, electrical and electronic items,… etc. Such large quantity of construction demolition waste, if disposed of haphazardly without proper disposal sites, leads to the destruction of ecology, flora and fauna including micro-organisms. Further, it gives an ugly appearance to natural scenic beauty of the region and causes havoc on the environment. Out of all construction wastes, usually construction demolition concrete waste is generated in maximum quantity and can be processed to reuse through proper treatment (Poon, 1997).

Glass waste is another such material generated through demolition of buildings and, if dumped haphazardly, may cause injury to human and animals in addition to health hazards (Shao et al., 2000; Metwally, 2007). The utilization of construction demolition concrete waste and waste glass in a systematic manner for the production of such materials which are used for construction in bulk will be an appropriate proposition. Concrete is a material which finds bulk utilization in construction and the production of conventional concrete is becoming costly day-by-day due to the

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increase in costs of raw materials, such as fine and coarse aggregates as well as cement. Moreover, concrete is carbon-intensive, as it uses materials in large quantities and the production of cement or mining of natural aggregates is causing havoc on the environment. Hence, if construction demolition concrete waste is processed to obtain coarse and fine aggregates which can replace natural aggregates, the preservation of precious natural resources and the environment is possible (Tavakoli and Soroushian, 1996). Again, if glass waste is processed and used to replace fine aggregate in concrete, it can help in minimizing damage to the environment which might otherwise occur due to its improper dumping (Ismail and Al-Hashmi, 2009). The present experimental study is an attempt in this direction, which is focused upon exploring the possibility of utilizing these waste materials along with superplasticizers and fibers in the production of concrete through testing of its compressive strength.

Utilization of construction and demolition (C & D) waste in concrete as fine aggregate and coarse aggregate has been investigated by many investigators. Frondistou-Yannas (1977) revealed that recycled concrete matches the mechanical behaviour of conventional concrete if it is enriched in gravel at the expense of mortar with an achieved compressive strength of nearly two thirds and a modulus of elasticity equal to or less than that of the control mix. Hansen and Narud (1983) found that the compressive strength of recycled concrete is strongly correlated with the water–cement ratio of the original concrete if other factors are kept the same and if the water–cement ratio of the original concrete is the same or lower than that of the recycled concrete, new strength will be as good as or better than the original strength. Hansen and Hedegkd (1984) showed that the addition of a plasticizing, an air entraining, a retarding and an accelerating admixture to the original concrete had little or no effect on the properties of recycled concrete. Tavakoli and Soroushian (1996) indicated that the strength of recycled aggregate concrete is affected by the strength of the original concrete, percentage of coarse aggregate in the original concrete, ratio of top size of aggregate in the original concrete to that of recycled aggregate and the Los Angeles abrasion loss as well as water absorption of the recycled aggregate.

Sagoe-Crentsilet and Brown (2001) observed that the processing of recycled concrete aggregates commercially produced smoother spherical particles than those produced in the laboratory, which improved the workability of concrete. The compressive and tensile strengths of hardened concrete showed no significant differences between recycled concrete and concrete made with natural aggregates, but recycled aggregates caused higher drying shrinkage and reduced the abrasion resistance slightly. Ajdukiewicz and Kliszczewicz (2002) examined the mechanical properties of high-performance and high-strength concretes made with recycled aggregates and concluded that water content should be modified in the recycled concrete mix design in order to obtain the same workability. The compressive strength decreased slightly with recycled aggregates depending on the type of fine aggregate used in concrete. Olorunsogo and Padayachee (2002) investigated the durability of concrete made with different percentages of recycled concrete coarse aggregates and showed that durability quality of recycled concrete is reduced with increases in the quantities of recycled aggregates and the quality improved with the age of curing which occurred due to cracks and fissures created within the recycled aggregate during processing, making aggregate susceptible to ease of fluid permeation, diffusion and absorption. Khatib (2005) showed that strength reduced by nearly one fourth for crushed concrete, but practically nil or slight reduction in strength was observed for 50% or 100% replacement of fine aggregate with crushed brick. The rate of strength development in concrete after 28 days was higher than that of control, indicating further cementing action in the presence of fine recycled aggregate.

Evangelista and Brito (2007) showed that the use of fine recycled concrete aggregates does not jeopardize mechanical properties of concrete, for replacement up to one third. Khaldoun (2007) reported that 28-day compressive strength of recycled aggregate concrete decreased only by one tenth, whereas modulus of elasticity reduced only very slightly and the trends of development of compressive strength and strain at peak stress in recycled aggregate concrete were similar to those in natural aggregate concrete. Yang et al. (2008) showed that the properties of fresh and hardened concrete containing recycled aggregates were dependent on the relative water absorption of aggregates, whereas the moduli of rupture and elasticity of recycled aggregate concrete were lower than the design equations specified in standards when the relative water absorption of aggregates is above 2.5%. Padmini et al. (2009) revealed that recycled aggregate concrete requires relatively lower water–cement ratio as compared to parent concrete to achieve a particular compressive strength and the difference in strength between the two increases with the strength of concrete. Corinaldesi (2010) showed that structural concrete up to C32/40 strength class can be manufactured by replacing 30% virgin aggregate with recycled concrete aggregate, but lower strains were observed, especially for earlier curing time upon addition of finer coarse recycled concrete aggregate.

Fonseca (2011) reported that the influence of different curing conditions on the mechanical performance of concrete made with coarse recycled aggregate from crushed concrete is nearly similar to that of conventional concrete. Agrela (2012) revealed that the use of construction and demolition waste aggregates in roads is entirely feasible and that the benefits associated with these aggregates extend beyond the environmental aspects of their use. Sallehan and Ramli (2013) showed that the use of different acid molarities to remove or minimize loose mortar particles attached on the surfaces of recycled concrete aggregate significantly improved its physical and mechanical properties. The reduction of loose mortar covering recycled concrete aggregate particles significantly improved the surface contact between new cement paste and aggregate, improving the strength of concrete. Andreu and Miren (2014) revealed that considering mechanical properties, 100% replacement of natural coarse aggregates was possible when recycled concrete aggregate was produced from original high strength concrete with a minimum compressive strength of 60 MPa, but up to 50% replacement was possible considering the durability properties. Neno et al. (2014) assessed the performance of mortars using recycled concrete aggregates with same particle size distribution as that of natural aggregates and reported that mortar with 20% replacement ratio performed better than the reference mortar, except for adhesive strength and dimensional stability. Silva et al. (2014) proposed performance -based classification, mainly for use in concrete construction, thereby measuring the quality of recycled aggregates which can be used to produce concrete with predictable performance. Tsoumani et al. (2015) compared the properties of several recycled aggregates and indicated that fine recycled aggregate should not be used due to its low quality, whereas coarse recycled aggregates can be used in concrete production. Salesa et al. (2017) revealed that concrete from recycled and multi-recycled coarse aggregates obtained from high quality precast parent concretes has equivalent behaviour to that of the control concrete. The compressive strength was slightly higher in the first and second recycled concretes than in the control concrete, but the density of recycled concretes decreased with respect to the control showing increasing differences with each cycle of recycling.

The literature review shows that construction and demolition waste can be used in the production of concrete without any compromise on mechanical strength. However, aggregates obtained from construction demolition waste should be properly cleaned and dislodged off any loose particles before use in concrete. Otherwise, the strength may be adversely affected. The water absorption of these aggregates should be minimum (comparable to that of original aggregates) and particle size distribution similar to that of natural aggregates. Recycled aggregates obtained from original high-strength concrete can be effectively used in the production of moderate strength recycled aggregate concrete without any effect on strength. However, it should be noted that durability properties are dependent upon water absorption and porosity which should be controlled carefully. Using construction and demolition waste aggregates in concrete can help in minimizing the mining of scarce natural aggregates in addition to reducing the negative impact of release of greenhouse gases and ensuring sustainable development of concrete industry.

The use of superplasticizer in concrete without or with construction and demolition waste has been researched by some investigators. Pereira et al. (2012) showed that concrete with incorporation of recycled aggregates and superplasticizers was found to have poorer performance relative to reference concrete with superplasticizer. But, the mechanical performance of concrete with recycled aggregates and superplasticizers was generally superior to that of reference concrete with no admixtures and of conventional concrete with low-performance superplasticizers.

Matias et al. (2013) evaluated the effects of the introduction of superplasticizers on some mechanical properties of concrete with recycled concrete aggregates and identified the weaknesses and strengths of the recycled aggregate concrete. Cartuxo et al. (2016) indicated that incorporation of fine recycled concrete aggregate increased the water absorption by immersion, water absorption by capillary action, the carbonation depth and the chloride migration coefficient, while the use of superplasticizers highly improved these properties. From durability point of view, the simultaneous incorporation of fine recycled concrete aggregate increased water absorption by immersion and high-performance superplasticizers represent a viable sustainable solution for structural concrete production. Literature studies revealed that mechanical strength of concrete containing C & D aggregates with superplasticizer is generally improved compared to that of C & D aggregate concrete without superplasticizer. Further, the addition of superplasticizers to recycled aggregate concrete improved its durability properties.

The utilization of glass waste as replacement of cement and fine aggregate or coarse aggregate in concrete has been explored by many investigators. Shao et al. (2000) showed that ground glass having a particle size finer than 38 mm exhibited a pozzolanic behavior with smaller glass particle size, leading to a higher reactivity with lime, a higher compressive strength in concrete and a lower expansion. Compared to fly ash concrete, concrete containing ground glass exhibited a higher strength at both early and late ages. Topcu and Canbaz (2004) showed that waste glass was found to have no significant effect upon the workability of concrete and only a slight impact in the reduction of its strength. Waste glass cannot be used as aggregate without taking into account its alkali-silica reaction, as well as without the need for high-cost or rigorous energy. Metwally (2007) showed that optimum content (10%) of finely milled waste glass has pozzolanic characteristics and using it as a mineral admixture in concrete had a bad effect on workability, but improved considerably the mechanical properties of concrete in terms of compressive, splitting tensile and bond strengths at later ages. Further, expansion due to alkali-silica reaction was obviously minimized by increase in the glass content. Ismail and Al-Hashmi (2009) showed that the flexural strength and compressive strength of specimens with 20% waste glass content were higher than those of the control specimen at 28 days and the expansion reduced by about two thirds as compared with that of the control mix.

Khatib et al. (2012) studied the performance of concrete as partial replacement of cement with waste glass and concluded that the maximum compressive strength occurs at around 10% glass powder and beyond 10% it tends to decrease and is lower than that of the control. Nassar and Soroushian (2012) in their experimentation on strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement concluded that water absorption of concrete is observed to be significantly reduced with the introduction of milled waste glass as partial replacement for cement in both low and high water-cement ratio mixes. Castro and Brito (2013) evaluated the mechanical properties of concrete made with glass along with durability performance and showed that the particle size strongly affected the workability of concrete, but the durability-related properties of concrete were not significantly affected. Abu Salem et al. (2017) showed that waste broken glass can be used in asphalt concrete having maximum size of 2.36 mm and the optimal replacement ratio of 10% with the mix meeting the standards of asphalt mix design. The water stability of glassphalt can be improved by introducing hydrated lime or liquid antistripping agent with the latter being more effective. These studies indicated that optimum content of glass waste can be used in concrete with improvement in compressive strength and no significant effect on durability.

The behavior of concrete with polypropylene fibers and additives or recycled polyethylene terephthalate (PET) aggregate has been studied by some investigators. Toutanji (1999) showed that the use of 5% silica fume combined with 0.30% fiber volume fraction results in optimum mixture design for repair applications from the standpoints of workability, bond, strength, length change and permeability. Saikia and Brito (2014) indicated that the compressive strength, tensile splitting strength, modulus of elasticity and flexural strength of concrete deteriorate due to the incorporation of PET-aggregate and the deterioration of these properties intensifies with increasing content of this aggregate. But, abrasion resistance of concrete mixes containing various types of PET-aggregate is better than that of the reference concrete.

Kiani et al. (2015) studied the development of light-weight aggregate concrete using fine aggregate that is manufactured from waste polyethylene terephthalate (WPET) bottles and showed that the use of WPET particles up to maximum replacement level of 10% produces concrete with acceptable strength. The replacement of cement with 5% WPET improves the compressive strength of concrete compared to the control concrete. Saravana and Sumathi (2017) concluded that fly ash-based jute fiber reinforced concrete revealed better performance than ordinary concrete. The 7-day compressive strength of the composite containing fly ash up to 25% is slightly less than that of the control concrete mix, but the compressive strength is marginally higher than that of the control concrete mix at the age of 28 days and longer failure curves exhibited larger flexibility or ductility with the use of jute fibers in concrete. The introduction of fiber in concrete improves its strength, but the replacement of natural aggregate with PET-aggregate results in some reduction in compressive strength.

The characteristics of fiber-reinforced concrete containing waste glass as pozzolona have been studied by a few investigators. Chikhalikar and Tande (2012) investigated the characteristic properties of fiber-reinforced concrete containing waste glass as pozzolona and showed that the compressive strength increase is achieved up to 30% as compared to the control mix, but the peak increase occurred at 20% replacement. It can be inferred that the addition of fiber to concrete containing waste glass pozzolona substantially improves its compressive strength.

The review of literature on study of compressive strength and other characteristics of concrete containing construction demolition waste without or with superplasticizer establishes the efficacy of its utilization. The utilization of glass waste in concrete studied by many investigators highlights its importance, particularly as replacement of fine aggregate, resulting in the improvement of compressive strength. Use of fiber with or without glass waste in concrete has been studied by a few researchers showing that compressive strength is generally improved. However, there is no authentic experimental investigation covering the combined effect of construction demolition waste including glass waste without or with additives, such as superplasticizer and fiber. The present experimental study has been taken up with a view to explore the effect of construction demolition waste including glass waste without or with superplasticizer and fiber on compressive strength of concrete. The purpose of this research work is to establish the influence of these waste materials and additives on compressive strength of concrete in order to ensure their effective utilization replacing natural aggregates and preserving the environment.

## MATERIALS AND MIXTURES

**Cement:** Ordinary Portland cement (OPC) of ACC 43 grade brand obtained from a single batch was used. The physical properties of cement as determined are given in Table 1. Specific gravity was 3.15 and fineness was 2800 $cm^2/g$. The cement satisfies the requirements of IS: 8112-1989 and its chemical composition is given in Table 2.

**Table 1. Physical properties of cement**

| Property | | Value |
|---|---|---|
| Standard consistency (%) | | 28 |
| Fineness (%) | | 2.1 |
| Initial setting time (minutes) | | 60 |
| Final setting time (minutes) | | 610 |
| Compressive strength ($N/mm^2$) after | 3 days | 25.6 |
| | 7 days | 34.1 |
| | 28 days | 45.4 |

**Table 2. Chemical composition of cement**

| Chemical constituent | Content (%) | Chemical constituent | Content (%) |
|---|---|---|---|
| CaO | 47.78 | MgO | 1.30 |
| $SiO_2$ | 30.88 | $SO_3$ | 1.67 |
| $Al_2O_3$ | 6.75 | Loss on Ignition | 6.20 |
| $Fe_2O_3$ | 3.57 | Cl | 0.011 |

**Fine Aggregate:** Fine aggregate consists of aggregation of mineral grains obtained from the disintegration of rocks. The sand used in the experimental study was crushed sand from natural boulders. Specific gravity of fine aggregate is 2.63 and water absorption is 0.09%. The particle size distribution curve of fine aggregate is shown in Figure 1. As per IS: 383-1970, the fine aggregate lies in grading zone II, which is good quality sand for concrete work. The fineness modulus of sand is 2.60 and it is suitable in concrete work.

**Coarse Aggregate:** Coarse aggregate consists of crushed stone used for making concrete. The stone is quarried from quarries, crushed in the crusher and then graded to suit different requirements. Crushed angular hard sandstone of maximum size of 20 mm from a local quarry was used as coarse aggregate. The specific gravity of coarse aggregate is 2.64 and fineness modulus is 6.57. The impact value of coarse aggregate is 18% and its crushing value and water absorption are 22% and 0.02%, respectively (IS: 2386-1963). Coarse aggregate conforming to graded aggregate of nominal size of 20 mm as per IS: 383-1970 was used and its particle size distribution curve is shown in Figure 1.

**Construction and Demolition Waste Fine Aggregate:** Construction and demolition waste fine aggregate was obtained from fines recovered from demolished flooring concrete (compressive strength = 30 MPa) crushed to size finer than 4.75 mm. The specific gravity of C & D fine aggregate is 2.59 and the water absorption is 0.15%. The particle size distribution curve of C & D fine aggregate is shown in Figure 1, which is almost overlapping the particle size distribution curve of fine aggregate. As per IS: 383-1970, the C & D fine aggregate lies in grading zone II, which is good quality sand for concrete work. The fineness modulus of C & D fine aggregate is 2.58, which indicates its suitability in concrete work. Construction demolition waste fine aggregate was processed in such a way so as to attain the particle size distribution and fineness modulus as close as possible to those of natural fine aggregate to reduce the effect of particle gradation on strength (Neno et al., 2014).

**Construction and Demolition Waste Coarse Aggregate:** Construction and demolition waste consists of coarse aggregate recovered from demolished flooring concrete (compressive strength = 30 MPa) crushed to size finer than 4.75 mm. It was dislodged of all loose materials and crushed to size finer than 40 mm, but coarser than 4.75 mm. The specific gravity of C & D coarse aggregate is 2.61 and fineness modulus is 6.78. The impact value of C & D coarse aggregate is 20% and its crushing value and water absorption are 24% and 0.08%, respectively. C & D coarse aggregate conforming to graded aggregate of nominal size 20 mm as per IS: 383- 1970 was used and its particle size distribution curve is shown in Figure 1, which nearly coincides with the particle size distribution curve of coarse aggregate. The processing of construction demolition waste coarse aggregate was carried out in such a way to achieve particle size distribution and fineness modulus as close as possible to those of natural coarse aggregate. The water absorption and durability expressed in terms of impact value and crushing value for C & D waste coarse aggregate were almost the same as of natural coarse aggregate so as to minimize the effect on the durability of concrete produced (Olorunsogo and Padayachee, 2002). The control of water absorption was important, as the properties of fresh and hardened concrete containing C & D aggregates were dependent on the relative water absorption of aggregates (Yang et al., 2008).

**Waste Glass Fine Aggregate:** Glass forms as a result of solutions containing alkali and alkali metal oxides in addition to other metal oxides and contains primarily silica ($SiO_2$). Waste glass of used window pan was taken as replacement of fine aggregate. As per IS: 383-1970, the waste glass fine aggregate lies in grading zone I and its fineness modulus is 2.97, which makes it suitable for concrete work. The specific gravity of waste glass fine aggregate is 2.40 and its particle size distribution curve is shown in Figure 1, which is approximately parallel and matching with the particle size distribution curve of fine aggregate or C & D fine aggregate to decrease the effect of particle gradation. The chemical composition of waste glass is given in Table 3.

**Table 3. Chemical composition of waste glass**

| Constituent | Content (%) | Range (%) |
|---|---|---|
| $SiO_2$ | 72.3 | 70-75 |
| $Na_2O$ | 14.2 | 12-18 |
| $K_2O$ | 0.4 | 0-1 |
| CaO | 9.4 | 5-14 |
| $Al_2O_3$ | 1.5 | 0.5-2.5 |
| MgO | 2.2 | 0-4 |

**Superplasticizer:** Superplasticizer Conplast SP 430 based on Sulphonated Napthalene polymers and special additives was used in the experimental study. It is added generally in the range of 0.6%-1.2% by weight of cement. The use of superplasticizer produces pumpable concrete and concrete with high workability. In this study, 0.9% superplasticizer was used to prepare the test specimens.

**Plastic Fibers:** Plastic fibers (Recron 3S) of 6 mm size were used in this study to the extent of 100 g/bag of cement (50 kg). Use of plastic fibers reduces cracks during plastic stage and hardening stage, decreases seepage and protects steel in concrete from corrosion. It increases abrasion resistance by over 40% and increases life of roads, walkways, floors,… etc. Workability of concrete is increased and rebound loss is substantially reduced.

**Water:** Potable water conforming to stipulations of IS: 456-2000 (reaffirmed in 2011) is used for mixing and curing. The properties of water are suitable for use in concrete work.

**Proportions of Mixtures:** The proportions of mixtures and material combinations used for compressive strength tests performed in the laboratory are given in Table 4. Three specimens each of size 150 mm x 150 mm x 150 mm were prepared at a water-cement ratio of 0.50 (reduced by 10%; i.e., to 0.45 for specimens with superplasticizer and fiber) to the desired grading in air-dried conditions as per IS: 456-2000. Each batch of concrete was tested for consistency as per IS: 1199-1959 immediately after mixing.

**Table 4. Material proportions used in tests**

| Description of specimens |
|---|
| **A1** - Cement: sand: aggregate: 1: 2: 4 = 9 specimens. |
| **A4** - Cement: sand: aggregate: 1: 2: 4 + 0.9% superplasticizer + fiber = 9 specimens. |
| **B1** - Cement: sand (C & D): aggregate (C & D): 1: 2: 4 = 9 specimens. |
| **B4** - Cement: sand (C & D): aggregate (C & D): 1: 2: 4 + 0.9% superplasticizer + fiber = 9 specimens. |
| **C11**, **C12 and C13** - Cement: sand: aggregate: 1: 2: 4 (sand replaced by waste glass = 10%, 20%, 30%) = 27 specimens. |
| **C41**, **C42 and C43** - Cement: sand: aggregate: 1: 2: 4 + 0.9% superplasticizer + fiber (sand replaced by waste glass = 10%, 20%, 30%) = 27 specimens. |
| **D11**, **D12 and D13** - Cement: sand (C & D): aggregate (C & D): 1: 2: 4 (sand replaced by waste glass = 10%, 20%, 30%) = 27 specimens. |
| **D41**, **D42 and D43** - Cement: sand (C & D): aggregate (C & D): 1: 2: 4 + 0.9% superplasticizer + fiber (sand replaced by waste glass = 10%, 20%, 30%) = 27 specimens. |

Concrete was filled in three layers and each layer was compacted. The test specimens were stored in the laboratory at a place free from vibrations under damp matting for 24 hours and then immersed in clear water at a temperature of 24-30°C. The specimens were tested for compressive strength in a computer-controlled universal testing machine after curing periods of 3, 7 and 28 days immediately after removal from water while they were still in wet condition. The test results of the specimens giving maximum compressive strength are presented and compared with those of the control specimen and the possibility of using different waste materials as well as superplasticizer and fiber in concrete has been studied.

## RESULTS AND DISCUSSION

### Stress-Strain Characteristics of Concrete

Stress-strain curves of various concrete specimens reveal sudden failure as indicated by the small post-peak portions. Typical stress– strain characteristics of concrete specimens consisting of fresh/ C & D aggregate without (A1/B1) and with optimum waste glass fine aggregate (20% replacement, C12/D12) after 28 days of curing period are shown in Figure 2. For the control specimen (A1), the maximum compressive strength of 21.29 N/mm$^2$ is attained at a strain level of 2.20%, whereas for the specimen containing C & D waste aggregate (B1), the maximum compressive strength of 25.15 N/mm$^2$ is attained at a strain level of 3.14%, which is higher than that for the control specimen (A1). Thus, the strength of concrete is improved upon replacement of natural aggregate with C & D aggregate (obtained from processing of high-strength demolished concrete; i.e., 30 MPa), possessing similar particle gradation and comparable water absorption and durability parameters (Andreu and Miren, 2014; Salesa et al., 2017). The strength of C & D aggregate concrete was better than that of natural aggregate concrete due to refined processing of construction demolition waste to achieve aggregate with similar particle gradation and comparable values of water absorption, specific gravity and durability properties, such as impact value and crushing value. When optimum content (20%) of fine aggregate is replaced with waste glass in fresh aggregate concrete (C12), maximum compressive strength of 29.17 N/mm$^2$ is attained at a strain level of 2.31%; the failure occurring at a slightly higher strain level after achieving higher compressive strength compared to those of control specimen (A1) and specimen (B1). Compressive strength of specimens with 20% waste glass content was higher than that of the control specimen after 28 days of curing (Ismail and Al-Hashmi, 2009). Improvement in strength may be attributed to the angular shaped glass particles which led to better packing and pozzolanic reaction in the concrete mass.

In C & D waste aggregate concrete, upon 20%

replacement of fine aggregate with waste glass (D12), the maximum compressive strength of 27.44 N/mm$^2$ is attained at a strain level of 2.38%; the failure occurring at a slightly higher strain level after achieving higher compressive strength compared to those of the control specimen (A1) and C & D waste aggregate specimen (B1), but the compressive strength is less than that for fresh aggregate specimen (C12). Though the strength achieved was better than that of the control specimen, it was not as much as in natural aggregate glass concrete due to partial segregation of harsh glass particles.

Stress-strain characteristics of concrete specimen consisting of fresh/ C & D aggregate including superplasticizer and fiber without (A4/B4) and with optimum waste glass fine aggregate (20% replacement, C42/D42) after 28 days of curing are shown in Figure 3. In fresh aggregate concrete specimen containing superplasticizer and fiber (A4), the maximum compressive strength of 20.10 N/mm$^2$ is attained at a strain level of 4.89%; the strength being slightly less than that for the control specimen (A1). For the specimen containing C & D waste aggregate with superplasticizer and fiber (B4), the maximum compressive strength of 17.30 N/mm$^2$ is attained at a strain level of 2.54%, which is less than those of specimen (A4) and control specimen (A1). The deterioration of strength may be due to partial loosening of the concrete matrix in the presence of superplasticizer and fiber.

When optimum content (20%) of fine aggregate is replaced with waste glass in fresh aggregate concrete specimen containing superplasticizer and fiber (C42), the maximum compressive strength of 31.79 N/mm$^2$ is attained at a strain level of 1.60%; the failure occurring at a lesser strain level after achieving higher compressive strength compared to those of all specimens A1, B1, C12, D12, A4, B4 and D42. Better packing and pozzolanic reaction of the angular shaped glass waste particles in the presence of superplasticizer and fiber may be the reason for the increase in improvement of strength of concrete. In C & D waste aggregate concrete with superplasticizer and fiber, upon 20% replacement of fine aggregate with waste glass (D42), maximum compressive strength of 20.98 N/mm$^2$ is attained at a strain level of 2.11%, which is nearly the same as that for the control specimen (A1), higher than those of specimens (A4) and (B4), but lesser than those of specimens B1, C12, D12 and C42. The strength was not much affected due to the addition of C & D aggregate particles coated with set mortar, which inhibited the formation of proper bonding with harsh glass particles.

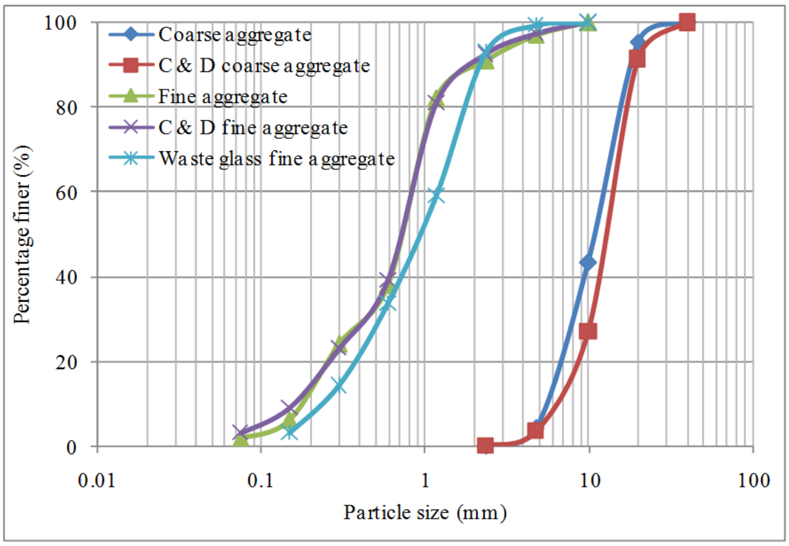


**Figure (1): Particle size distribution curves for constituent materials**

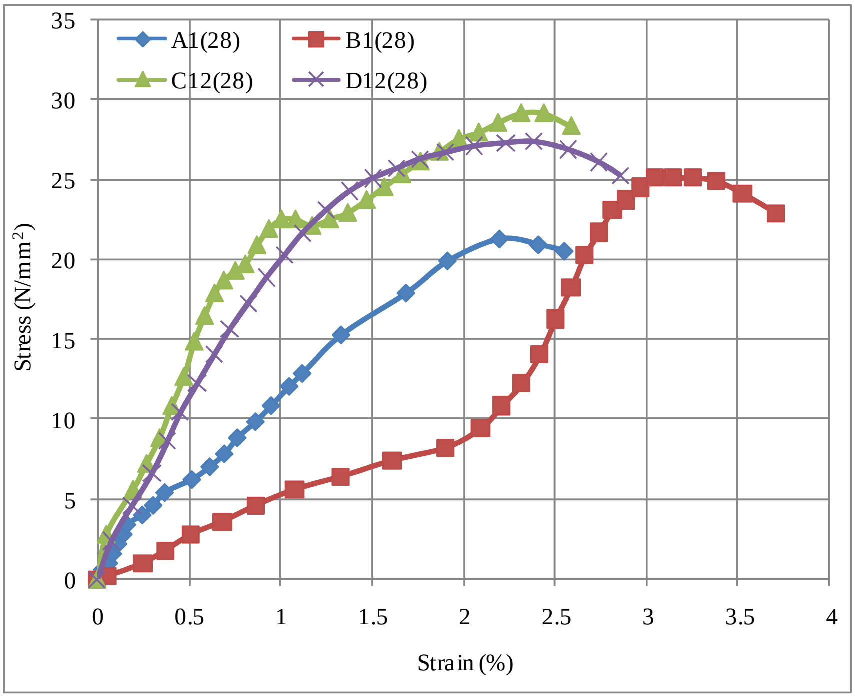


**Figure (2): Stress-strain characteristics of fresh/ C & D aggregate concrete without/with glass waste**

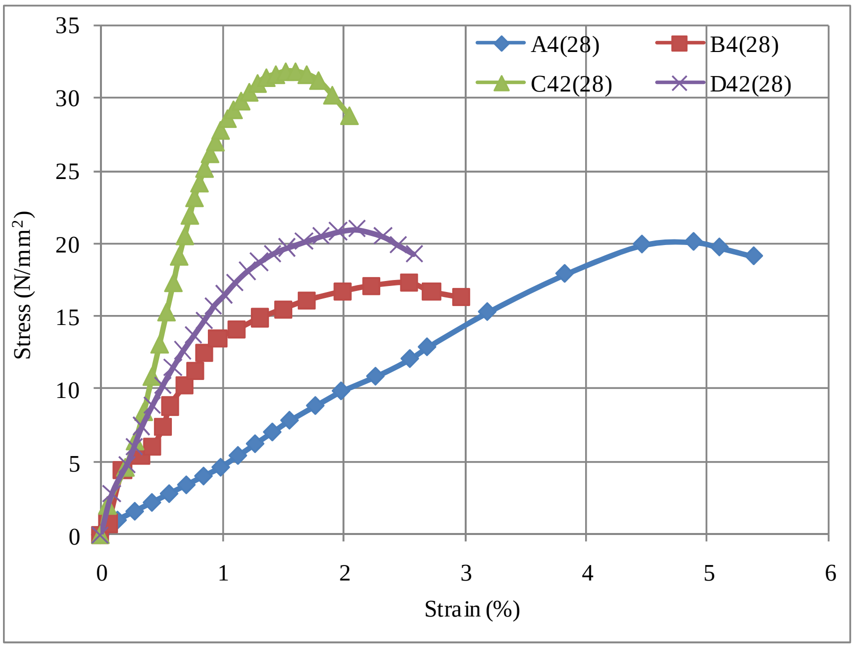


**Figure (3): Stress-strain characteristics of fresh/ C & D aggregate concrete without/with glass waste (with superplasticizer and fiber)**

**Comparison of 28-day Compressive Strength**

The comparison of 28-day compressive strength of concrete consisting of different waste materials and superplasticizer and fiber with that of control cube is shown in Figure 4. The compressive strength of concrete consisting of cement: sand: aggregate: 1: 2: 4 + 0.9% superplasticizer + fiber (sand replaced by waste glass = 20%), C42 was the highest (48% higher than that of control cube A1), followed by that of concrete consisting of cement: sand: aggregate: 1: 2: 4 (20% sand replaced by waste glass), C12 was 38% higher than that of control specimen. The compressive strength of the concrete consisting of cement: sand (C&D): aggregate (C&D): 1: 2: 4 (20% sand replaced by waste glass), D12 was higher by 28% compared to that of the control specimen, whereas that of concrete consisting of cement: sand (C&D): aggregate (C&D): 1: 2: 4; B1 was higher by 18% compared with that of the control specimen. Thus, optimum replacement of fine aggregate with waste glass and superplasticizer + fiber yields the highest strength, followed by that of specimen with optimum replacement of fine aggregate with waste glass. The effect of superplasticizer and fiber with waste glass yields the highest strength because of the formation of proper bond with glass in the presence of fiber. The glass particles were angular in shape, which helped in interlocking of particles and pozzolanic reaction in concrete matrix. The waste glass provided good interlocking, but the effect reduced in the presence of C & D aggregate particles. The strength improved upon the use of C & D aggregate particles obtained from parent concrete possessing higher strength (30 MPa).

The compressive strength of concrete consisting of cement: sand: aggregate: 1:2:4 + 0.9% superplasticizer+ fiber, A4 was slightly smaller and that of cement: sand (C&D):aggregate (C&D): 1: 2:4+0.9% superplasticizer+ fiber, B4 is the smallest compared to the compressive strength of the control specimen. The compressive strength of concrete consisting of cement: sand (C&D): aggregate (C&D): 1: 2: 4 + 0.9% superplasticizer + fiber (sand replaced by waste glass = 20%), D42 is almost the same as that of the control specimen A1. Use of superplasticizer + fiber in normal concrete yielded slightly less strength because of loosening of matrix in the presence of fiber. The strength deteriorated on the use of C & D aggregate along with superplasticizer + fiber due to the presence of hard old mortar adhering to surfaces of C & D aggregate particles, which inhibited the formation of proper bond. However, the deterioration in strength of C & D aggregate concrete in the presence of superplasticizer + fiber diminished due to the addition of optimum content of well graded glass replacing fine aggregate which caused pozzolanic reaction in concrete.

**Effect of Age of Curing on Compressive Strength**

**Fresh Aggregate Concrete without/with Glass Waste**

The effect of age of curing on compressive strength of cement and fine aggregate consisting of sand and waste glass in replacement of (10%, 20% and 30%) with fine sand and coarse aggregate (1:2:4) is illustrated in Figure 5. The replacement of 10%, 20% and 30% of sand with waste glass yields a compressive strength of 9.05 N/mm$^2$, 12.25 N/mm$^2$ and 11.89 N/mm$^2$ (15.91 N/mm$^2$ for control cube), respectively after 3 days, increasing to a compressive strength of 25.9 N/mm$^2$, 29.17 N/mm$^2$ and 26.76 N/mm$^2$ (21.29 N/mm$^2$ for control cube), respectively after 28 days. The compressive strength with 10% replacement of sand shows a lower value in comparison to 20% and 30% replacement at 3 days, but after 28 days, the compressive strength of 20% replacement shows higher value than 10% and 30% replacement. The percentage replacements of sand with waste glass show higher values of compressive strength in comparison to compressive strength of concrete for cement: sand: aggregate (1: 2: 4) without waste glass. The improvement in strength with age of curing may be attributed to better interlocking and slow pozzolanic reaction of angular glass particles in the concrete matrix which was optimized at 20% glass content.

Similar results showing increase in compressive strength with age have been reported by some researchers. Ismail and Al-Hashmi (2009) used waste glass as a partial replacement for sand at 10%, 15% and 20% with 900 kg of concrete mixes and showed that the compressive strength of specimens with 20% waste glass content was 4.23% higher than that of the control specimen at 28 days. Castro and Brito (2013) tested mixes containing 0%, 5%, 10% and 20% of glass aggregates (GA) as replacement of natural aggregates (NA) and revealed that though there is some decrease in compressive strength initially as the replacement rate increases, mixes with GA are totally feasible, even though there are some differences in performance as a function of particle size of GA used to replace NA.

**Fresh Aggregate Concrete without/with Glass Waste+ Superplasticizer and Fiber**

The influence of age of curing on compressive strength of cement and fine aggregate consisting of sand and waste glass in replacement of (10%, 20% and 30%) with fine sand and coarse aggregate with superplasticizer and fiber as additives (1:2:4) is shown in Figure 6. The replacement of 10%, 20% and 30% of sand with waste glass shows a compressive strength of 10.12 N/mm$^2$, 10.30 N/mm$^2$ and 9.92 N/mm$^2$ (15.91 N/mm$^2$ for control cube), respectively after 3 days, increasing to a compressive strength of 25.75 N/mm$^2$, 31.79 N/mm$^2$ and 24.14 N/mm$^2$ (21.29 N/mm$^2$ for control cube), respectively after 28 days. The compressive strength of fresh aggregate concrete with 30% replacement of sand with waste glass shows a lower value in comparison to 10% and 20% replacements at 3 days, but after 28 days, compressive strength of 20% replacement shows a higher value than 10% and 30% replacements. Increase in strength with age may be due to better interlocking and delayed pozzolanic reaction of angular glass particles, as well as better bond formation in the presence of superplasticizer and fiber. Similar results illustrating increase in compressive strength of concrete have been reported by some investigators. Chikhalikar and Tande (2012) investigated characteristic properties of fiber-reinforced concrete containing waste glass as pozzolona and showed that compressive strength increase is achieved up to 30% as compared to the control mix, but the peak percentage increase is at 20% replacement.

**C & D Aggregate Concrete without/with Glass Waste**

The development of compressive strength with age in concrete consisting of cement: sand (C&D): aggregate (C&D): 1: 2: 4 (sand replaced by waste glass= 10%, 20% and 30%) is revealed in Figure 7. The replacement of 10%, 20% and 30 % of sand with waste glass shows a compressive strength of 9.75 N/mm$^2$, 10.26 N/mm$^2$ and 9.42 N/mm$^2$ (15.91 N/mm$^2$ for control cube), respectively at 3 days, increasing to a compressive strength of 22.53 N/mm$^2$, 27.44 N/mm$^2$ and 21.48 N/mm$^2$ (21.29 N/mm$^2$ for control cube), respectively after 28 days. The compressive strength of C & D waste aggregate concrete with 30% replacement of sand with waste glass shows a lower value in comparison to 10% and 20% replacements at 3 days, but after 28 days, compressive strength of 20% replacement shows a higher value than 10% and 30% replacements. The strength increased with age due to better packing of glass particles and slow pozzolanic reaction, but the improvement in strength was less, since old hard mortar coating the C & D aggregate particles did not allow the formation of proper bond.

Similar increase in compressive strength of concrete consisting of C & D aggregate with age has been reported by some researchers. Olorunsogo and Padayachee (2002) showed that with increase in quantities of recycled aggregate, quality improved with the age of curing. Khatib (2005) revealed that when fine aggregate in concrete was replaced with 0%, 25%, 50% and 100% crushed concrete, the strength is reduced by 15%-30% during initial age and beyond 28 days of curing, the rate of strength development in concrete containing crushed concrete is higher than that of the control, indicating further cementing action in the presence of fine recycled aggregate. Padmini et al. (2009) concluded that though the compressive resistance of recycled aggregate is lower than that of fresh aggregate, the values are generally within acceptable limits. Sallehan and Ramli (2013) indicated that concrete containing 15% untreated recycled concrete aggregate met target compressive strength of 50 MPa at 28 days of curing. Andreu and Miren (2014) showed that compressive strength at early age is more dependent on water added at mixing time, but after 28 days, recycled aggregate concrete showed a comparable behaviour to conventional concrete.

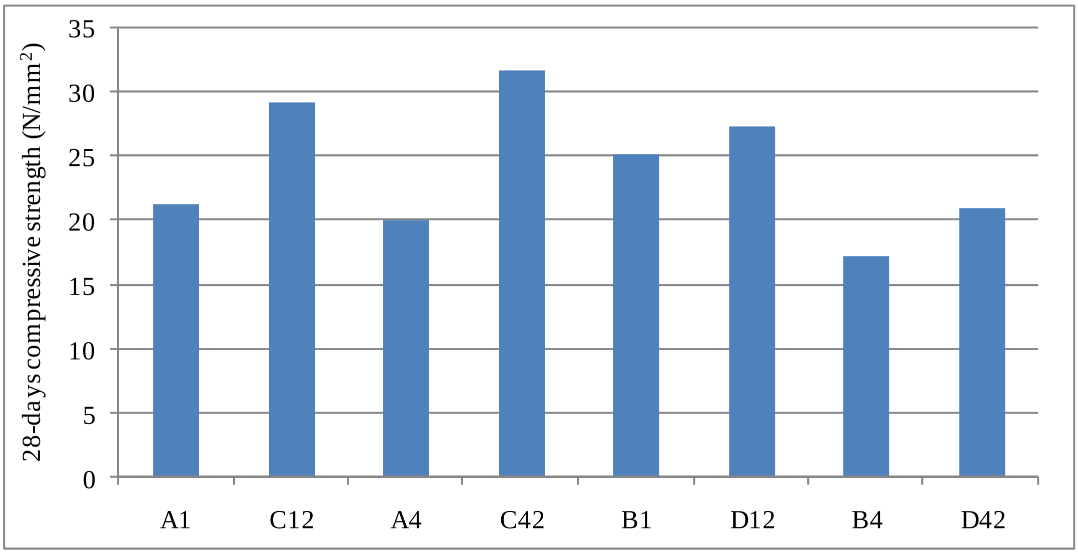


**Figure (4): Comparison of 28-day compressive strength of concrete without/with various admixtures**

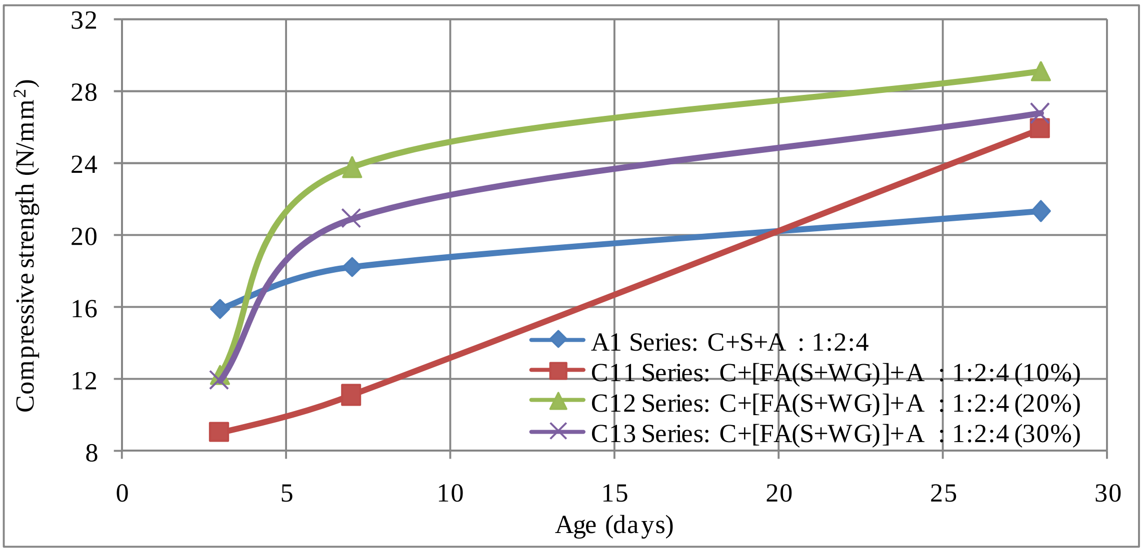


**Figure (5): Compressive strength of concrete with age (fresh aggregate + glass waste)**

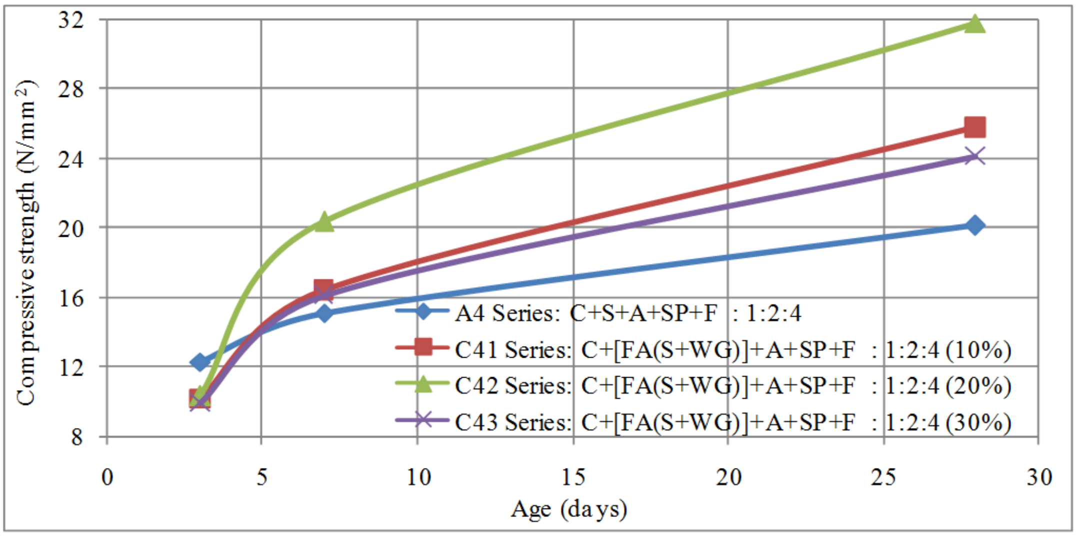


**Figure (6): Compressive strength of concrete with age (fresh aggregate + glass waste + additives)**

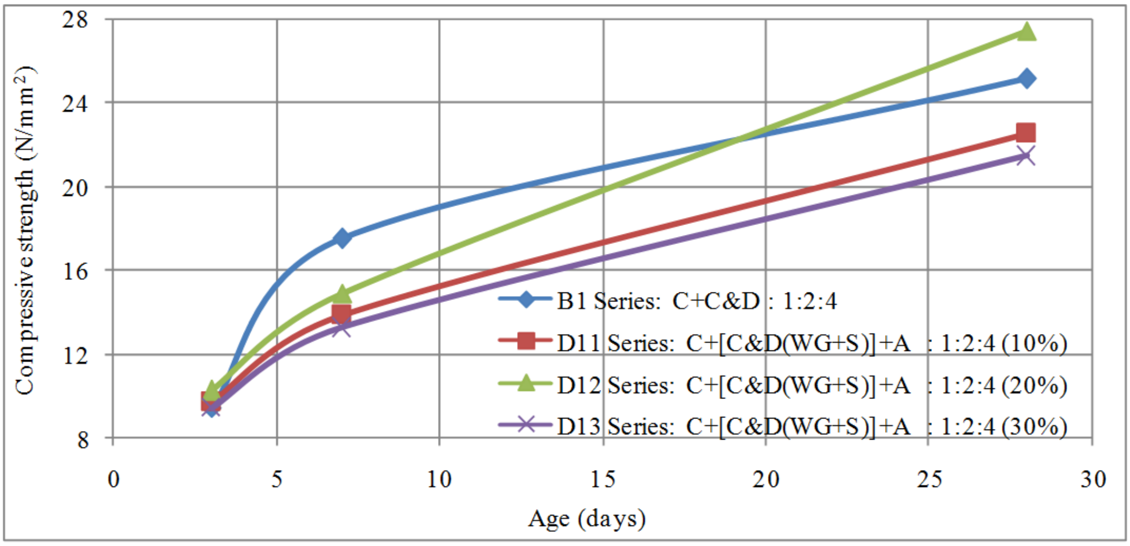


**Figure (7): Compressive strength of concrete with age (C & D aggregate + glass waste)**

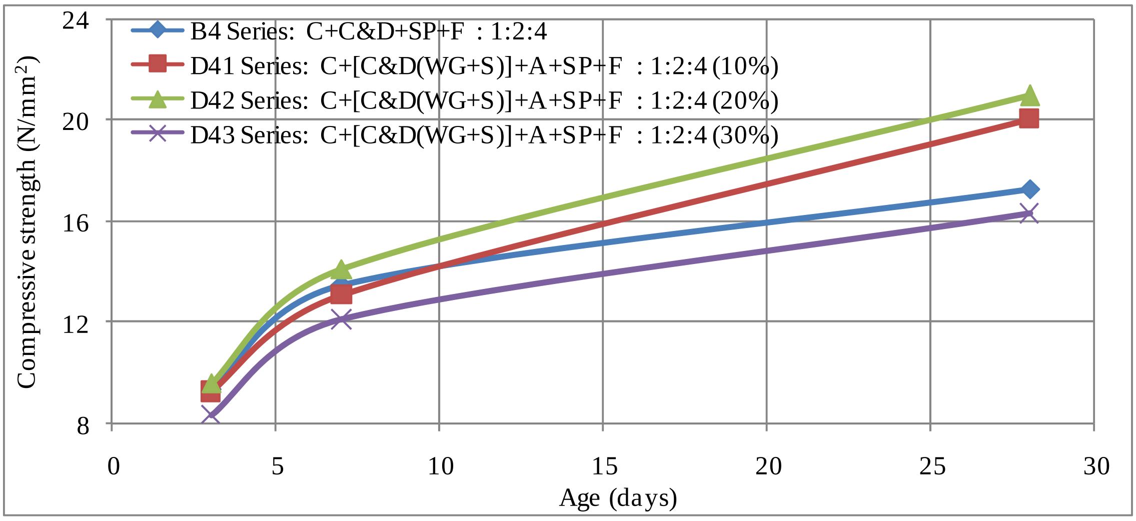


**Figure (8): Compressive strength of concrete with age (C & D aggregate + glass waste + additives)**

**C & D Aggregate Concrete without/with Glass Waste Including Superplasticizer and Fiber**

The variation of compressive strength with age in concrete consisting of cement: sand (C&D): aggregate (C&D): 1: 2: 4 (sand replaced by waste glass = 10%, 20% and 30%) along with superplasticizer and fiber is indicated in Figure 8. The replacement of 10%, 20% and 30 % of sand with waste glass shows a compressive strength of 9.26 N/mm$^2$, 9.61 N/mm$^2$ and 8.33 N/mm$^2$ (15.91 N/mm$^2$ for control cube), respectively after 3 days, increasing to a compressive strength of 20.05 N/mm$^2$, 20.58 N/mm$^2$ and 16.30 N/mm$^2$ (21.29 N/mm$^2$ for control cube), respectively after 28 days. The compressive strength of C & D waste concrete including superplasticizer and fiber with 30% replacement sand with waste glass shows a lower value in comparison to 10% and 20% replacements at 3 days. After 28 days, compressive strength of 20% replacement shows a higher value than 10% and 30% replacements. Deterioration of strength in C & D aggregate concrete in the presence of superplasticizer and fiber may be attributed to the formation of improper bond in concrete matrix. But, when glass was added partially replacing C & D fine aggregate in the above matrix, the decrease in strength was only marginal, as better interlocking and slow pozzolanic reaction due to angular glass particles improved the strength with age.

## CONCLUSIONS

The experimental study on compressive strength of concrete with C & D aggregate, glass waste and superplasticizer and fiber additives leads to the following conclusions:

(1) The stress-strain curves of various concrete specimens reveal sudden failure as indicated by the small post-peak portion.

(2) The 28-day compressive strength of concrete consisting of construction and demolition waste aggregates increased as compared to that of the control specimen.

(3) Upon replacement of fine aggregate with glass waste to the extent of 30%, an improvement in compressive strength was observed.

(4) If both construction and demolition waste aggregate and glass waste replacing fine aggregate were used, compressive strength increased.

(5) When fine aggregate was replaced with glass waste including the use of superplasticizer and fiber, compressive strength increased.

(6) However, when construction and demolition waste aggregate and waste glass replacing fine aggregate including superplasticizer and fiber were used, compressive strength was not much affected. If superplasticizer and fiber were added to natural aggregate or C & D aggregate concrete, compressive strength deteriorated marginally.

(7) Thus, construction and demolition waste with or without glass waste can be used in concrete, yielding improved compressive strength, thereby solving the problem of disposal. The utilization of these waste materials in concrete will help in saving the natural resources and preserving the environment.

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