Shear Strength of Steel Fiber Reinforced Reactive Powder Concrete & Geopolymer Concrete – A Comparison

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ABSTRACT

Reactive Powder Concrete (RPC) is an ultra-high strength concrete composite prepared by the replacement of natural aggregates with quartz powder, silica fume and steel fibers. The use of RPC yields high strength, high ductile concrete with optimized material use and contributes to economic, sustainable and ecofriendly constructions. Past research has indicated that RPC offers significant improvement in the mechanical and physical properties owing to its homogenous composition with less defects of voids and microcracks. This leads to enhancement of ultimate load capacity of RPC members and results in superior ductility, energy absorption, tensile strain-hardening behavior, crack control capability and durability. Geo-polymer concrete (GPC) is a type of concrete that is made by reacting aluminate and silicate bearing materials with a caustic activator. Usually, waste materials such as fly ash or slag from iron and metal production are used, which helps lead to a cleaner environment. This paper attempts to review the effect of steel fibers on the shear strength of steel fiber reinforced RPC and compare the results with those of geopolymer concrete.

Keywords: Reactive powder concrete, Geo-polymer concrete, Shear strength, Modes of failure.

1 Introduction

In recent years, the use of concrete have been substantially increased due to industrialization and civilization; and hence the impact on the environment also. This lash on the nature must be controlled and the need for sustainable construction has to be foreseen without compromising the quality and strength of concrete. Structural engineers should battle the ignorance of the society and must bring the sustainability circle, thus reducing the impact of concrete on the environment. In any structural member, high shear strength, superior ductility and low crack propagation style can be obtained if the capability of controlling the crack and capacity of tensile strength strain is attained.

Concrete materials of high performance are in high request as it has vast functional requirements. The shear capacity significantly depends on the behavior under tension due to shear failure which usually happens when the tensile stress is exceeded by the principal tensile stress with in the shear span. Also a diagonal crack propagates through the web of beam. Past research revealed that Ultra high performance concretes (UHPC) like Reactive Powder Concrete (RPC) and Geo-Polymer Concrete (GPC) can be used with high efficacy. Use of such concrete ensures enhanced properties like superior ductility, high durability, high compressive strength, energy absorption etc. compared to normal concrete.

RPC is UHPC prepared by replacing the ordinary aggregates of normal concrete with silica fume, steel fibers, quartz powder, etc. It has high strength & high ductility. Without steel fibers, RPC is brittle. GPC is a novel cementitious material after gypsum and ordinary Portland cement. The most common source of material is low

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calcium fly ash. GPC has high compressive and tensile strengths. It gains full strength quickly. GPC emits 95% less carbon dioxide.

There is a need to study the shear strength and behavior of RPC and GPC as it is one of the least explored area of research as far as the green concretes are concerned; especially in case of RPC. Several experimental studies were conducted to pronounce the behavior of GPC under shear. This paper attempts to review and compare the shear strength and behavior of RPC and GPC beams.

2 Reactive powder concrete

Reactive powder concrete, also known as ultra high performance concrete, provides usage of composite materials in different structures like high rise buildings, bridges, etc. RPC is a homogenous material and it consists of less micro-cracks and minimum voids. This helps in enhancing the ultimate load capacity of the structural members. Voids in high performance concrete makes it vulnerable to heat. RPC reduces this vulnerability due to the presence of dense micro size material. RPC includes fine quartz sand and some pozzolanic materials are added to replace coarse aggregates. Steel fibers are embedded in the cementitious matrix for improving the tensile strength and enhancing the performance of concrete. Compared to traditional concrete, RPC has high ductility, crack control capability, durability and it is more reliable. The micro structure of the concrete could be improved using silica fume owing to micro filling phenomena. Silica fume also chemically react to form an additional binder material. It is noted that volume and property of the fibers are relied by tensile strength, energy absorption and strain [11].

Use of silica fume enhanced the microstructure of concrete. This helped in decreasing the voids and hence the vulnerability of the concrete to heat would be reduced. Microstructure of the concrete can be produced by improving the uniformity and firmness of the particle size [6].

Light weight RPC could be obtained using aggregates like pollytag, expanded clay aggregate and expanded polystyrene breads. Among these, expanded clay aggregate had the highest strength with low water absorption rate [8] owing to the placement of mix in large pores on aggregate surface. A water cement ratio of 0.20 can be applied in RPC due to the presence of silica fume, fine sand and water reducer.

With the increasing shear stirrups ratio and longitudinal ratio, ultimate shear capacity of the RPC girder also increased. The ultimate load of RPC increased by 12% after the application of shear reinforcements. The ductility and toughness properties of the cement material could be embraced by the use of waste steel fiber. RPC can be compacted using vibrating table to avoid segregation of the fiber [1].

2.1 Effect of steel fibers in concrete

Kannan et al. [2] conducted tests on RPC specimens containing quartz powder, sand, silica fume & steel fibers and found out the mechanical properties like compressive strength, flexural strength, ductility and energy absorption under various proportion of steel fibers. Ridha et al [1] conducted shear tests on 18 RPC beams with parameters like span to depth ratio, longitudinal reinforcement, percentage silica fume and steel fibers.

2.1.1 Compressive strength

Compressive strength of RPC was very high compared to conventional concrete. It was found that compressive strength is directly proportional to the proportion of steel fibers to some extent. About 10 to 15 % of the compressive strength is increased due to the addition of steel fibers. RPC without steel fibers have a compressive strength 1.5 times less than RPC with 2% steel fibers.

If the percentage of silica fume increased, then strength also increases (for the same proportion of steel fibers). Also elastic modulus increases with increase in fiber content. Fig-1 shows ultimate load, deflection and the compressive strengths of RPC found from Ridha et al. (C_1) and Kannan et al. (C_2). C_1 had a change in silica fume proportion with steel fiber proportion. The amount of silica fume plays an important role in the strength of RPC.

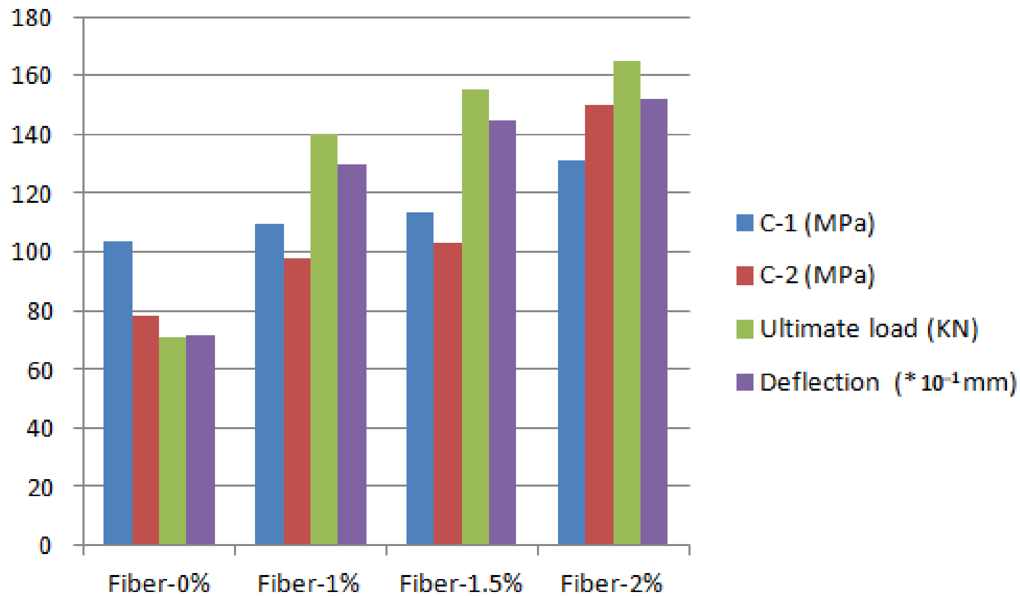

Figure 1: Compressive strength and load-deflection behavior of RPC.

2.1.2 Flexural strength

The flexural strength of concrete was enhanced by the usage of steel fiber [2]. By adding 2% of steel fiber, flexural strength increased by 2.30 times as compared to normal concrete. Ridha et al. found that the ductility of the 2% steel fiber beams was very much higher as compared to zero steel fiber beams. As the steel fibers produce a bridging effect in the concrete, the development and propagation of cracks were reduced to much extend [1]. Ductility was increased by 5.21 times as compared to concrete without fiber.

2.1.3 Modes of failure

RPC beams with steel fiber less than 2% usually undergo diagonal tension failure. When the steel fiber is 1%, the mode of failure was shear compression. This changed to diagonal tension failure when the shear span to depth ratio changed from 2.5 to 4.5 [1]. For 2% steel fiber beams, diagonal cracking load was almost 2 times of normal beams. In 2% steel fiber beams, the variation of proportion of silica fume does not had a major impact on cracking loads. Due to the pinching forces by the randomly oriented steel fibers, higher energy was required for the propagation of cracks. Mode of failure changes from shear failure to flexural failure for RPC tapered beams [10].

It was found that in T beams, as the shear span ratio varies from 1 to 4, the mode of failure was either diagonal compression failure or shear compression failure. RPC had high tensile strength due to the presence of steel fibers [9].

2.1.4 Energy absorption

The steel fiber increased the energy absorption capacity by 25 times of that of conventional RPC. The energy absorption of RPC beams was higher when the steel fiber was limited to 2% along with 30% silica fume. Beams with steel fiber of 2% had energy absorption which was 9 times more as compared to RPC beams without steel fibers. Total energy absorbed decreased by 6.9% for beams with longitudinal reinforcement of 5.9% compared to beams of longitudinal reinforcement 3.4%

2.1.5 Deflection and cracks

The presence of fiber resulted in low deflection at cracking load and high deflection at ultimate load. Deflection of RPC beams with 2% steel fiber was about 2.5 times as that of beams without steel fibers. While considering the deflection at the first cracking, there was no significant difference between the deflection of beams without fibers and beams with 2% steel fibers. Bridging effect of steel fibers helped in the high ultimate load. The ultimate load capacity was high for 2% steel fiber beams. RPC tapered simply supported beams had an increase in deflection by 40% compared to the NC beams.

2.2 Shear strength of RPC

Not much research has been conducted in RPC under shear behavior. Ridha et al [1] conducted an experimental study on the shear strength of the RPC beams. In this study, monotonic loading had been applied on RPC beams to find the behavior under shear. Dial gauge can be used to find out the deflections & strains. Eighteen slender RPC beams were tested in this investigation. Fig-2 shows the RPC beam details. The test parameter included span to depth ratio, longitudinal reinforcement ratio, percentage steel fiber and silica fume.Table-1 shows the material property of RPC mix.

Table -1: Material properties of RPC[1].

Density of fine silica sand (size<0.3mm) (Kg/m³)	Silica fume		Steel fibers	
	Density (Kg/m³)	Specific surface area (m²/g)	Density (Kg/m³)	Tensile strength (MPa)
1000	50–300	21	0–164	2600

2.2.1 Load-deflection behavior

After the formation of diagonal cracks in shear span, sudden failure occurred in RPC beams without steel fibers. The curve was linear until the cracks grow. The load deflection curves initiates with a stable form in linear form. It changed to non linear form disparity slope. After this stage, for a small increase in load, high deflection recurred. When the amount of steel fiber is increased, stiffness of RPC beams was enhanced.

With increasing shear span to depth ratio, deflection at ultimate load decreased. For beams with 2% steel fibers, deflection decreased by 3.1% and 35% when the shear span to depth ratio increased from 3.0 and 4.5. The ductility ratio of beams with 30% silica fume was 26.3% more comparing to beam with 5% silica fume.

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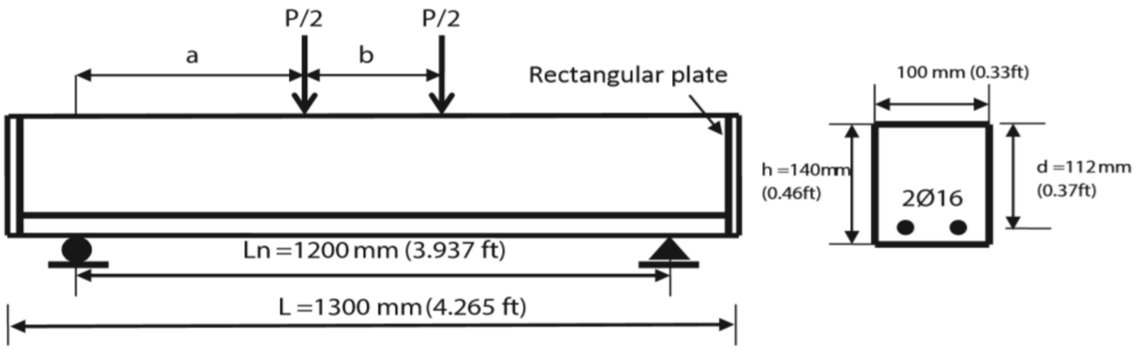

Figure 2: Typical beam for shear test [1].

2.2.2 Proportion of silica fume

Deflection decreased with increase in silica fume content. The bond between RPC matrix and steel fibers increased due to the pozzolanic reaction with silica hydrates. The crack control capability of concrete was enhanced by increasing the silica fume content. Compared to the beams of silica fume content of 5% , beams with 30% silica fume have 33% more deflection at ultimate load. The energy absorption is 72% more for 30% silica fume beams.

2.2.3 Longitudinal reinforcement

As the longitudinal reinforcement increased, deflection decreased due to the prevention of widening of flexural cracks and hence enhancing the crack control capability. The deflection of beam with longitudinal reinforcement of 5.9% reduced by 10.5% at ultimate load. The increase in longitudinal reinforcement led to more deflection at cracking load while it caused less deflection at ultimate load.

2.2.4 Formation of cracks

Steel fibers inhibited the propagation of cracks. With the increase of steel fiber percentage, width of the crack decreased. The bond strength between RPC matrix and the fibers increased with the fiber content and a bridging effect of fiber along the cracks was seen. At the beginning of failure, crack width increased with the increase in longitudinal reinforcement ratio. Crack width decreased with the increase in proportion of silica fume. By the addition of silica fume, presence of pores was considerable reduced. This enhanced the bond strength. The load-crack width curve of beams with 2% steel fibers and 20% silica fume improved compared to beams with silica fume 10%.

In RPC beams, reserve shear capacity was required to resist shear and no web reinforcement was required. As per the design codes, there should be a minimum web reinforcement to ensure the reliability and safety of the structure. Ridha et al considered diagonal cracking load as the shear load. As cracks forms due to shear, a part of load would be carried by the stirrups. RPC beams with no steel fiber had the ultimate load to cracking load ratio of 1.42. RPC with steel fiber had ultimate load to cracking load ratio varying from 1.9 to 3.4. Ozcebe et al found that 30% of shear capacity was reserved and 0.3mm shear crack is allowable [12].

2.2.5 Modes of failure

The mode of failure of beams with 25% and 30% silica fume were shear flexure failure. 5% silica fume beams had shear compression (SC) failure. For beams with 2% steel fibers, maximum crack width at failure increased with high shear span to depth ratio due to the increase in moment. Considering average of all RPC beams, shear strength was about 5.5MPa. In most of the beams, 0.3mm cracks were formed [1]. Fig-3 shows percentage of different modes of failure in the shear test.

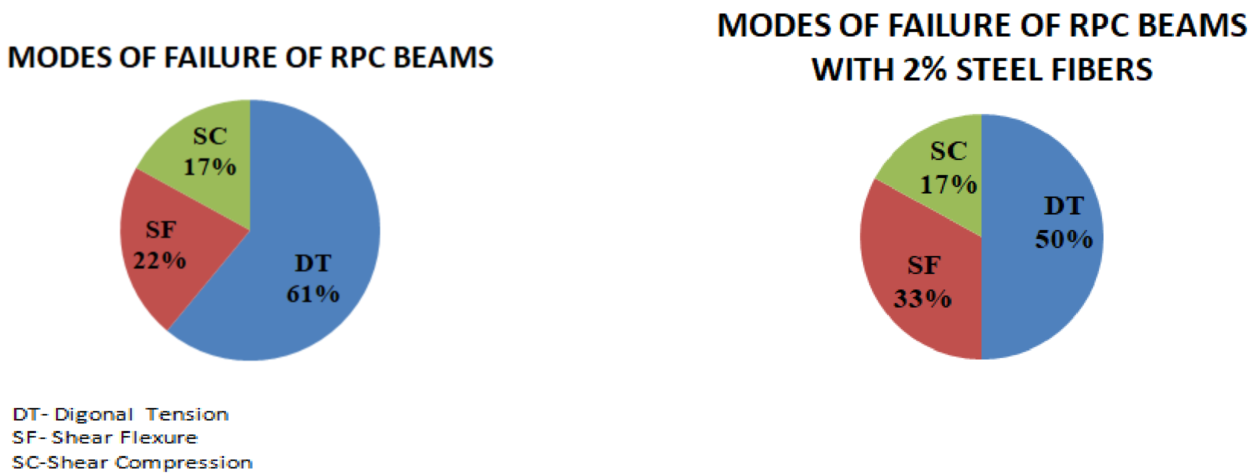

Figure 3: Different modes of failure of RPC beams.

2.2.6 Strains in RPC

As the volume fraction of steel fiber increased, the strains in the concrete decreased completely. The neutral axis changes towards the tension face of the beams due to steel fibers. Tension property of the fibers was the main reason for this shifting of neutral axis. Depth of the tension was also decreased. Increase in longitudinal reinforcement ratio led to minimizing of concrete strains. The shifting of neutral axis towards the tension face with the increase in longitudinal reinforcement caused the reduction in concrete strains. The first cracking load was also higher compared to conventional concrete. Beams with 30% silica fume caused reduction in 28% of concrete strains. Shear resistance of the beam was higher which reduced the concrete strains. With the increase in shear span to depth ratio, tensile and compressive strains increased owing to the increase in applied moment.

2.3 Shear strength of geopolymer concrete

Geopolymer concrete consists of materials which usually contain alumino silicates, fly ash, red mud, blast furnace slag and an alkaline solution also. Mostly fly ash is the material used for preparing geopolymer concrete [5]. Geopolymerization reaction creates strong bond between the materials. Geopolymer binders can be obtained from byproducts of steel and mineral industries. This makes it an eco friendly concrete. Alkali activator solution has a vital role in the higher compressive strength of the concrete. Alkali solutions like sodium silicate with sodium hydroxide can be used with high efficacy. Using different codes shear strength of GPC beams with different shear and flexural reinforcement can be found [13].

It was found that due to the increase in load, stiffness of the specimens decreased [3]. It was noted that the beams had 94% of shear strength and 99% of yield stiffness compared to the conventional beams. This was because of the extension of shear cracks. They found that GPC deep beams with shear span to depth ratio of 1.5 showed better performance. Crack distribution and the mode of failure of GPC beams were almost identical. The shear strength of the GPC beams was not much affected by yield strength of longitudinal reinforcement as the longitudinal bars does not yield.

It was noted from Yacob et al.[4] that parameters like span to depth ratio, shear reinforcement, compressive strength, etc which affects the conventional concrete also influences geopolymer concrete. It was found that

GPC beams showed similar behavior as compared to conventional concrete with same reinforcement in load deflection trait.

Shear test on 18 GPC beams with parameters span to depth ratio, longitudinal bar strength, longitudinal reinforcement ratio and beam depth were conducted. Depth of beams were 300mm or 400mm and width was 200mm [3]. Sand, Fly ash and slag were mixed for 3 minutes. Sodium carbonate was mixed for another 3 minutes. Alkaline solution was added and thoroughly mixed. Standard cubes of 150mm and cylinders of 150mm*300mm were cast. To increase the concrete strength of the specimens, steam curing was implemented in GPC and normal concrete beam specimens and concrete cylinders at 80℃ for 24h. Material properties of reinforcing bars can found using standard tensile tests [3].

2.3.1 Compressive strength

The compressive strength of concrete with longitudinal reinforcement ratio of 2.7% was higher than concrete with reinforcement 1.8%. But the shear strength of beams with longitudinal reinforcement 2.7% is less by 5% compared to the other. The compression zone depth increased as high strength bar is used. This increased the shear strength. The cracking resistance was improved by the use of high beam longitudinal reinforcement ratio. Fig-4 represents comparison of percentage variation of compressive strengths of GPC and conventional concrete [14]. GPC-1 is GPC which was modified in the steps of preparation while GPC-2 was normal GPC.

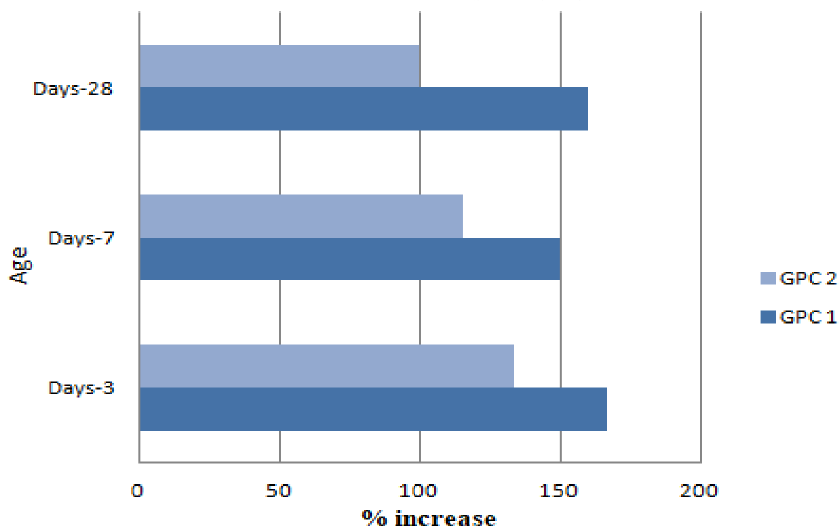

Figure 4: Variation of compressive strength of GPC compared to conventional concrete

2.3.2 Modes of failure and longitudinal reinforcement

Modes of failure include shear compression (SC), diagonal tension (DT), flexural failure (F) and combination of shear compression and flexural failure (SF). Intermediate beams with 2.7% longitudinal reinforcement failed by diagonal tension. Deep beams with 1.8% longitudinal reinforcement fail by shear compression failure. Ordinary beam with 1.8% longitudinal reinforcement deflected more than any beam. Deep beams with normal strength bars of longitudinal reinforcement ratio of 1.8% showed less deflection. As the shear span to depth ratio varied from 2 to 2.4, the mode of failure changed from shear to shear flexural failure mode.

Considering intermediate beams, beams with high strength bars of longitudinal reinforcement ratio of 1.8% had the highest shear strength. Mode of failure of this beam was diagonal tension failure. [3]

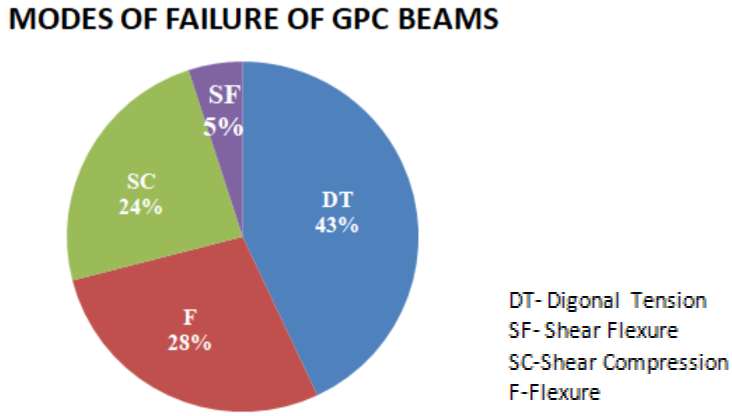

Figure 5: Different modes of failure of GPC.

Figure 5 shows percentage of different modes of failure of GPC beams. Slender beams with 2.7% longitudinal reinforcements with normal bars had the least shear strength. The mode of failure of such beam was diagonal tension. A material is said to be tough if it is able to absorb energy without rupture. A material will be subjected to ductile failure if it has high fracture toughness. Beams failed by shear flexure had larger toughness factor [4].

2.3.3 Shear span to depth ratio

As the shear span to depth ratio varied from 2 to 2.4, the mode of failure changed from shear to shear flexural failure mode. In GPC deep beams with shear span to depth (a/d) ratio of 1.5, shear strength was 80% higher than that of beams with a/d of 2.5. While in intermediate beams, shear strength of beams with a/d of 2.5 was 25% more than slender beams. Owing to the low stiffness in long span of beam, the slender beams had larger deflection at mid span. With a constant stress, the strains increased. Beams failed with shear flexure had less significance of shear deformation in the beam.

2.3.4 Formation of cracks

GPC specimens exhibited smaller number of cracks but had lower load resistance at the allowable maximum crack width compared to conventional concrete. Flexure cracks were formed during the early stage due to the insufficient reinforcement. Diagonal cracks were induced as the load increased due to the increased shear stress. The diagonal crack width was larger than flexural crack width.

2.3.5 Shear strength

Shear strength of GPC beam was higher for beams with small spacing of stirrups and a shear span to depth ratio of 2. The shear strength of the beam was a bit more than that of conventional beam with large spaced stirrups and same span to depth ratio. Beams with high strength bars of longitudinal reinforcement ratio of 1.8% had highest shear strength. The yield stiffness of beams with depth of 400mm was about 1.5 times compared to 300mm depth. Shear strength was more for less shear span to depth ratio. The shear stiffness of the beam was increased by decreasing the spacing between the stirrups [3].

Fig-6 shows the comparison of mechanical properties of RPC, GPC & Conventional concrete (CC). RPC beams had more percentage of compressive strength, flexural strength and shear strength as compared to GPC and CC beams.Percentage variation of strength depicts the percentage variation of the strength of RPC and GPC with respect to conventional concrete.

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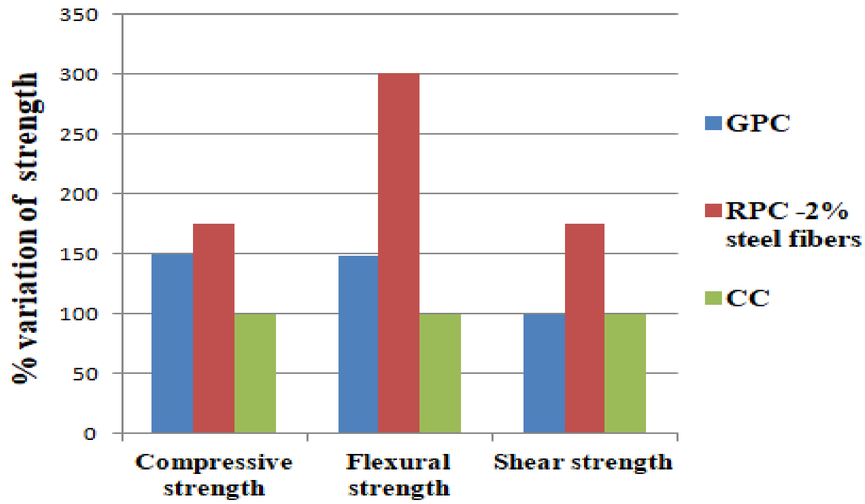

Figure 6: Comparison of RPC and GPC with conventional concrete.

3 Conclusions

The practice of sustainable construction has to be developed as far as the environment is concerned. The impact of the industries on environment has to be reduced. Reactive powder concrete and Geo-polymer concrete are two green concretes which ensure efficiency and sustainability. They can withstand high strength compared to conventional concrete. An attempt has been made to review the effect of steel fibers in RPC and the shear strength of RPC and GPC beams were studied.

1. The stiffness of RPC beams were enhanced due to the addition of steel fibers.RPC beams behaved as a ductile material during failure. Steel fibers reduced the rate of propagation of crack.
2. The ductility and absorbed energy increased with the addition of steel fibers (ductility is 5.21 times of fiberless beams) due to the presence of steel fibers which produced a bridging effect.
3. The increase in content of silica fume resulted in an increase in the diagonal crack load and the ultimate load due to the enhanced particle packing efficiency and bond strength.
4. No shear reinforcement was required in RPC beams which led to diagonal tension failure in most of the beams. Most of RPC and GPC beams failed by diagonal tension mode of failure due to the increase in shear span to depth ratio.
5. RPC beams with 5% silica fume failed by shear compression failure, while GPC beams with high strength bars failed by shear compression due to less shear span to depth ratio and increased shear reinforcement.
6. GPC and RPC exhibited better shear performance as compared to conventional beams. GPC showed similar behavior as conventional concrete in load deflection trait, while RPC with steel fibers showed better performance.
7. Ductility of RPC beams was much higher than GPC beams due to the presence of steel fibers. RPC beams without steel fibers were brittle in nature.
8. Increase in shear span to depth ratio decreased the shear strength of GPC and RPC beams.

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