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Research Article

Properties of steel fiber self-compacting concrete incorporating quarry dust fine powder

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ABSTRACT

Self-compacting concrete (SCC) has great potentials as it offers several environmental, economic and technical benefits. Moreover, the use of fibers extends its possibilities since fibers arrest cracks and retard their propagation. Incorporation of Quarry Dust (QD) in SCC help to reduce environmental hazards during the production of QD. This study evaluated the fresh and hardened properties of steel fiber self-compacting concrete (SFSCC) incorporating QD. The optimum fiber and QD contents with no adverse effects on fresh and hardened properties were determined. A comparative study on behavior of SCC and SFSCC mixtures in terms of workability, compressive strength, compressive strength development ratio, tensile, flexural and energy absorption capacity was carried out. Test results showed that compressive strength increased with increase in QD contents at fixed fiber content by mass of Portland cement (PC) and then decreased. Strength development ratio (C28/C7) for SCC was 1.13, while it was 1.06, 1.08, 1.10 and 1.01 after reinforcing with 0.10, 0.20 and 0.30 contents of fiber. The compressive, tensile, flexural and energy absorption capacity or Toughness of SFSCC increased with the inclusion of the aforementioned contents of steel fiber up to 0.20 % volume of total binder at constant QD content and then decreased when compared with control SCC values. From these results, optimum value for the variables studied was obtained from mix QD_{20} + 0.2fr. Hence, steel fiber and QD could be successfully used in SCC production not minding the slight draw back on workability of SCC caused by inclusion of steel fiber, but with a modified dosage of super-plasticizer (SP), fresh and hardened properties, in accordance with specifications in relevant code(s) can be achieved.

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1. Introduction

Self-compacting concrete (SCC) is concrete that is self-compacted that flows under its own weight through restricted concrete sectional forms without segregation and bleeding. To achieve this, it should have a relatively low yield value to ensure high flow ability, a moderate viscosity to resist segregation and bleeding so as to maintain homogeneity during transportation, placing, curing to ensure adequate structural performance and long term durability. As stated by Alden (2014), SCC can be classified into three types: the powder type, viscosity agent type and the combination type. The powder type SCC is characterized by the large amounts of powder (all material < 0.15) which is usually in the range of 550 to 650 kg/m^3. This provides the plastic viscosity and hence the segregation resistance. The yield point is determined by the addition of SP. Due to the high content of powder, SCC may exhibit more plastic shrinkage of creep than ordinary concrete mixes, however, this can be overcome with the addition of fibers. For the viscosity type SCC, the powder content is lower (350 to 450 kg/m^3). The segregation resistance is mainly controlled by viscosity modifying Admixture (VMA) and the yield point by addition of SP. In the combination type of SCC, the powder content is between 450 to 550 kg/m^3 but in addition, the rheology

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is also influenced by a viscosity modifying agent (VMA) as well as an appropriate dosage of the SP (EFNARC, 2002). Introduced in the late 1980s by Japanese researchers, Nagamato and Ozawa (1997), if well designed ensures a good balance between deformability and stability. This is achieved by careful mix proportioning of the constituents. The use of SCC has/off-set a growing shortage of skilled labuor and has proved beneficial economically due to its advantages such as faster construction, reduction on site manpower, better surface finishes of structural elements, easier placing, improved durability, reduction in noise level and others just to mention but a few. It is obvious that, SCC, being a new type of concrete with two incompatible properties – high flow ability and segregation resistance and with an improved performance still has a draw- back yet to be addressed – weak in tension resistance. To overcome this, utilization of fibers essentially for bridging cracks has attracted the attention of researchers. Parameters such as fiber type, volume content, size, shape and aspect ratio affects properties of SCC and reduce its workability (Poon et al., 2007; Aydin, 2007). Steel fibers have a substantially high strength and high young modulus of elasticity compared with other types of fibers. This may lead to an enhanced flexural rigidity and has great potential for crack control despite its high volumetric density. Also, it is conductive in SCC constituents in terms of reduction in volume ratio of aggregate to cementitious material (Okamura, 1997), increase in paste volume and water–binder ratio, controlling maximum coarse aggregate particle size and the use of viscosity enhancing admixtures such as fly ash, silica fume, Limestone powder and others. These steps taken in conjunction with EFNARC specifications normally yield an acceptable SCC mix. Meyer et al. (1996) and Narayan and Nathan (2009) compared properties of SCC containing QD and that of conventional concrete so as to ascertain their performance which showed SCC with QD having better properties over that for conventional concrete. It is conductive in electric and magnetic fields and thus its content must be reduced to a certain level (Rao and Ravindra, 2010; Grunwald and Walraven, 2001). Their work on the effect of four types of steel at varying contents on the workability of two SCC mixes with and without fibers showed that the flow behavior of fiber reinforced mixtures differs from that of plain SCC. Their observations also indicated that when a homogeneous distribution is achieved with critical fiber content, the formation of its structure of the granular skeleton has a high measure of absorption energy during its deformation.

Toughness is a measure of the ability of the material to absorb energy during the deformation estimated using the area under the stress-strain curve or Load-deflection curve (Balaguru and Shah, 1992; Dawood and Ramli, 2009a). The toughness of plain concrete is low because it cannot absorb more energy without interruption. In other words, toughness is a property that consists of high resistance and ductility. A material that can absorb shaking and shocking without breakdown or failure is said to have a high toughness, unlike plain concrete which is brittle because of its low plastic deformation before failure (Hadian, 1966). Low failure toughness of plain concrete in service is a significant deficiency which can be off-set by the incorporation of discontinuous fiber in the concrete. The main contribution of steel fiber to concrete is observed after matrix cracking. If a proper design is made, after the matrix cracking, randomly distributed, short fiber in the matrix arrest micro cracks, bridge these cracks, undergo a pull-out process and limit crack propagation (Banthia and Trottier, 1995; Kurihara et al., 2000); thus, improving the toughness of the concrete, Nataraja et al. (1999), Banthia and Sappakittipakorn (2007). Dawood and Ramli (2000b) studied the effect of steel fiber on toughness. The study showed that the toughness improves with the increasing content of fiber, the reason being the ability of fiber in arresting cracks at both micro and macro levels. At micro-level, fibers inhibit the initiation of cracks, while at macro-level fiber provide effective bridging and impart sources of toughness and ductility. The concrete brittle behavior is then replaced with a non-brittle fracture behavior related to a post-cracking bearing capacity. So, steel fibers are being increasingly employed in industrial floors, road pavements, tunneling and channels linings among other applications. Di Prisco et al. (2009) stated that one of main reasons for this increasing use of replacing entirely or partially conventional reinforcement in structural applications is due to its benefits such as savings in labour and crack control. The addition of steel fiber as reported by Nataraja et al. (1999), has significantly improved many of the engineering properties of mortar and concrete, notably impact strength and toughness. Flexural strength, fatigue strength, tensile strength and the ability to resist cracking, spalling are also enhanced. The work of Mohammadi et al. (2008) showed the influence of mixed aspect ratio of steel fibers on the fresh and hardened properties of fibrous concrete. Further studies on the use of fibers and pozzolans in SFSCC shows that the parameters influencing compressive strength differs from the one that influences flexural toughness of fibrous concrete.

The fresh and hardened properties of SFSCC aforementioned need to be assessed. European Federation for specialist construction chemicals and concrete system (2002) specified tests and test values to be used in assessing the fresh properties of SCC while relevant codes of practice for testing mechanical properties of concrete are available. These were used to test and obtain values in assessing the fresh and mechanical properties of the SFSCC. Researchers have reported results of investigations on various aspects of SCC and the use of fibers in concrete. Steel fiber used in this study was obtained from worn out tires littered at refuse dumps which is an eye sore. Their disposal is a challenge. Currently, the only means of disposal is by burning which pollutes the air constituting health hazards to all and sundry. The steel wires used as fibers for concrete reinforcement is the framework of a vehicle tire considered as waste but utilized more purposeful thus reducing the health hazard caused by burning them. Furthermore, at Quarry sites, heaps of QD powder can be seen here and there and in most cases end up in landfills. Apart from the heaps being an environmental threat to health, its dumping as landfills is a breach of the ecosystem. To overcome this problem, QD is introduced as a partial replacement of PC in SFSCC. This is an attempt to further reduce cost with less PC used in the study. It is therefore imperative to investigate the fresh as well as hardened properties of SFSCC containing QD powder, highlighting the benefits of SFSCC incorporating QD both in the fresh and hardened states as well as its potentiality as a structural load resisting element. Recent works by researchers to enhance mechanical properties of fiber has attracted attention world- wide; but yet to be extended to SCC. This is not unconnected with the negative effect inclusion of fiber in concrete has on its workability which can be offset using SP. The incorporation of a pozzolana in SFSCC and how it affects its properties is also another perspective to be fully explored. However, it is not clear if SCC blended with QD and steel fiber will behave like plain SCC? Thus, the study evaluated the fresh and mechanical properties of steel fiber (obtained from worn out tires) self-compacting concrete incorporating QD with a view to obtaining optimum content for steel fiber and QD and its effect on the fresh and hardened properties.

2. Materials and Method

2.1. Materials

2.1.1. Cement

Portland cement used in all mixtures is a locally available product of grade 41 N manufactured by Dangote Cement Company Plc Nigeria which conformed to BS EN 196-6; 1997 as tested during the study. Physical properties of PC and QD are shown in Table 1.

Table 1. Properties of cement and quarry dust (QD).

Property	PC	QD
Colour	gray	off-white
Specific gravity	3.15	2.39
Spec surface area (cm^2/g)	3000	4580
Soundness	4.8	
Setting times (mins)		
Initial	161	172
Final	202	230

2.1.2. Steel fiber

Steel fiber used for the study was obtained from worn out tires, circular section, mean diameter of 0.5 mm and cut into length of 20 mm was in four proportions of 0%, 0.1%, 0.2% and 0.3% by mass of binder with an aspect ratio of 40 (Fig. 1). It was optimized by conducting slump flow tests for various mixes in accordance with EFNARC specifications. The SFSCC mix with a volume fraction of steel content and a slump flow with at least 600 mm spread diameter with homogeneous distribution of the fibers was considered as the optimum volume fraction of the steel fiber.

Fig. 1. Steel fibers from worn out tires.

Crushed granite of 10 mm and 19 mm maximum nominal sizes with specific gravity of 2.60 and 2.66 with average fineness modulus of 6.86 was used. Locally available sharp river sand with a specific gravity of 2.39, a fineness modulus of 2.75 with particle size distribution (PSD), (Fig. 2) was used. QD obtained from a local quarry site in Minna, Niger state, Nigeria used for the study was sieved with a 150 μm sieve. A Poly-carboxylic ether (master Glenium ACE 456) based SP which conforms with ASTM C 494, type F was used.

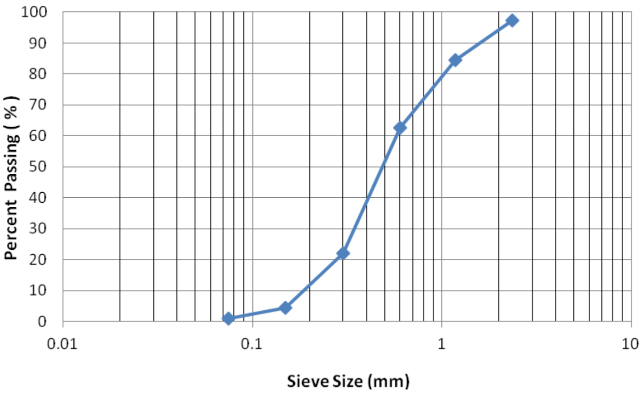

Fig. 2. Particle size distribution for sand.

2.2. Mix proportion

Selection and proportion of SFSCC constituents were based on principles and EFNARC guidelines. Furthermore, the rational approach proposed by Okamura and Ouchi (1998) for mix design was adopted. In other words, solid materials contents and water/binder ratio were fixed while SP dosage was adjusted so as to achieve optimum viscosity and flow ability. Mix proportions for SFSCC containing QD was also based on packing density approach. Maximum packing density was achieved by aggregate blending (19 mm and 10 mm) and the powder phase (PC + QD) using slump flow cone studies in accordance with EFNARC specifications, 2002. A total of nine (9) concrete mixtures were used with cementitious materials content, cement and QD replacement of PC at different levels and the mixes evaluated using slump flow tests. The bulk specific gravity, dry- rodded unit weight (DRUW) of the coarse aggregates blending 30:70 (19 mm and 10 mm) attained in accordance with EFNARC specifications is 1477.33 kg/m^3 and with percentage blending of coarse aggregate is 50.14. Volume of sand used for the study is 42% of mortar volume. A constant W/B ratio of 0.40 was used for all the mixes. Details of mix proportions is as shown in Table 2.

Table 2. Mix proportions.

Mix ID	Total Binder	PC	QD	CA	FA	Water	SP	W/B
SCC	400	400	xx	741	848	160	2.0	0.4
QD$_{10}$+0.1fr	400	360	40	741	848	160	2.2	0.4
QD$_{20}$+0.1fr	400	320	80	741	848	160	2.22	0.4
QD$_{30}$+0..1fr	400	280	120	741	848	160	2.25	0.4
QD10+0.2fr	400	360	40	741	848	160	2.30	0.4
QD20+0.2fr	400	320	80	741	848	160	2.32	0.4
QD30+0.2fr	400	280	120	741	848	160	2.33	0.4
QD10+0.3fr	400	360	40	741	848	160	2.35	0.4
QD20+0.3fr	400	320	80	741	848	160	2.36	0.4
QD30+0.3fr	400	280	120	741	848	160	2.37	0.4

N.B All materials are in kg/m^3 , SP = superplasticizer

2.3. Method

2.3.1. Fresh property tests

The study was conducted in two phases; based on mix proportions (Table 2), each mix constituents were measured and dry-mixed thoroughly. Seventy percent (70%) of water content was gradually added and then mixed for another three minutes. The remaining 30% water content was mixed with SP and gradually added to the mix and the mixing continued for another three minutes leading to the attainment of a homogeneous mix. Fresh property tests such as slump flow, T$_{50}$ and J-Ring were conducted to determine the filling and passing abilities of the mixtures in accordance with ASTM C 642-13 and EFNARC specifications. The slump cone placed on a flat base was filled with fresh SFSCC mix and the excess flushed with a straight edge. The cone was then lifted vertically off the base. The horizontal diameter flow of the fresh mix is a measure of the filling ability of the mix (Fig. 6). The measurement was done twice perpendicular to each other and an average value taken. The test was carried out for each mix. The T$_{50}$ test is the time taken (secs) the SFSCC mix takes to spread horizontally to 500 mm diameter which is a secondary indicator of the flow ability of the mix. For the J–Ring test, the slump cone was filled with fresh SFSCC, and the excess flushed with a straight edge. The cone is vertically lifted out of the J–ring earlier placed on the flat base and the fresh mix flows through the ring which acts as an obstruction to the flow (Fig. 7). The flow spread is also measured twice perpendicular to each other and the average value is a measure of the passing ability of the mix. The test was carried out for each mix.

2.3.2. Tests for hardened properties

On completion of tests for fresh properties, the SFSCC specimens were cast in steel cube mould (100x100x100 mm) for compressive strength test, cylindrical 150x150x150 mm in diameter for splitting tensile strength test and 100x100x500 mm prisms for flexural strength and absorption capacity. The test specimens were de-molded after 24 hours and cured in water for 7, 14, 28, 56 and 70 days respectively and then tested for the aforementioned variables. The tests were conducted in accordance with BS 811, ASTM C 496/C496M -04, ASTM C 293/C293M–10 and ASTM C 1609/C1609M respectively. For the compressive strength test, a compression testing machine of 2000kN capacity was used and each test result was an average of three cube specimens (Fig. 3).

Fig. 3. Compressive strength test.

For the tensile strength test, since it is difficult to determine the tensile strength directly, it was determined indirectly. The cylindrical concrete specimen (150x150 mm) was placed horizontally between the loading surfaces of the compression testing machine (Fig. 4). A compression load, *P* was applied diametrically and uniformly along the length of the cylindrical specimen until failure occurred along the vertical diameter. The tensile strength was determined using Eq. (1).

$$F_t = \frac{2PL}{DL} \tag{1}$$

where F_t is tensile strength, *P* is failure load, *D* is the diameter of cylindrical specimen and *L* is length of cylindrical specimen. The test was conducted in accordance with ASTM C 496 (2011).

Fig. 4. Tensile strength test.

For the flexural strength, when a structural element is subjected to a bending load, its resistance to the bending load is the flexural strength. The prisms were tested under third–point loading gradually to failure (Fig. 5).

Fig. 5. SFSCC prisms tested for flexural strength.

The flexural strength is expressed as the load acting on the cross section of the prism until failure as expressed in Eq. (2).

$$F_r = \frac{PL}{bd^2} \tag{2}$$

where F_r is flexural strength, *P* is failure load, *L* is span, *b* and *d* are width and depth of section of prism. Test result is an average value of two prisms.

SCC reinforced with steel fibers gives it additional ability to absorb larger amount of energy to withstand large deformations prior to failure. The absorbed energy is called its energy absorption capacity of the material or flexural toughness which is represented by the area under the load–deflection curve for a concrete prism subjected to a four–point or three–point loading test. This energy is a reflection to what extent the SFSCC can with stand loading conditions until failure. Sample prisms (100x100x500 mm) cast (2 nos) from each mix, on attainment of curing durations of 28 and 56 days were subjected to a third-point loading test set up for the evaluation of flexural toughness. A load-deflection curve is plotted for each prism and the area under the curve is the flexural toughness. The flexural performance of SFSCC prism incorporating QD was evaluated from the area under each curve in accordance with the works of Low and Beaudoin (1994), Jastrzebski (1997) and ASTM C 1609/C 1609M respectively as shown in Fig. 6.

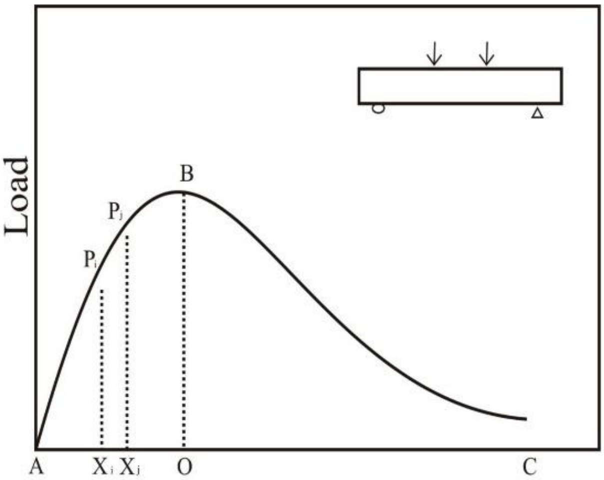

Fig. 6. Theoretical load-deflection curve.

Flexural toughness was determined as the entire area under the load-deflection curve derived from deflections and Loads. It is the sum of all finite area increments over the entire region under the ABC curve, which is work done leading to fracture which represents the flexural toughness of the test specimen. It was determined for each specimen using Eq. (3):

$$T = \sum \frac{[P_i + P_j]}{2} [x_j - x_i] \tag{3}$$

where P_i and P_j are two different loads applied for a finite increment and $[x_j - x_i]$ is the change in deflection within the finite increment, *T* is flexural toughness

3. Test Results and Discussion

3.1. Fresh properties

The results of fresh properties for all the mixes used for the study are shown in Table 3.

From the results in Table 3, slump flow values for SCC and SFSCC differs significantly. The SCC value of 730 mm when compared with that for mix QD10+0.1fr decreased to 722 mm (1.10%). This led to an increase in flow time from 3.72 secs to 3.93 secs (6.18%). For mix (QD10+0.2fr compared with control value experienced a flow spread decrease of 1.18%. This also led to a flow time increase of 8.87%. The trend continued with the rest mixes when compared with control values. This indicates that the addition of steel fiber and QD decreased workability of SFSCC (filling and passing ability). It is an established fact that fibers reduce workability and with the addition of QD with high specific surface area (Blaine value=4580), Table 1 compared with that for cement (3000) absorbs large amount of water on the surface of the particles which produced negative effect on flow ability of fresh SFSCC. Results of J-Ring spread flow and T_{50} for J–ring spread flow also followed the same trend with that of the slump flow spread. All the mixes except QD30+0.3fr met EFNARC and Brite EuRAM specifications. The result has shown that for SFSCC mixes, QD and steel fiber additions to SCC resulting to a decrease of flow spread greater than 25% of control value and an increase in flow time of at least 50% of control value does not meet EFNARC and Brite-EuRAM specifications.

Table 3. Slump flow, J-Ring and T_{50} test results.

S/no	Mix ID	% Decrease in SF	Slump flow (mm)	T_{50} (secs)
1	SCC		730	3.72
2	QD10 + 0.1fr	(1.11)	722	3.95
3	QD20 + 0.1fr	(1.18)	721.50	4.05
4	QD30 + 0.1fr	(1.28)	720.80	4.42
5	QD10 + 0.2fr	(2.10)	715	4.80
6	QD20 + 0.2fr	(2.96)	709	5.21
7	QD30 + 0.2fr	(13.71)	642	6.85
8	QD10 + 0.3fr	(21.67)	600	8.76
9	QD20 + 0.3fr	(26.30)	578	10.52
10	QD30 + 0.3fr	(47.47)	490	12.85

Fig. 7. J–Ring flow spread.

Fig. 8. Slump flow spread.

3.2. Hardened properties

3.2.1. Compressive strength

The compressive strength for 7, 14, 28, 56 and 70 days for all mixes are shown in Table 4.

It can be observed that there is increase in compressive strength for all mixes with increase in age of curing. However, when control mix values are compared with other mixes for 7 and 14 days, compressive strength of SCC is higher than that of other mixes. This is because strength development is mainly due to PC hydration.

Also, for mixes other than SCC, PC content is lower because it has been replaced with QD thereby lowering its mineral content such as C_3S responsible for faster hydration. But at 28 days, the compressive strength of other mixes picks up, equals or even surpasses the control values. This is due to the fact that in addition to PC hydration, the QD which replaced part of PC reacts with calcium Hydroxide ($Ca(OH)_2$), a by- product from the Pc hydration to form more Calcium silicate hydrate which accounts for the increase in strength. The results also indicates that compressive strength increased with increase in QD replacement level of PC up to 20% by mass of PC and addition of steel fiber up to 0.20% by mass of PC and then decreased for all curing ages and for all mixes. The highest strength development occurred at 20 % replacement level and thereafter decreased. This is because at 0 to 20% replacement level, more hydration products are formed as hydration continues leading to the formation of more cementing materials like C-S-H and C-S-A-H hydrates which give rise to increase in compressive strength for all the mixes (Taha et al., 1981). However, at 30 % replacement level, there is more QD volume content and less $Ca(OH)_2$; which reduce pH level of the solution and hinders further hydration, leading to reduction in strength. This is called the dilution effect. Also, with high content of QD and its high specific surface area, will require more water but since water binder ratio is constant, there is less water for hydration which leads to less hydration and decrease in strength. Furthermore, at the 30% replacement level, there is high fiber content, non-uniform distribution, balling and high specific surface area leading to interference in strength development. Optimum fiber content of 0.20fr by volume had already being attained at mix design process.

Table 4. Compressive strength for mixes.

Age (Days)	7	14	28	56	70
mix ID	Compressive strength (N/mm^2)				
SCC	19,87	20.52	24.78	25.86	30.63
QD10+0.1fr	17.95	19.42	24.98	26.38	30.83
QD20+0.1fr	18.67	20.71	24.93	29.80	31.14
QD30+0.1fr	16.93	17.13	23.02	23.75	24.48
QD10+0.2fr	18.24	19.46	24.57	25.02	26.53
QD20+0.2fr	19.19	20.22	24.95	26.12	36.78
QD30+0.2fr	16.93	17.13	21.02	23.75	24.48
QD10+0.3fr	15.72	16.44	20.49	22.11	23.62
QD20+0.3fr	15.58	16.01	19.51	21.48	22.49
QD30+0.3fr	15.25	16.72	20.88	21.88	23.72

3.2.2. Strength development – fiber content relationship

A comparison between strength development with time was examined so as to establish if steel fiber content enhances strength gain. The effect of fiber content on the maturity of SFSCC could be traced through the rate of strength gain. Fig. 9 shows the strength gain ratios for all the mixes in terms of fiber content. Strength development for SCC was 1.03 for C14/C7 and became 1.08, 1.10, 1.06 and 1.01 after reinforcing with steel fiber content of 0.1, 0.20 and 0.30 respectively. Compared with SCC value (1.03), the strength development values for SFSCC increased to a maximum and then decreased after attainment of optimum fiber content. This is the effect of fiber used. The same trend can be seen for series C28/C7, C56/C7 and C70/C7. It can be deduced that the tested SFSCC mixtures with different constituents did not show a pronounced negative effect on the maturity of concrete but rather led to higher strength gain. The same contribution to strength gain by steel fiber content for the mixes can be observed in Table 4.

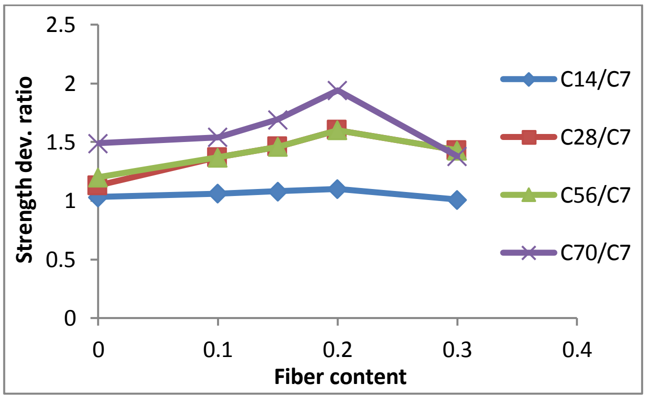

Fig. 9. Strength development ratio against fiber content.

The tensile strength of QD blended SFSCC is in Table 5. The results followed the same trend with that of compressive strength. This is because tensile strength is closely related to compressive strength and there is a theoretical relationship between them already established in literature.

Table 5. Tensile strength test results.

Age (Days)	7	14	28	56	70
mix ID	Tensile strength (N/mm^2)				
SCC	2.80	2.94	3.09	3.20	3.98
QD$_{10}$+0.1fr	2.68	2.82	3.25	3.58	3.95
QD20+0.1fr	2.69	2.86	3.37	3.60	3.85
QD30+0.1fr	2.70	2.76	3.32	3.46	3.79
QD10+0.2fr	3.34	3.92	3.95	4.50	4.55
QD20+0.2fr	3.47	3.82	3.98	4.83	4.97
QD30+0.2fr	3.30	3.72	3.81	4.01	4.12
QD10+0.3fr	2.89	2.99	3.61	3.69	3.72
QD20+0.3fr	2.74	2.88	3.71	3.76	3.80
QD30+0.3fr	2.88	3.01	3.72	3.85	3.88

3.2.3. Flexural strength

Table 6 below shows the results of the flexural strength of the tested prisms. Trend in the result values is similar to that for tensile and compressive strength values aforementioned.

When the values of other mixes are compared with SCC values, they increase marginally with age of curing; For example, QD10+0.1fr increased by 0.77% at 28 days and 0.66% at 56 days and for QD20+0.2fr, there was an increase of 32% at 28 days and 32.34% at 56 days which is the optimum. These changes are due to same reasons given earlier for compressive strength values.

3.2.4. Energy absorption capacity

The load–deflection response of the miniature beams (prisms) tested for energy absorption capacity is as shown in Figs. 10-12.

Table 6. Flexural strength for mixes.

Age (Days)	28	56
mix ID	Flexural strength (N/mm^2)	
SCC	9.06	9.10
QD10+0.1fr	9.13	9.16
QD20+0.1fr	9.22	9.35
QD30+0.1fr	9.12	9.16
QD10+0.2fr	10.25	10.35
QD20+0.2fr	13.30	13.39
QD30+0.2fr	12.07	12.32
QD10+0.3fr	10.12	10.19
QD20+0.3fr	9.42	9.78
QD30+0.3fr	9.12	9.25

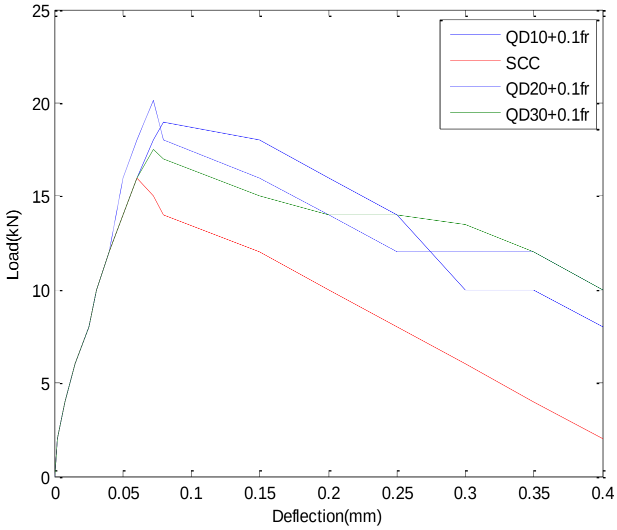

Fig. 10. Load-deflection response for prisms (SCC, QD10+0.1fr, QD20+0.1fr and QD30+0.1fr).

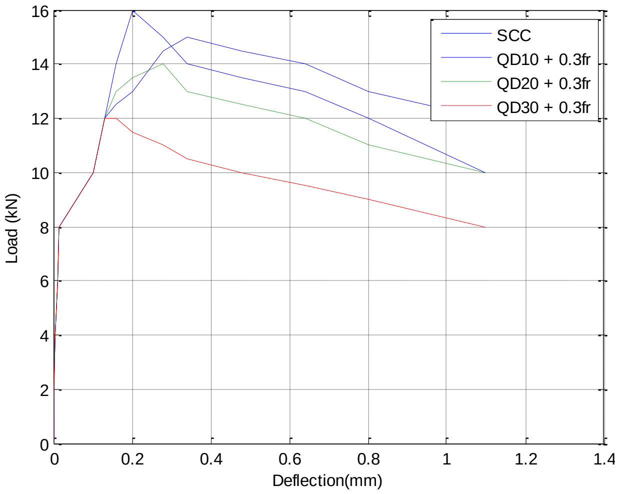

Fig. 11. Load-deflection response for prisms (SCC, QD10+0.3fr, QD20+0.3fr and QD30+0.3fr).

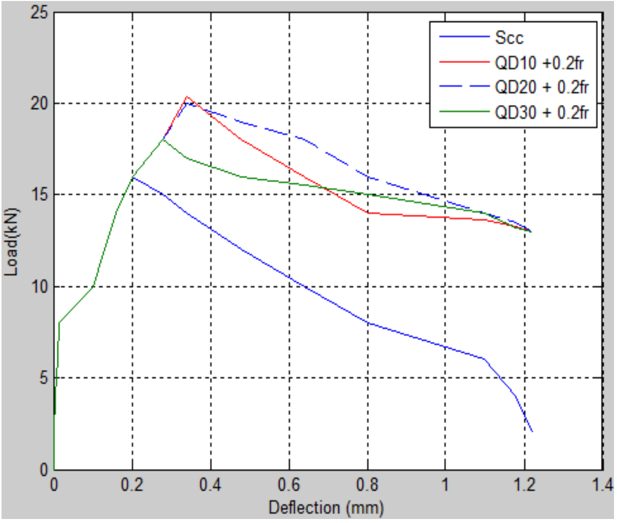

Fig. 12. Load-deflection response for prisms (SCC, QD10+0.2fr, QD20+0.2fr and QD30+0.2fr).

The flexural absorption capacity for each prism was calculated from their Load-deflection curves using Eq. (3) derived from Fig. 5 as stated in the works of Low and Beaudion (1994), and Jasttrzeski (1997). These values are provided in Table 7.

Table 7. Flexural absorption capacity (T_f).

mix ID	Flexural absorption capacity (Nmm)
SCC	9.06
QD10+0.1fr	9.13
QD20+0.1fr	9.22
QD30+0.1fr	9.12
QD10+0.2fr	10.25
QD20+0.2fr	13.30
QD30+0.2fr	12.07
QD10+0.3fr	10.12
QD20+0.3fr	9.42
QD30+0.3fr	9.12

From Table 7, the energy absorption capacity, (T_f), for SCC is 3231 Nmm due to its low tensile strength and strain capacity. The SCC prism failed immediately on attainment of load capacity. Prisms of other mixes also failed abruptly, though, after an appreciable increase in load. None of the prisms failed in a ductile manner. Compared with the values of other mixes indicated an increase in T_f (enhanced by addition of steel fiber and QD) of 34% for Mix QD10+0.1fr, 38% for QD20+0.1fr and 35% for QD30+0.1fr. For Mixes with constant 0.2% fiber content and a stepwise increase of 10% QD up to 30%, increased by 81%, 85% and 77% while for mixes with 0.3% constant fiber content with stepwise increase 10% QD up to 30 %, increased in T_f by 76%, 73% and 69% respectively. In the same vein, at constant contents of QD and varying percentage fiber contents, similar results for T_f were obtained for all the mixes, with Mix QD20+0.2fr again attaining the highest percentage increase (85%) in T_f . Changes in the mixes giving rise to increase in T_f can be attributed to nucleating action and pozzolanic reactions of QD on one hand and the bridging ability of steel fibers which delay crack occurrence on the other hand; and for the decrease in T_f in some mixes can also be attributed to dilution effect of QD, balling, non-uniform distribution and poor orientation of the steel fibers (Altun et al., 2007).

4. Conclusions

SCC concrete with slump flow of 730 mm, SFSCC mixtures containing QD with varying slump flow with a constant w/b ratio of (0.40), slightly modified SP content with cement content 280 to 400 kg/m^3 was studied. Results and discussion of the study indicated that:

- Proportioning of constituents of SFSCC containing QD and steel fiber led to the development of SFSCC with high fresh and hardened properties. The inclusion of steel fibers slightly affected the fresh properties as evidenced in the values measured for both filling and passing abilities of SFSCC (Table 3).
- Compressive strength of SFSCC increased with increase in fiber content up 0.20% and then decreased. This is further strengthened as evidenced in the strength development – fiber content relationship.
- The inclusion of steel fibers enhanced the mechanical behavior of SFSCC as it improved the compressive strength which ranged from 1 to 10% at 14 days, 18 to 22% at 28 days, 5 to 16% at 56 days and 5 to 29% at 70 days with varying contents of steel fiber.
- Inclusion of QD improved the strength of SFSCC especially for values at latter ages (28 to 70 days thus contributing to reduction in cost of cement.
- There was no indication of a pronounced negative effect on maturity of concrete from the tested SFSCC mixtures, but rather led to a higher strength gain. The strength development factor for control mixture was 1.13 for C14/C7, and decreased to 1.06, 1.08, 1.10 and 1.01 after being reinforced with 0.10, 0.20 and 0.30 contents of fiber. It improved and ranged between 1.37 to 1.43 and 1.54 to 1.69 for C56/C7 and C70/C7 respectively.
- In the production of SCC mixtures beside steel fiber, the use of QD extends their technical and environmental benefits as it minimized air pollution and health hazards resulting from its production.
- Optimum mix obtained from the study is QD20+0.2fr which yielded highest percentage increase in nearly all the variables studied.
- Flexural energy absorption capacity, T_f, increased from 34% to 85% of SCC.
- The study was carried out at a constant w/b ratio (0.40) with a modified SP dosage, without considering effect of fiber orientation and even distribution. Further investigation is required to consider effect of aforementioned variables on the behavior of SFSCC incorporating QD.

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