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RESEARCH ARTICLE

Effect of Fly Ash on Properties of Self-Compacting High Strength Lightweight Concrete

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Abstract
As known, fillers directly affect the properties of self-compacting concrete. Fly ash is one of the common fillers used in production of SCC. Using lightweight concrete is extremely important for reducing the self-weight of structures, especially in heavy ones, like high rise buildings. It enables to decrease additional loads in case of renovation or/strengthening of existing structures. Moreover, self-compaction avoids using vibrations for compaction of concrete in existing structures. Therefore the present study is aimed at investigating the effect of change in fly ash content on the properties of self-compacting lightweight concrete (SCLWC). For this reason slump flow test, J-Ring test, L-Box test and V-funnel test were conducted to find workability of the fresh concrete mixture. Further compressive strength, splitting tensile strength, modulus of elasticity and flexural strength of the hardened concrete were obtained. Three concrete mixes of SCLWC with different fly ash contents were prepared to find the best workability and hardened concrete properties. The results of this study form a basis for proportioning of effective concrete mixtures suitable for repairing existing structures and elements.

Keywords
self-compacting concrete, lightweight concrete, superplasticizer, coarse aggregate, fine aggregate

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1 Introduction

As known, self-compacting concrete (SCC) is highly flowable, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation. It doesn't require any vibration for compaction and can flow through narrow spaces without segregation and excessive bleeding [1]. Therefore SCC is one of the greatest innovations of concrete technology. It was introduced in construction industry in early 1990s. Similar to the normal vibrated concrete (NVC), SCC mixtures consist of aggregate, cement, water, admixtures and some mineral additions. Unlike NVC, SCC has high quantity of fillers (eg. silica fume, fly ash, limestone powder etc.) and superplasticizer (high-range water reducing admixture) added to improve its flowing property.

As SCC flows under its own weight without or very little use of vibration, it results in saving a lot of labor effort and bring economy to the concreting. Moreover, it can also flow through narrow and complex geometries where the use of vibrator is almost impossible.

Use of SCC in construction industry is getting more and more popularity all over the world because of inherited advantages and studies on its hardened properties. SCC can be classified mainly into 3 different types [2]:

- powder type;
- viscosity type and
- combination type

The first type has a high amount of powder (all material <0.15 mm) ranging from 550–650 kg/m^3, which provides the plastic viscosity and thus resistance to segregation whereas the yield point is determined by the addition of suitable superplasticizers. In the second type there is less powder content ranging from 350–450 kg/m^3. In this type additional minerals or fillers are not used for segregation resistance. An admixture called viscosity modifying agent (VMA) is used to control the segregation, while yield point is controlled by the superplasticizer. The third type has a powder content of 450–550 kg/m^3, but additionally rheology is controlled by the use of appropriate dosage of VMA and superplasticizer.

As it is mentioned above, SCC is a high workable concrete which flows and compacts under its own weight. Workability is either defined qualitatively as the ease of placement of concrete or quantitatively by rheological parameters [3]. The fresh state properties of SCC are often found with the use of rheometers to determine the viscosity and yield strength when the concrete is in plastic state [4]. Following the available experimental data, the type and amount of powder content in SCC effects its properties. It is known that fly ash reduces the amount of superplasticizer required to achieve the desired slump flow in cement based concrete as Gesoglu et.al. while studying the fresh and hardened properties of self-compacting concrete concluded that use of fly ash greatly reduces the amount of superplasticizer required [5]. Using a blend of different fillers like fly ash, lime stone powder or other type of natural pozzolanic materials improves the overall performance of SCC like flow, strength, microstructure, relative water absorption and early volume stability [6, 7].

The use of fly ash in SCC improves the concrete resistance to segregation and bleeding and increases the filling and passing properties [8]. A study focused on investigating the influence of various fly ash contents on hardened properties of SCC [9] reports that increase in fly ash yields a decrease in early flexural strength at 7 days and 28 days however, overall there is an improvement in flexural strength at 90 days while rheological properties are improved with increase in fly ash percentage. Use of high fly ash volumes improves the workability but decrease the SCC strength [10].

Numerous studies have also been conducted to study the compressive strength of SCC. To achieve high fluidity and stability (low yield stress along with moderate plastic viscosity), high proportion of powder (cement and fillers) at relatively low water/cement ratio is used incorporating high range water reducers (super plasticizers) and in some cases VMA as well. The type and composition of fillers have more effect on compressive strength of SCC than the water/cement ratio [11].

In a study [12] conducted to investigate the hardened properties of SCC, it was found that the compressive strength of SCC compared to NVC is greater at same water-cement ration whereas the modulus of elasticity of SCC is slightly lower than that of NVC.

The effect of cement replacement by fly ash (FA) and silica fumes (SF) on compressive strength of SCC was also investigated [13]. It was found that as higher is the FA content replacing cement, the concrete strength increases and the maximum value is achieved at 30% cement replacement.

Behaviour of concrete with steel fibers in SCC and NVC was studied [14]. It was found that the bond behaviour of steel fibers embedded in SCC is better that those embedded in NVC. In another study [15] it was found that, in serviceability limit state, the bond strength of SCC is higher than normal concrete where as in ultimate limit state, it is about 15% lower.

The absence of cracks is very important for maintaining the continuity of structures and preventing the reinforcements from corrosion. Cracking problem occurs when diagonal tension arises from shear stress development [16]. Thus study of tensile strength is very important in predicting the cracking behavior of structures in its design. It is known that increasing the w/c ratio from 0.35 to 0.7 in SCC, decreases the tensile strength of concrete by about 51% [17].

Filho et al. [18] investigated the hardened properties of SCC. They found that similar to the NVC, modulus of elasticity for SCC is also sensitive to paste and gravel content. For a given compressive strength of SCC, modulus of elasticity increased with the increase in maximum aggregate size and volume of coarse aggregate.

Research has been carried out to study self-compacting high strength concrete. Bogas et.al produced self-compacting lightweight concrete with compressive strengths of 37.4 MPa and 60.8 MPa. They noticed that, with water to powder ratio of 0.8 or less, the deformation velocity of concrete is too low which makes its application inappropriate [19].

Dvorkin et al. used mathematical modelling for design of self-compacting high strength concrete with metakaolin admixture [20]. It was reported that optimal concrete composition can be proportioned by applying experimental and traditional formulas. It was also shown that lower concrete cost is provided when polycarboxylate superplasticizer is used because in that case the required concrete compressive strength and metakaolin efficiency is achieved at lower dosages of the most expensive concrete components. Recent studies demonstrate that using ground granulated blast furnace slag as cement replacement ranging from 20% to 80% replacement, self-compacting concrete with strength of 30-100 MPa could be produced [21].

For use of SCC in structural purposes, hardened properties needed to be studied in detail. A number of studies have been conducted in recent years to investigate these properties [5, 8, 11, 13]. Some similar studies have already been carried out in recent years to study the properties of SCLWC. In a study [19] conducted on SCLWC, using different lightweight aggregates in conjunction with natural sand and fly ash as the filler material replacing cement in different amounts, SCC with slump flow of around 700mm, density of around 2000 kg/m^3 and compressive strength of 60MPa were produced, however there is no data available on the splitting tensile strength and flexural strength of hardened concrete, which is one of the main focus of this study. In another study [22] SCLWC with density of around 1900kg/m^3 and slump flow of above 600mm were produced. They used natural coarse and fine aggregate using different replacement contents of aggregates by expanded polystyrene and using silica fume as a filler material, however there is no data available on the hardened properties of produced concrete. Choi et al. [23] conducted research on fluidity and mechanical properties of high-strength lightweight self-compacting concrete. They used different proportion of natural coarse, natural fine, light-weight coarse and light-weight fine aggregate to produce concrete with density of above 2000 kg/m^3, compressive strength of above 40MPa and slump flow of above 600mm but there is still no investigation on the flexural strength of concrete. Most of these researches produced SCLWC with slump flow of above 600mm and concrete density of around 2000 kg/m^3 or more using the combination of natural and lightweight aggregates. As the aim of this study is to develop a mix design which will be developed further by addition of steel fibers, to be used as strengthening material in existing structures. So to reduce additional load of strengthening material on existing structures to minimum level, it is intended to reduce the density of concrete further more with considerably high strength and very good self-compaction which will be affected by addition of fibers to it. Thus, the study is aimed at reducing the density of concrete to at least less that 1800 kg/m^3, with compressive strength of more than 50MPa and slump flow of considerably higher than 700mm. For the purpose of reducing the density to this level, only light weight coarse and fine aggregates are used with no addition of natural aggregates or sand.

2 Research Aims, Scope and Novelty

Hardened properties included in this research study are compressive strength, tensile strength, modulus of elasticity, bond behaviour with steel etc.

The objectives of this study are as under:

- development of SCLWC with slump flow of more than 700mm, 28 days cylinder compressive strength of more than 50 MPa and concrete density of less than 1800 kg/m^3.
- effect of change in FA content in SCLWC on fresh state properties i.e. workability, air content and fresh state density.
- effect of change in FA content on hardened properties i.e. compressive strength, split tensile strength, modulus of elasticity and flexural strength of SCLWC.

In this study, the powder type SCC is studied because it is further intended to be used with fibers, so to improve internal transition zone (ITZ), more fines are used. The powder content ranges from 560 to 610 kg/m^3. Trial mixes were performed to select the minimum powder content to produce SCLWC, which came out to be close to 100 kg/m^3, therefore the quantity was fixed at 100 kg/m^3 for the base mix. This quantity of fly ash was then increased by 25 kg/m^3 for two subsequent mixes replacing the lightweight fine aggregate keeping quantity of all the other ingredients constant to study the change in concrete properties and on the basis of the results, select the most optimum quantity of fly ash. As the powder consists of cement and fly ash, cement content is kept constant at 460 kg/m^3 whereas the fly ash was kept at 100, 125 and 150 kg/m^3 of concrete, denoted as SCLWC100, SCLWC125 and SCLWC150, respectively.

3 Methodology

The fresh state properties studied in this research are the workability, air content and the mix density. Slump flow test, J-Ring test, L box test and funnel tests are conducted to find the workability of concrete. The concrete density was found by filling a cylinder of known volume and weighing it, while air content was calculated using the actual density (A) and theoretical density (T) of the concrete considering air content of 0 % as per ASTM C138/C138M. The hardened properties included compressive strength, splitting tensile strength, modulus of elasticity and the flexural strength of the concrete. The ASTM procedures are followed for testing of all the properties under consideration. The tests used to determine the workability of concrete are slump flow test, J-Ring test, Funnel test and L box test. 3 cylinders with a diameter of 100 mm and 200 mm height each were casted to test the compressive strength, splitting tensile strength and modulus of elasticity. 3 small scale beams with dimensions 80 × 80 × 400 mm each were casted to test the flexural strength of each concrete type using third point loading test.

4 Materials

Expanded clay lightweight round coarse aggregate (CA) and crushed fine aggregate (FA) as shown in Fig. 1 were used for all the concrete mixes.

Fig. 1 Lightweight fine and coarse aggregate

Laboratory tests were conducted to find the properties of the aggregates like specific gravity and water absorption of the which are presented in Table 1.

Table 1 Aggregate properties

Material	Size (mm)	Specific gravity	Water absorption(%)
Coarse aggregate	4-8	1.45	8.2
Fine aggregate	0-4	1.55	18.5

Portland cement CEM-I 42.5R produced by LAFARGE was used and fly ash was added as the only filler. Polycarboxylatether based superplasticizer produced by BASF was used as high range water reducing agent. The properties are shown in Table 2.

Table 2 Binders and admixture properties

Material	Type	Specific gravity
Cement	CEM-I 42.5R	3.15
Fly ash	Class F	2.08
Superplasticizer	Glenium ACE 391 (FM)	1.07

5 Concrete Mix Design

A powder type SCLWC was developed for this research study. The water cement ratio was kept constant at 0.4. Trial mixes were performed to finalize the mix design for the SCLWC with desired fresh state properties and optimum dosage of superplasticizer, which was considered as the reference mix design. Fly ash was increased in two subsequent mixes to study the change in fresh and hardened properties. The compositions of all the three types of concrete mixtures are given in Table 3.

Table 3 Concrete mix composition

Concrete type	Quantities (kg/m^3 of concrete)					
	Cement	Fly ash	Super plasticizer	CA	FA	Water
SCLWC100	460	100	12	303	540	269
SCLWC125	460	125	12	303	520	269
SCLWC150	460	150	12	303	500	269

6 Experimental Program

6.1 Fresh mix properties

To assess the workability of each concrete slump flow test, J-Ring test, L box test and funnel tests were performed as per EFNARC [24]. The air content and the fresh concrete density were obtained according to the ASTM provisions [25].

6.2 Hardened concrete properties

The hardened properties studied in this study are compressive strength (CS), splitting tensile strength (STS), modulus of elasticity (E) and flexural strength (FS). 12 cylinders with diameter 100 mm and height of 200 mm were casted for each concrete type. Curing of all samples and their testing was performed according to the ASTM standard [26]. 6 cylinders were used for testing the compressive strength, 3 cylinders were tested at concrete age of 7 days to obtain the early strength gain and the other, 3 at 28 days for comparison among the concrete types as per ASTM standards [27].

3 cylinders were tested for splitting tensile strength and modulus of elasticity at 28 days as per ASTM standards [28, 29]. The flexural strength was obtained by testing 3 small scale 80 mm × 80 mm × 400 mm beams for each type of concrete. These beams were tested at 28 days in third point loading test as per ASTM standard [30]. Clear span was kept constant at 240 mm and load applied at 80 mm from both supports. Fig. 2 represents the arrangement for flexural strength test.

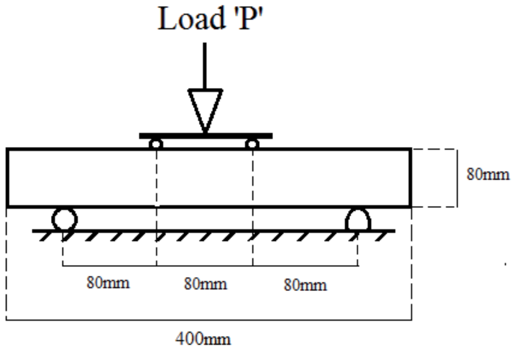

Fig. 2 Flexural strength test arrangement

7 Results and Discussion

7.1 Fresh mix properties

Table 4 represents the relation between the fresh concrete density and the air content. It is evident from this table that as the air content reduces, the fresh concrete density increases. The second factor that can cause an increase in fresh concrete density is replacement of lightweight fine aggregate by relatively heavy weight fly ash. As it is evident from Table 3, once the quantity of relatively lightweight fly ash is increased by 25 kg, it replaces 20 kg of fine aggregate having same volume. So increase in concrete density is around 5 kg/m^3, although it is not significant.

Table 4 Change of air content with concrete density

Concrete type	Air content (%)	Fresh state density (kg/m^3)
SCLWC100	3.93	1709
SCLWC125	2.28	1741
SCLWC150	2.22	1744

The fresh state properties of the three concrete mixes that were used in the present study are shown in Table 5. As it follows from this table, concrete workability is slightly reduced from fly ash content of 100 kg to 125 kg but increases again once the content is increased to 150 kg. However the change in workability is very slight.

Table 5 Fresh state concrete properties

Concrete type	Slump flow according to EFNARC (mm)	V-funnel time (sec)	Passing Ability
SCLWC100	795	13	0.94
SCLWC125	785	14	0.93
SCLWC150	805	12	0.97

According to EFNARC [22], the slump flow values are 550–650 mm, 660–750 mm and 760–850 mm for Slump flow classes 1 2 and 3 SCC, respectively. As per viscosity classes of this standard, viscosity class 1 SCC has T500 value of ≤ 2 sec, while V funnel time is ≤ 8 whereas for viscosity class 2 SCC, T500 is >2 and V funnel time ranges from 9 to 25 sec. According to this standard, once the value of h2/h1 in L box test is greater than 0.8, the SCC has good passing ability. Considering the test results of this research study, the SCLWC under consideration lie in slump flow class 3 and viscosity class 2 SCC have very good passing ability.

Wu et al. [31] studied the workability of self-compacting lightweight concrete. They used fly ash as the only filler for production of SCLWC and cement ranging from 400–425 kg/m^3 of the concrete mixture. The obtained slump flow values ranged from 760 to 800 mm, which is quite similar to the results of this study (Table 3). V funnel time according to ranges from 18 to 24sec, which is considerably higher compared to the values that were obtained in the present study while the available h2/h1 values from the L box test ranges from 0.85 to 0.95, which is slightly on lower side compared to current study results. So we can safely assume that the SCLWC obtained in this study have very good self-compaction as well as passing ability.

7.2 Hardened Concrete Properties

The results for hardened concrete properties at 28 days are summarized in Table 6.

Table 6 Hardened concrete properties

Concrete Type	CS (MPa)	STS (MPa)	E (MPa)	FS (MPa)	Density (kg/m^3)
SCLWC100	59.4	3.14	17,235	3.35	1678
SCLWC125	67.4	3.95	17,332	3.68	1699
SCLWC150	64.4	3.93	17,302	3.05	1703

7.2.1 Compressive Strength (CS)

As it can be seen from Table 6, there is an increase in concrete compressive strength once the quantity of fly ash is increased from 100 kg/m^3 to 125 kg/m^3, but strength decreases slightly once the quantity is further increased above 125 kg/m^3 to 150 kg/m^3. This effect is evident at 7 and 28 days. There is comparatively higher increase in compressive strength of concrete, around 8 MPa with slight increase of density from 1678 kg/m^3 to 1699 kg/m^3 The reason of increase in CS may be the most optimum quantity of fly ash needed to fill in the pours within the concrete structure. As the fly ash is not too heavy with specific gravity of 2.07, there is not significant increase in the density of concrete. This may be further investigated by studying the concrete structure on microscopic level to come up with the final conclusion. The relation between the compressive strengths of the investigated three type of concretes at 7 days and at 28 days is represented graphically in Fig. 3. It should be noted that the two lines are almost parallel, which means that the trend of change in concretes compressive strength with change in fly ash content, is similar at both 7 days and 28 days with maximum compressive strength achieved by SCLWC125.

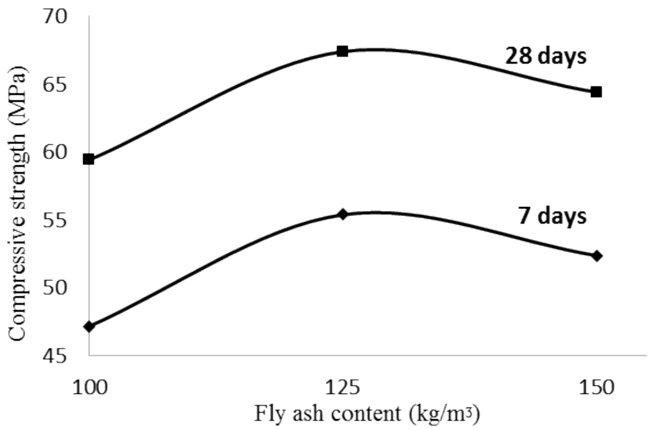

Fig. 3 Change of concrete compressive strength with fly ash content

7.2.2 Splitting Tensile strength (STS)

Test results of splitting tensile strength are summarized in Table 6. Similar relation to that of compressive strength is visible in this case as well, but the strength of SCLWC125 and SCLWC150 is very close with slight decrease in strength. Result shows that SCLWC125 has the maximum splitting tensile strength as well, with strength quite close to SCLWC150 but significantly higher than SCLWC100 as represented graphically in Fig. 4. As the behaviour of concrete in splitting tensile strength test is similar to that of compressive strength tests, the change in splitting tensile strength of concrete may be attributed to the change in compressive strength having direct relation as compressive strength increases to increase the splitting tensile strength of concrete.

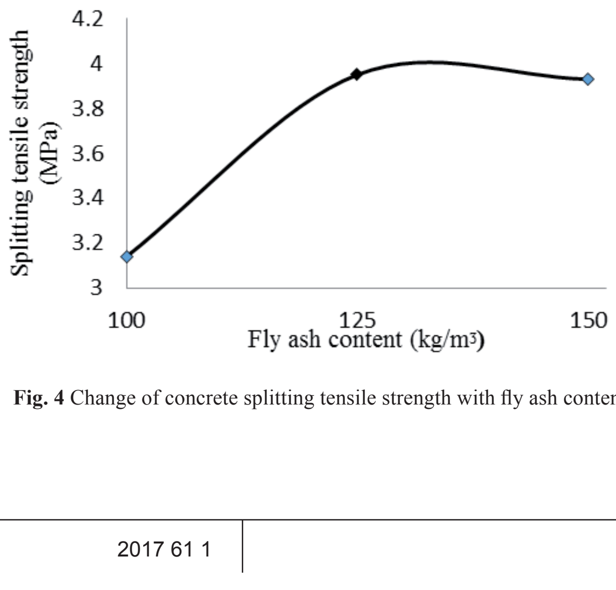

Fig. 4 Change of concrete splitting tensile strength with fly ash content

7.2.3 Modulus of Elasticity (E)

The data for this test is summarized in Table 6. Similar to compressive and split cylinder strength, modulus of elasticity also increase with increase in fly ash content but decreases slightly once fly ash quantity is increased further above 125 kg/m^3, however the change in the modulus of elasticity values is not significant. For normal weight concrete, the modulus of elasticity ranges between 25,000 MPa and 35,000 MPa, where as in this study, it is quite low in the range of 17,000 MPa which may be attributed to the use of lightweight aggregates which are more porous and the stiffness is quite low compared to normal weight aggregates.

7.2.4 Flexural strength (FS)

The results for this test are summarized in Table 6. A slightly different behavior is observed in this case. The flexural strength increase from SCLWC100 to SCLWC125 but it decreases by a huge margin, even less than SCLWC100 once quantity of fly ash is increase from 125 kg to 150 kg/m^3 of concrete. The increase of FS from SCLWC100 to SCLWC125 may be justified on the bases of the fact that CS of concrete increased which has direct relation with FS of concrete but the reason for huge reduction in FS of SCLWC150 with small decrease in CS is unknown which may be verified by further research on micro structure of concrete. This relation is graphically represented in Fig. 5, in which this behaviour can be clearly observed.

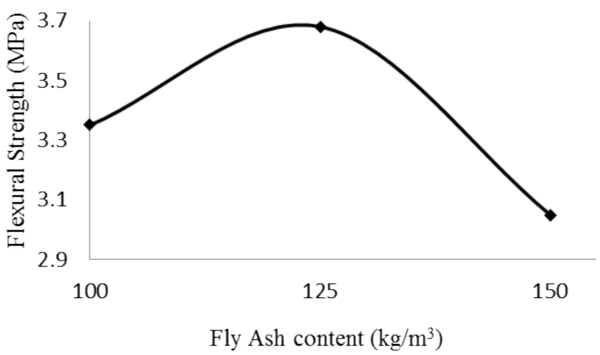

Fig. 5 Change in concrete flexural strength with fly ash content

The displacement of the mid span of the beam with increase in load was also noted which is represented in Fig. 6. 3 lines in each graph represents 3 samples in each case. In case of SCLWC100, average of the maximum load taken by the beam specimens before failure is 7.15 KN with corresponding average mid span displacement of 0.22 mm, for SCLWC125 average maximum load is 7.86 KN with average mid span displacement of 0.28 mm whereas in case of SCLWC150, the average maximum load is 6.52 KN with average mid span displacement of 0.2 mm. It may be observed from these results that the rate of mid span displacement with increase of load is similar in the three cases. Increase of maximum load is due to the increase of maximum deflection that the specimens can take before failure point is reached.

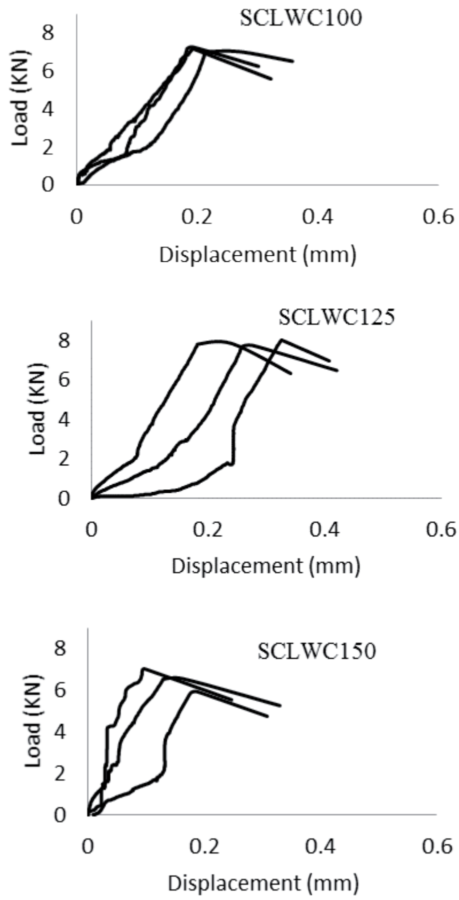

Fig. 6 Load-deflection curves

8 Conclusions

This study has been carried out to investigate the effect of change in fly ash content on the fresh and hardened properties of SCLWC. The obtained experimental results show that lightweight self-compacting concrete with hardened dry density of 1700 kg/m3 and slump flow of 800 mm can be achieved using fly ash as the only filler in range of 15% to 25% of the total powder content.

Concrete cylinder compressive strength of more than 50 MPa can be achieved for self-compacting lightweight concrete, using 450 kg of cement per cubic meter of concrete mixture. Increase in fly ash content as filler in SCC that may improve the fresh properties of the mix not always yields better mechanical properties of concrete after hardening.

With the increase of fly ash content from 100 kg/m^3 to 125 kg/m^3, the compressive strength increased by 13.5 % but decreased by 4.5 % when the fly ash quantity was further increased to 150 kg/m^3 however, the modulus of elasticity remained almost unaffected by this change of fly ash content with just 0.5 % increase and then 0.2 % decrease with subsequent increase of fly ash by 25 kg/m^3.

There is significant increase of up to 26 % in splitting tensile strength and 10 % increase in flexural strength of concrete when 25 kg/m^3 of fly ash was added increasing its quantity from 100 kg/m^3 to 125 kg/m^3 . The splitting tensile strength remained at the same level with just 0.5 % reduction in it while flexural strength reduced by significant margin with 17 % reduction, when fly ash content was increased by the same amount to 150 kg/m^3.

The investigated type of concrete may be used for repair works of existing buildings. As it is a lightweight material, it will cause less additional self-weight. Moreover, it is self-compacting, therefore the use of vibrator will not be required. Hence labor resources and noise hazards in the built-up areas will be significantly reduced.

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