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Strength and behaviour of recycled aggregate geopolymer concrete beams

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Abstract. In the present day scenario, concrete construction is rapidly becoming uneconomical and non sustainable practice, due to the scarcity of raw materials and environmental pollution caused by the manufacturing of cement. In this study an attempt has been made to propose recycled aggregates from demolition wastes as coarse aggregate in geopolymer concrete (GPC). Experimental investigations have been conducted to find optimum percentage of recycled aggregates (RA) in GPC by replacing 20%, 30%, 40%, 50% and 60% of coarse aggregates by RA to produce recycled aggregate geopolymer concrete (RGPC). From the study it has been found that the optimum replacement percentage of recycled aggregates was 40% based on mechanical properties and workability. In order to study and compare the flexural behaviour of RGPC and GPC four beams of size 175 mm×150 mm×1200 mm were prepared and tested under two point loading. Test results were evaluated with respect to first crack load, ultimate load, load-deflection characteristics, ductility and energy absorption characteristics. Form the experimental study it can be concluded that the addition of recycled aggregate in GPC causes slight reduction in its strength and ductility. Since the percentage reduction in strength and behaviour of RGPC is meager compared to GPC it can be recommended as a sustainable and environment friendly construction material.

Keywords: recycled aggregate; geopolymer concrete; mechanical properties; flexural behaviour

1. Introduction

The major issue faced by the construction industry at present is the need for environment friendly construction materials for sustainable development. The construction industry, which uses Portland cement as the major constituent of concrete and other cement based construction materials is the major contributor of greenhouse gases. In addition to that, the manufacture of cement causes reduction in natural resources like limestone and fuel (Bakhrev 2005). In order to reduce the carbon footprint it is necessary to find alternate low emission binders for cement. Geopolymers are one such alternate binder to cement. It is a type of alumino-silicate polymer, produced by the chemical activation of molecules which are rich in alumina and silica (Sarker 2011). Concrete made by using geopolymers as binders are known as geopolymer concrete (GPC). Experiments have proved that fly ash can be used as a source material to produce geopolymer

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Table 1 Properties of aggregates

Type of aggregate	Specific gravity	Moisture content (%)	Bulk density(g/cc)	Fineness modulus	Void ratio	Porosity (%)
Fine aggregate	2.85	1.40	1.80	2.6	0.59	37
Coarse aggregate	2.76	0.44	1.62	7.1	0.76	43
Recycled aggregate(RA)	2.48	0.50	1.35	5.3	0.70	45

Table 2 Mix proportion for GPC

Constituent materials	Quantity (kg/m^3)
Fly ash	408
Sodium Silicate solution	103
Sodium Hydroxide solution	41
Coarse aggregate	1248
Fine aggregate	600
Water	14.5
Superplasticizer	10.2

since it posse's pozzolanic properties. Since GPC uses waste material like fly ash as the main ingredient, it can be regarded as a sustainable green material. Studies conducted on the mechanical properties of GPC by (Ganesan *et al.* 2015, Kumaravel and Thirugnanasambandam 2013, Sujatha *et al*. 2012, Rajamane *et al.* 2011) showed that it has better engineering properties and durability characteristics than conventional concrete.

It is found that the construction waste accounts for 30-40% of the municipal waste, with a share of 25-40% global energy consumption every year and they were simply dumped in as landfills. Since aggregates makes up the major portion of the concrete it leads to the investigation on the use of recycled aggregates in concrete. If they are utilized for the construction purpose we can save our environment from disposal sites of these materials and hence reduce the exploitation of natural resources (Vanchai *et al*. 2013). The idea of combining geopolymer concrete and recycled aggregate has led to the development of recycled aggregate geopolymer concrete (RGPC). RGPC is a welcome contribution to the construction industry as they can effectively reduce the environmental impacts caused by the disposal of fly ash and demolition wastes and make the concrete ecofriendly.

2. Experimental programme

In the experimental programme the fresh and hardened properties of GPC and RGPC with varying percentages of recycled aggregates (RA) were investigated and the optimum percentage of RA was fixed based on the above properties. After fixing the optimum replacement percentages, beams of size 125 mm×175 mm×1200 mm were cast and tested in order to investigate and compare the flexural behaviour of RGPC and GPC.

2.1 Materials used

The ingredients of GPC were low calcium fly ash (Class F), coarse aggregate (CA), fine aggregate (FA), alkaline solutions and superplasticiser. Crushed granite aggregates of nominal size 20 mm and river sand conforming to Zone II of IS 383-1970 reaffirmed in 2002, were used as coarse aggregate and fine aggregate respectively. A mixture of sodium silicate solution and sodium hydroxide solution were chosen as the alkaline solution to activate the source material. For the production of RGPC, recycled aggregates were prepared by crushing the tested concrete specimens obtained from the laboratory. The properties of coarse aggregate, fine aggregates and recycled aggregates used are given in Table 1. In order to improve the workability of concrete naphthalene based superplasticiser was used for both GPC and RGPC.

2.2 Mix design and preparation of specimens

Geopolymer concrete mix of grade M30 was designed based on the guidelines given by (Rangan 2006). Mix proportion for M30 GPC is shown in Table 2. For the preparation of GPC mix, coarse aggregate and fine aggregate in saturated surface dry condition were mixed in the mixer with fly ash for about two minutes. Then the alkaline solutions, superplasticiser and extra water were added to the mix and mixed for another two minutes. For the preparation of recycled aggregate geopolymer (RGPC) mix, RA was added in varying percentages of 20%-60% with an increment of 10% and the designations used to identify these mixes are given in Table 3. The recycled aggregates were immersed in water prior to casting so that all the dry and loose materials attached to its surface are removed and is made clean. Two stage mixing approach proposed by (Vivian *et al*. 2008) was adopted to improve the properties of RGPC. In this method of mixing, first recycled aggregate, fine aggregate, fly ash and a portion of the alkaline solution was fed into the mixer and mixed well for 60 seconds. Then the remaining coarse aggregate, water, alkaline solution and superplasticizer are added and mixed well for another two minutes. The workability of fresh geopolymer concrete was determined immediately after mixing by conducting standard slump test. The slump values of various mixes are given in Table 3. Standard cubes of size 150 mm, cylinders of 150 mm diameter and 300 mm height and prisms of size 100 mm×100 mm×500 mm were cast to determine the hardened properties. Immediately after casting all the specimens were covered with polythene sheets in order to prevent moisture loss. After casting, all specimens were kept at room temperature for one day and then transferred to an oven for elevated temperature curing at 60℃ (Djwantoro *et al*. 2004). After curing for a day, the specimens were removed from the oven and left to air-dry at room temperature for 24 hours before demoulding. After 28 days of curing, the specimens were tested in the laboratory to investigate the hardened properties. The hardened properties of the tested specimens are given in Table 3.

From Table 3, it can be seen that the slump value decreases with increase in RA content. The reduction in slump value may be due to the pores and old mortar attached to the surface of RA which absorbs the solution. For RGPC3 having 40% RA the slump reduced by 21% as compared to GPC. On further increasing the RA content the slump values reduced rapidly and the mix becomes more stiffer. From Table 3 it is also observed that the hardened properties reduced on increasing the percentage of RA. This may be due to the porous structure of the recycled aggregates used. The variation in the hardened properties was observed around 10% in the case of RGP3, containing 40% of RA. Beyond 40 % the reduction in fresh and hardened properties was more. Therefore based on the observations from the fresh and hardened properties a mix with 40% of RA and 60% of natural coarse aggregates was considered as the optimum mix of RGPC.

After fixing the optimum mix proportion of RGPC, beam specimens of size 1200 mm×125

Table 3 Designation and properties of mixes

Mix	% of RA	Slump (mm)	Compressive strength (N/mm^2)	Split tensile strength (N/mm^2)	Flexural strength (N/mm^2)
GPC	0	100	37.2	3.56	4.26
RGPC1	20	95	36	3.43	4.10
RGPC2	30	88	34.2	3.29	3.97
RGPC3	40	79	32.8	3.15	3.84
RGPC4	50	70	29.0	2.78	3.26
RGPC5	60	55	23.3	2.20	2.97

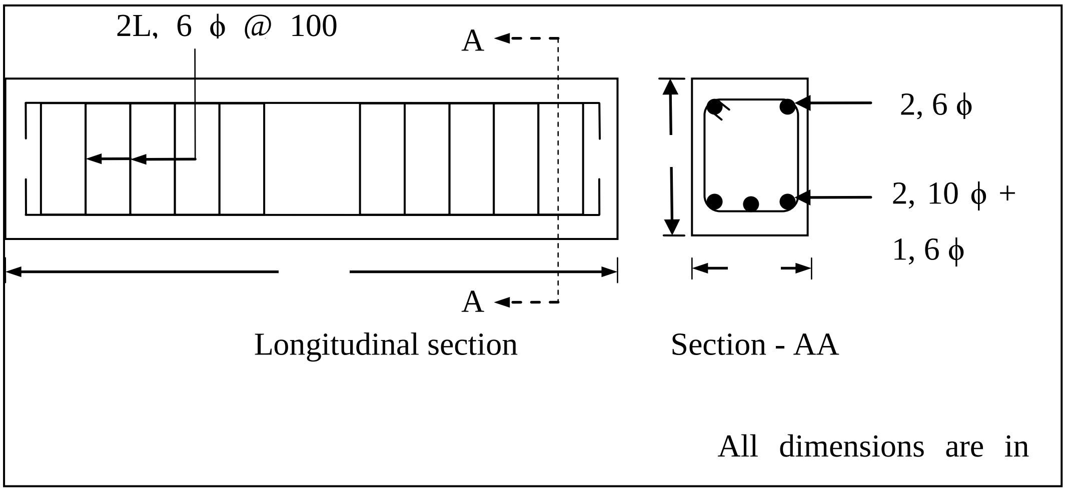

Fig. 1 Reinforcement details

Fig. 2 Specimens inside oven

mm×175 mm, were cast using GPC and RGPC as explained above. All the beams were designed as under reinforced sections and the reinforcement details are as shown in Fig. 1. Two 10 mm bars and one 6 mm bars were used on the tension side and two 6 mm diameter bars were used at the compression side. Two legged stirrups of 6 mm diameter were provided at 100 mm c/c distance as shear reinforcement. After casting all the beams were covered with polythene sheets to prevent

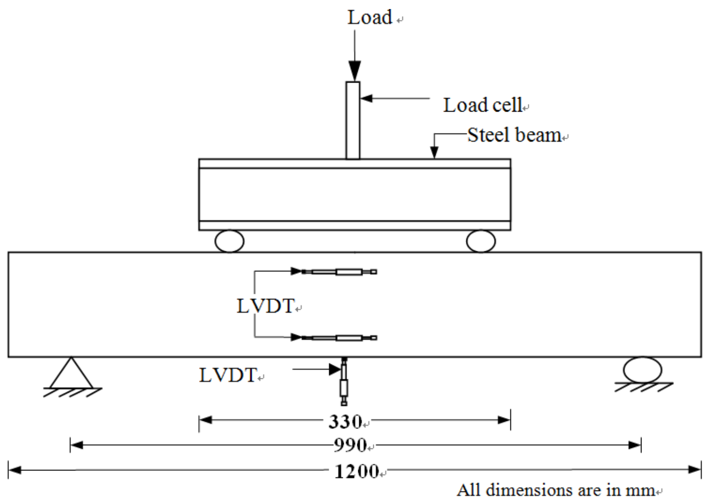

Fig. 3 Schematic diagram of test setup

Fig. 4 Test setup

moisture loss and were kept at room temperature for one day. Then the specimens were transferred to oven for elevated temperature curing at 60℃ (Djwantoro *et al*. 2004) as shown in Fig. 2. After curing for a day, the specimens were removed from the oven and left to air-dry at room temperature for 24 hours before demoulding.

2.3 Testing of beam specimens

After 28 days of casting the beams were tested under simply supported condition and were subjected to two-point loading. The span of the beam was kept as 990 mm. Load was applied using 250 kN hydraulic jack and was measured using load cell of 100 t capacity. The schematic diagram of the test setup and the test setup is shown in Figs. 3 and 4 respectively. The deflection at mid-span was measured with the help of dial gauge of least count 0.01 mm. Deformations at mid-span using LVDT's across the depth of the beam at 20 mm below the top and 20 mm above the bottom

Fig. 5 Crack pattern

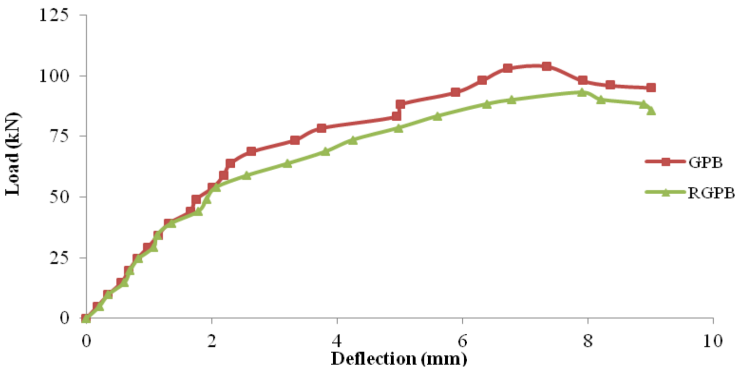

Fig. 6 Comparison of load-deflection behaviour

2.4 Crack pattern and failure modes of specimens

On commencement of testing cracks were not observed. As the load increased gradually, flexure cracks developed in the bending zone. With further increase in load the existing cracks got widened and propagated and new cracks were formed along the span. The width and the spacing of cracks varied along the span. At the ultimate stage, most of the cracks traversed up to the top of the beams. On increasing the load further, cracks propagated in a vertical direction and new cracks started to appear throughout the shear span. The failure of beam was indicated by yielding of tensile reinforcement and crushing of concrete in the compression zone. The crack patterns of geopolymer concrete beams and recycled aggregate geopolymer beams are shown in Fig. 5. It was observed that the number and width of cracks were more in the case of RGPB specimens as compared to that of the GPB specimens. This may be due to the reduction in tensile strength of recycled aggregate geopolymer concrete due to the porous structure of RA.

3. Test results

Test results were evaluated with respect to load-deflection behaviour, first crack load, ultimate load, energy absorption capacity, toughness index, displacement ductility and curvature ductility.

Table 4 First crack load, ultimate load and ductility

Beam designation	First crack load (kN)	% variation	Ultimate load (kN)	% variation	Displacement ductility	% variation
GPB	24.52	21.53	102.40	9.08	1.44	10.4
RGPB	19.24		93.10		1.29	

Table 5 Energy absorption capacity and toughness index

Beam designation	Energy absorption capacity (kN mm)	% variation	Toughness index	% variation
GPB	235	15.7	107	16.82
RGPB	198		89	

3.1 Load-deflection behaviour

The load deflection data obtained from the experiment were used to plot load deflection graphs and is shown in Fig. 6. From the graphs it is observed that RGPB slightly inferior behaviour than GPB. This may be attributed to the use of recycled aggregate.

3.2 First crack load and ultimate load

The load at which the first crack starts to appear is known as the first crack load. It was determined from the load-deflection curve, where the point at which the curve deviates from linearity. The peak load at which the beam fails is considered as the ultimate load. The first crack load and ultimate load of all the tested specimens are shown in Table 4. From the table, it can be seen that the first crack load ultimate load of RGPB beams are 21% and 9% respectively less than that of GPB beams. This may be due to the use of recycled aggregates which brings in early cracking on the surface as the presence of voids reduces the bond strength between the constituent particles of the concrete.

3.3 Displacement ductility

Ductility refers to the ability of structural members to withstand large deformations after the yielding of tensile reinforcement without much reduction in the load carrying capacity. The ductility index is calculated as the ratio of deflection at ultimate load (δ_u) to the deflection at yield load (δ_y) and is given by Eq. (1).

$$\lambda = \frac{\delta u}{\delta y} \tag{1}$$

The displacement ductility of all the tested specimens is given in Table 4. From the table it can be seen that the displacement ductility of RGPB beams are slightly lesser than that of the GPB beams, this may be due to the porous nature of recycled aggregate.

3.4 Energy absorption capacity and toughness index

The area under the load deflection curve indicates the energy absorption capacity. The energy

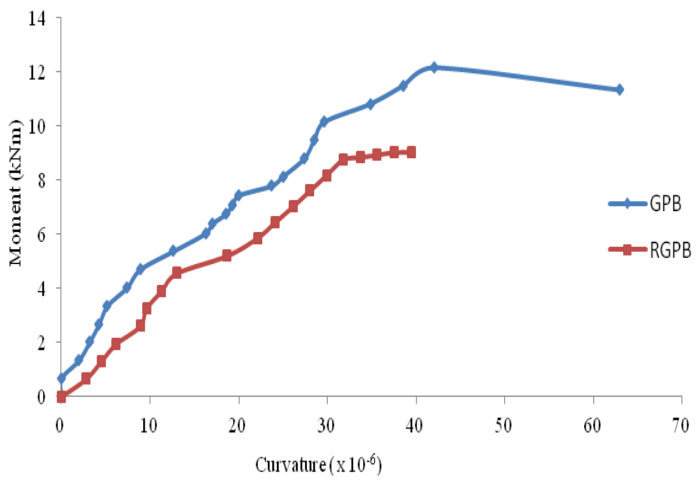

Fig. 7 Moment curvature relationship

absorption capacity is an essential property required for seismic resistant structures. Increased energy absorption capacity improves the performance under fatigue, impact and impulse loading. The energy absorption capacities of beams were calculated as the area under the load deflection curve up to the ultimate load and are given in Table 5. The concrete is effective in resisting the load until the formation of the first crack. At this stage concrete is unable to resist the tensile stress and it is completely taken up by the steel at the cracked section. The ratio of area under the load deflection graph up to ultimate load to the area under load-deflection graph up to first crack load is called toughness index. The toughness index of all the tested specimens is given in Table 5. From the table it is seen that the energy absorption capacity and toughness index of RGPB beams were less than that of GPB beams. This may be due to the reduced load carrying capacity of RGPB beams compared to GPB beams.

3.5 Moment curvature relationship

From the recorded values of loads moments were calculated. From the LVDT readings placed at the tension side and compression side of the beam strains were calculated and curvature of the beam was calculated by using Eq. (2). These values are used to plot moment curvature graph and is given in Fig. 7.

$$\varphi = \frac{\varepsilon s + \varepsilon c}{d} \tag{2}$$

From the figure it can be seen that relationship is almost linear up to the point of first cracking. After that the curve is non linear. The moment carrying capacity of RGP beams is less than that of GPB beams. When steel starts yielding, a large increase in curvature occurs. This indicates the ductile behaviour of the specimens. The reduced curvature of RGPB specimens is due to the use of recycled aggregates which have reduced bond strength as compared to that of the natural aggregates used in GPB specimens.

3.6 Curvature ductility

Table 6 Curvature ductility

Beam designation	Curvature at ultimate load(ϕ_u) (10^{-6})	Curvature at yield load (ϕ_y) (10^{-6})	Curvature ductility index ($\frac{\varphi u}{\varphi y}$)	% variation
GPB	47.4	15.62	3.03	9.6
RGPB	36.2	13.21	2.74	

Curvature ductility was calculated from the moment curvature plots. This used the same concept as that of the displacement ductility. It was calculated as the ratio of curvature at ultimate load (ϕ_u) to the curvature at yield load (ϕ_y). The curvature ductility of various specimens is given in Table 6. From the table it is observed that the curvature ductility of RGPB is slightly less than that of GPB specimens, which may be due to the porous structure of the aggregates used in RGPB beams. The porous structure increases the amount of voids present in the concrete hence reducing the ductility leading to earlier collapse of the structure.

4. Conclusions

The mechanical properties and flexural behaviour of recycled aggregate geopolymer concrete was investigated by conducting experimental investigations. From the test results, the following conclusions were drawn

- The optimum percentage of recycled aggregate in geopolymer concrete is 40% based on mechanical properties and workability.
- The flexural behaviour of RGPB beams is slightly inferior to that of GPB beams.
- The first crack load and ultimate load of RGPB beams are 21% and 9% respectively less than that of GPB beams.
- The displacement ductility and curvature ductility of RGPB beams were 10% less than that of GPB beams.
- The energy absorption capacity and toughness index of RGPB beams were almost 15% less than that of GPB beams.
- The crack pattern and failure mode RGPB beams and GPB beams were almost similar but the width of cracks in GPB beams is slightly more than that of GPB beams.
- From the study conducted it can be concluded that RGPC with 40% RA and 60% natural aggregate as coarse aggregate posse's almost similar behaviour to that of GPC. Since the maximum strength reduction of RGPC is only 20% compared to GPC it can be recommended as an environment friendly construction material.

Acknowledgments

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