Analytical and Experimental study on load-deflection characteristics of Ternary blend SCC beams

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Abstract: Development of newer concrete is the need of the hour to meet out today’s demand due to fast growing construction activities. Taller constructions with lesser space involve closer reinforcements lead to suffer the reach of concrete uniformly. Hence concrete with higher degree of flowability without compromising strength comes to the mind of constructor. Such concrete called self-consolidating or compacting concrete and is capable of compacting on its own with no external effort. This paper deals with load deflection performance of such concrete using mineral and chemical admixtures, so that good amount of cement will be minimized without compromising strength and workability. Detailed experimental investigations were done with industrial wastes as replacers to conventional binder (cement) in ternary form. Experimental results of ternary SCC was compared with the results of conventionally vibrated concrete (CVC). Finite element model was developed using ANSYS and was validated with experimental results. It was inferred that ternary SCC beams exhibited more ductile nature compared to CVC beams.

Keywords: SCC; SF; MK; GGBS; load deflection; ANSYS; FEA.

1. INTRODUCTION

Rapid urbanization forces construction industry to prefer concrete with better accessibility. It is also important that concrete chosen should not have any drawbacks like inferior quality, transport problem etc. Hence a concrete with better accessibility to the location, lesser noise during placement and elimination of external agency for compaction was identified and used in many applications. It is self-consolidating or compacting concrete and well known application was construction of Akashi-Kaikyo Suspension Bridge, Japan also the longest suspension bridge in the world. Many research works were carried out on SCC and its performance through mechanical behaviour. There were some works on admixture based SCC and its performance also. Let us see some of the available literature in this area and findings from them.

SCC performance was investigated and they found that, more the volume of coarser particles more will be the toughness and critical crack opening. However it is worthy to note that when the mix is rich enough, then it will influence the larger toughness and crack nature will be minimal [1]. Another investigation was made on compressive strength in SCC due to the effect of size of specimen. It was assessed that increase in size of specimen reducing the strength [2]. An investigation was made on rheological properties of SCC namely slump flow test according to ASTM C1611 standard and the detailed investigation on filling ability of SCC by T50 time frame was reported. Some researchers developed greener SCC using stainless steel reducing slag by replacing cement up to 50%. Results revealed that 30% replacement exhibited better resistance against compression and 10% replacement exhibited better resistance against sulphate attack [3].
A new method was developed for designing SCC mix with GGBS from 20% to 80%, in which the strength obtained from 30 to 100 MPa. Experiments were also conducted on high strength SCC mix using metakaolin as cement replacement by 7.5%, 15% and 22.5% in which very high strengths from 100 MPa to 120 MPa was obtained at 28 days and 90 days respectively [4-5]. An experimental study was conducted on SCC with mineral admixtures namely SF, MK and GGBS in binary blend combinations in which rheological and mechanical properties were studied. The authors have reported that GGBS based SCC mixes could be the feasible option in terms of strength and economy index. It was inferred that GGBS from 50% to 75%, SF up to 15%, and MK from 20% to 30% as partial cement replacement had improved durability properties in SCC [6-7].

Experiments were performed on polymer and expanded clay based self-compacting concrete to assess the physical and mechanical performance. Specimens were subjected to both static and dynamic loading. The type of clay material used was Belgian and Italian. They also applied linear elastic fracture mechanics to study the properties. They found that the results were encouraging due to its fulfillment of requirement of the purpose [8].

A model was developed for prediction of compressive strength using neural network and implemented under MATLAB environment. The results were compared with huge amount of earlier data published in literature. They found that the developed model was well suitable for prediction of compressive strength of fly ash based SCC [9]. Performance of SCC slab was studied for various parameters. Both experimental results and analytical model results were compared and found that there were some differences in predicted values. A new model also proposed to estimate the effective moment of inertia for SCC slabs for two different loads with and without fibers [10].

Certain research work was done on performance of SCC and normal concrete under accelerated corrosion condition. It was observed that there is a higher degree of matching between calculated value of mass loss and mass loss from the experiments conducted. It was also concluded that type of concrete has no influence on corrosion behaviour but on failure mode [11]. Flexural performance of perforated beam made from SCC was verified with performance of solid beam. Parametric study includes size of perforations, shape of perforations and configuration of reinforcement around the perforations. From the results it was inferred that perforations enhanced the flexural capacity of beam apart from facilitating/accommodating insertion of pipes through perforations [12].

Literature review reveals that work on structural behaviour of SCC with mineral admixtures is Scant. Hence there is a need to focus on performance of ternary blend SCC by replacing cement with three different mineral admixtures. In present study, flexure test was conducted with three ternary SCC mixes namely, C+5%MK+25%GGBS (S1), C+15%SF+25%GGBS (S2) and C+5%MK+20%SF (S3) along with CVC (C0) and reference SCC (S0). The cement was replaced with mineral admixtures to an extent of 40%. The novelty of present research work was to develop SCC with industrial wastes such as GGBS, SF and product from the naturally abundant material mainly called MK. Maximum quantity of cement replaced was restricted to 40 % due to retention of performance. Only limited works are available in load deflection characteristics of ternary SCC beams.

2. EXPERIMENTAL INVESTIGATIONS

2.1 Materials
Cement with no mineral admixtures added in the manufacturing stage (OPC) was used following the guidelines given in ASTM C 150 [13] was used. The mineral admixtures such MK, SF & GGBS used for replacing cement in ternary mixes fulfilled the requirements of pozzolanic materials as guidelines laid in ASTM C 1240 & ASTM C 618 [14-15]. The sizes of coarse aggregate were limited to 12.5 mm maximum and the norm followed was ASTM C 127 [16]. The properties of fine aggregates were assessed using ASTM C127 & ASTM C33 [16-17] and its size was limited to 2.36 mm. Workability and cohesiveness of the ternary SCC mixes were maintained by suitable workability and cohesiveness
agents.

Table 1 Quantity of material used for different mixes

| MIX Id | C  | SF | GGBS | MK | FA  | CA | W  | SP  | VMA | W/p |
|--------|----|----|------|----|-----|----|-----|-----|-----|-----|
| C0     | 600| -  | -    | -  | 396 | 1074| 196 | -   | -   | 0.33|
| S0     | 600| -  | -    | -  | 810 | 660 | 240 | 13.8| 0.90| 0.40|
| S1     | 420| 150| 30   | 30 | 810 | 660 | 240 | 13.8| 0.90| 0.40|
| S2     | 360| 90 | 150  | -  | 810 | 660 | 240 | 13.8| 0.90| 0.40|
| S3     | 450| 120| -    | 30 | 810 | 660 | 240 | 13.8| 0.90| 0.40|

2.2 Rheological Properties

To start with, mix proportioning was done from the guidelines given in ACI 211.1-91 [18] to a desired compressive strength of reference mix and for achieving the desired rheological properties in SCC, the proportions were adjusted with aggregates, workability agent and agent meant for segregation resistance (VMA). Number of trials was made to ensure the rheological properties fulfil the requirements laid by EFNARC. The details on requirement of materials for various mixes were tabulated in Table 1. Description on performing the rheological properties tests as per EFNARC & IS 10262 guidelines [19, 20 & 21] and was already published [7]. Tests performed through photos are given in Figures 1 to 5.

2.3 Specimen Details

In each and every category of mix (CVC, SCC and Ternary SCC), two beams were cast with the following specifications. Two numbers of 12 mm bars were used as tensile reinforcement and 10 mm bars were used compressive reinforcement. Stirrups of size 8 mm were used with a spacing of 150 mm c/c. A clear cover of 25 mm was maintained in all the sides of the beam. Cover blocks were used
to ensure the minimum cover at the soffit during placing concrete in wooden formwork. An overall length of the beam was 1200 mm with a cross section of 100 mm width and 200 mm depth. To have better holding of supports at the soffit, 100 mm on either side was given as offset. Hence the effective span for all calculations was 1000 mm.

2.4 Testing of Specimens

Beam specimens cast were tested to assess the load deflection characteristics of CVC, SCC and ternary SCC using self-balancing loading frame as shown in Figure 6. After desired period of curing the beam specimens were taken out and dried for certain period. Then all the surfaces of beam specimens were white washed and grids were formed by using pencil. The size of the grid was of 50 mm size on both vertical and horizontal directions. This was very much helpful during the measurement of cracks. An I section was used to serve as two point loading. At the soffit of an I section, there were two rollers at its ends were welded so that they will have line contact on the beam during loading. An I section was placed on the test beam in such a way that no question of eccentricity or development of overturning moment. Gradual application of load was ensured and corresponding deflection was measured at mid span using LVDT. Deflections were measured at suitable intervals and also at first crack and ultimate point. The details of loading set up can be seen in Figure 7.

3. RESULTS AND DISCUSSION

3.1 Experimental Results

In this section, the results of conventionally vibrated concrete, reference self-compacting concrete and self-compacting concrete with ternary mixes were analyzed for its load, deflection characteristics, crack width and ultimate load carrying capacity.

| Sl no | Description                        | First crack | Ultimate |
|-------|------------------------------------|-------------|----------|
|       |                                     | Load (kN)  | Deflection (mm) | Load (kN)  | Deflection (mm) |
| 1     | CVC (C0)                           | 41          | 1.66      | 101.5      | 15.73          |
| 2     | SCC 0 (S0)                         | 50          | 2.25      | 100.5      | 6.58           |
| 3     | C + MK 5% + GGBS 25% (S1)          | 50          | 3.08      | 127.1      | 10.85          |
| 4     | C + GGBS 25% + SF 15% (S2)         | 41          | 3.41      | 111.7      | 12.61          |
| 5     | C+MK5%+SF20% (S3)                  | 41          | 3.54      | 113.5      | 9.14           |

It is observed from the Table 2 that first crack load for conventionally vibrated concrete is equivalent to two ternary mixes S2 (C + GGBS 25% + SF 15%) and S3 (C+MK5%+SF20%) and less than reference self-compacting concrete and the other ternary mix S1 (C + MK 5% + GGBS 25%). Both reference SCC and ternary mix S1 prolonged first crack load to an extent of 22% more than the mix C0 due to cohesiveness. It was due to better flowability characteristics of SCC which makes stronger
than CVC. In the case of ternary mix S1, similar increase in first crack load was due to effective dispersion of cement particles, cohesiveness and pozzolanic activity of mineral admixtures. Since the particle sizes of both metakaolin and silica fume was of very small compared to cement, good amount of paste formation might has led to the possibility of crack propagation. The deflection measurements indicate that for the same magnitude of first crack load, the mix C0 and the other two ternary SCC mixes S2 & S3 yielded higher deflection. It means that addition of cohesiveness agent (VMA) in SCC mixes made the member more ductile nature and hence higher deflection. Ternary mix S0 & S1 yielded better loads at first crack and relatively with lesser deflection. Hence S1 could be an optimized mix among all the mix due to better resistance against loading and more ductility. Similar trend was also observed in load and deflection at ultimate stage. Ternary SCC mix yielded highest load carrying capacity among all the mixes and reasonably lesser deflection. Ultimate load carrying capacities of all the SCC mixes were found higher than the CVC mix. It is worthy to note that all the ternary SCC mixes have higher ultimate load carrying capacity than C0 and S0. Again it is an added evidence to ensure the cohesiveness, effective distribution of cementitious particles and pozzolanic activity posed by the mineral admixtures.

### Table 3 Crack width for CVC and Ternary SCC mixes

| Sl.no. | Mix composition                  | Crack width (cm) |       |
|-------|----------------------------------|------------------|-------|
|       |                                  | Min.             | Max.  |
| 1     | CVC (C0)                         | 0.10             | 0.20  |
| 2     | SCC 0 (S0)                       | 0.10             | 0.70  |
| 3     | C + MK 5% + GGBS 25% (S1)        | 0.10             | 0.50  |
| 4     | C + GGBS 25% + SF 15% (S2)       | 0.20             | 0.75  |
| 5     | C+MK5%+SF20% (S3)                | 0.10             | 0.50  |

Table 3 show the details of crack width for all the mixes used in the present work. Both minimum and maximum values of the same give an idea of ductile nature of the respective mix. Though there was no much difference in minimum width, higher magnitudes were observed in SCC and ternary SCC mixes. It was revealed that due to the influence of viscosity modifying agent (to ensure cohesiveness or resistance to segregation) with combine effect of another chemical admixture called workability agent, the SCC and ternary SCC mixes gave adequate notice or warning before failure of the flexural member. It is worthy to note this point because, a failure with due notice will be an added advantage in the field to go for any remedial or retrofitting or rehabilitation measure. It is also of immense use for the maintenance people who involved in monitoring the performance of built structure. Almost all the SCC mixes have 50% higher value in maximum crack width compared to conventionally vibrate concrete mix.

#### 3.2 Flexural Strength

Flexural strengths for both conventionally vibrate concrete and SCC mixes were calculated theoretically and tabulated in Table 4. From the values it was observed that flexural strength was enhanced in SCC due to chemical admixtures and further enhanced in ternary SCC mixes due to pozzolanic action induced by the mineral admixtures. Again here the ternary SCC mix S1 yielded better flexural strength compared to all other mixes. It confirms the similar trend of other parameters.

### Table 4 Flexural Strength

| Sl.no. | Mix | Flexural strength (MPa) |
|-------|-----|------------------------|
| 1     | C0  | 25.375                 |
| 2     | S0  | 25.125                 |
| 3     | S1  | 31.775                 |
| 4     | S2  | 27.925                 |
| 5     | S3  | 28.375                 |
Load deflection characteristics of ternary SCC mixes are depicted in Figure 8. There is a uniform trend between the load and deflection for all the ternary mixes and no zig-zag trend was observed. It ensured the uniformity of mixes prepared and not much deviation quality of the mixes. Among the three ternary mixes, mix S3 yielded little bit lower ultimate load carrying capacity and was due to the mineral admixtures. In the mix S3, both metakaolin and silica fume was of fine nature with least particles size compared to other two ternary mixes. Hence an optimized voids filling could not have been achieved in this particular mix.

3.3 Finite Element Modeling Results

For the current analysis, a beam of dimensions adopted experimental work was considered for finite element modeling. Reinforcement bars at tensile and compressive zone, stirrups dimension and spacing also of same dimensions as experimental work. The modeling of reinforcement and deflected profile was mentioned in the Figure 9 to 10 as shown.

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3.4 ANSYS Analysis of Ternary SCC Beam (S1)

When comparing the flexural strength capacity of different CVC and SCC ternary beams, S1 mix beam has performed better and for which numerical analysis was simulated.

After performing ANSYS analysis of the ternary blended SCC beam (S1) (C+ 5%MK + 25% GGBS) the stress and strain profiles, flexural strength and displacement were illustrated as below (Figures 11, 12 & 13).

3.5 Flexural strength

For an SCC ternary beam S1, the maximum flexural strength obtained through the experiment was 31.78 MPa, in which cement was replaced with MK 5% and GGBS 25% respectively, as shown in Figure 13. Then it was modeled using ANSYS and the flexural strength obtained through nodal and element solution was 34.82 MPa and 36.27 MPa respectively.
The nodal solution has obtained good correlation with the experimental solution in terms of percentage error was about 9.6%. Hence, the solution obtained through ANSYS has overestimated the flexural strength within the range of 10%, was agreeable.

3.6 Deflection
The load deflection curve obtained through the experiment and using ANSYS solution was compared. It was found that S1 SCC beam in which cement replaced by 5% MK and 25% GGBS has shown the good ductile behaviour with the maximum load carrying capacity of approximately 120 kN with a maximum displacement of nearly 8 mm has shown similar trend with the experimental solution could be noticed in Figure 14. Hence ductile nature of behaviour was exhibited in all SCC beams of ternary type.

3.7 Crack Width and Propagation
By referring Table 3, the crack width was mentioned from the experimental results. The cracks exhibited on the zone of flexure only, and then it propagated to the compression flange. Similar pattern was noticed from the ANSYS analysis also could be referred in Figure 12 for strain profile. Hence from the above ANSYS analysis and experimental solution, it was noticed that ternary SCC beam S1 was surpassing with other beams of same geometrical and material properties.

Load deflection characteristics from the finite element modeling of all the mixes are depicted in Figure 15. Similar to experimental results the uniform trend between the load and deflection for all the ternary mixes were observed in FEM results also. There was a small variation between experimental and numerical results in terms of magnitudes of ultimate load carrying capacity. FEM results underestimate the load carrying capacity of ternary SCC mixes. Especially in ternary mix S3 the difference in value was around 12%. In experiment also the mix S3 has yielded lower value of ultimate load carrying capacity.
4. CONCLUSIONS

- From the load–displacement curve between CVC and SCC ternary beams, SCC ternary mix S1 beam was ductile in nature along with highest load carrying capacity of 127.1 kN compared to other beams was observed in the flexure study.
- The other two SCC ternary mixes S2 and S3 yielded relatively better load carrying capacity compared to conventional vibrate concrete beams.
- The propagation of cracks were within the flexure zone was observed. The values of flexural strength by numerical nodal solution and experimental values had good correlation.
- The load displacement curve between experimental values and numerical ANSYS analysis follows a similar qualitative curvature pattern unanimously for all beams. Since boundary conditions differ from analytical and experimental values.
- As observed in the experimental study, the failure of beams were under flexure was confirmed with numerical modeling of deflection profile also. The wider cracks were seen in all SCC beams inferred that it was subjected to yield and then failure took place.
- All ternary blend SCC beams performed better than CVC beam in terms of flexural strength, deflection, first crack load and ultimate load. Hence replacement of cement upto 40% was made possible in producing ternary SCC and the mix S1 was an optimum mix from the results.

ACKNOWLEDGEMENT

The authors would like to thank the Vice Chancellor of SASTRA DEEMED UNIVERSITY for having provided experimental facilities in the School of Civil Engineering to do this research work and also for the continuous support and encouragement given throughout this research work.

CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.
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