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RESEARCH

Role of copper slag on improvement of strength, quality and durability of high-strength self-compacting concrete: an industrial waste

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Abstract

This paper aims at the experimental study of durability properties and long-term mechanical properties of self-compacting concrete with fly ash as secondary cementitious material and copper slag as inert material. Cement replaced with fly ash at 20% level and fine aggregate replaced with copper slag at 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. Twelve different mixes were prepared to assess the durability properties like RCPT, Sorptivity, and UPV. The microstructure of SCC was observed using a Scanning Electron Microscope (SEM). Mechanical properties like compressive, split tensile, and flexure strength at the ages of 28, 90, 180, and 365 days were evaluated. Compressive strength with CS improved from 85.53 to 102.89 MPa, Split tensile strength varies from 4.82 to 6.74 MPa, and flexural strength changes from 11.03 to 11.82 MPa at a 40% replacement level. All mechanical properties were enhanced with the use of copper slag. Copper slag improved the resistance against chloride penetration. RCPT showed optimum at a 50% CS which was reduced from 1054.74 to 401.26 coulombs. Sorptivity with 0.013 mm/s$^{1/2}$ to 0.006 mm/s$^{1/2}$ for 40 and 50% also. UPV varies from 4383 to 4565 m/s. 40% copper slag partial replacement enhanced the properties of self-compacting concrete, and up to 60% of fine aggregate can be substituted with industrial copper waste. By this investigation, copper slag can be used as a sustainable building material.

Keywords Self-compacting concrete · Fly ash · Durability · Copper slag · Industrial waste · Quality

Introduction

Self-Compacting Concrete (SCC) is a high-performance concrete, which gets compacted without external force. SCC is a next-generation development to the existing vibrating concrete. It works in compacting concrete with the help of its weight by increasing paste volume in the concrete. By increasing paste content, concrete can be easily pumpable to higher elevations and high congested reinforced structural members, where external vibration is impossible (Cu et al., 2020). To achieve this pumpable nature called flowability, chemical admixtures generally named super plasticisers are used. These super plasticisers play an exciting role in the plastic natured concrete to convert flowable or pumpable natured building material (Almohammad-albakkar & Behfarnia, 2021; Toledano-Prados et al., 2013).

In the mid-1980s, Japan hosted the first research experiments on self-compacting concrete (SCC) presented in January 1989 (García et al., 2013). Even while significant progress has been made in the development of this material since that time, it still has the drawback of not being very robust, considered a mix's ability to keep its qualities when exposed to extreme temperatures. Its content and properties have been tweaked slightly like components, manufacturing process, transportation, and placement. Limiting aggregate quantity, guaranteeing a low water powder ratio, and using super plasticisers are three strategies to obtain the properties of concrete without segregation and excellent deformability (Buari et al., 2019; Kannan & Ganesan, 2016).

Usage of super plasticiser and high cement content than the general vibrated concrete leads to the SCC as uneconomical. The application of mineral admixtures can limit this as secondary cementitious materials in concrete. Mineral admixtures are industrial by-products, which are hazardous in nature. However, mineral admixtures as SCM reduce the carbon footprint by scaling down cement production (Reddy et al., 2020; Sadiqul Islam et al., 2019). Different SCMs exist

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in the market like Fly ash, Silica Fume, Metakaolin, GGBS, Nano-Silica, Rice Husk Ash, etc.

Among these existing industrial wastes, fly ash is a highly accessible building material due to its production worldwide, especially in India (Dinakar et al., 2013). India is the third-largest consumer of coal as well as fly ash generators from thermal power production, followed by China and the United States of America. There are several methods to collect fly ash during the production of thermal energy in thermal power plants. Condensation, wet scrubbers, dry scrubbers, fabric filters, and electrostatic precipitators are the standard methods. The most common filters are fabric filters and electrostatic precipitators installed in cement and thermal power plants to collect the pollutants. Electrostatic precipitators are generally used in the majority of power plants. The collected contaminant named fly ash will be disposed of in two different ways depending on its particle size. Course sized ash is directly dumped into the ash ponds, which are located nearer or beside power plants. However, fine-sized ash is collected effectively using electrostatic precipitators, and this ash is hazardous in nature to the respiratory systems of all living beings. The collected ash is preserved in silos and transported to industries as an ash management process. Approximately 230 million tonnes of fly ash are generated annually in this country. 40–45% of generated fly ash has been consuming in cement, road, and concrete industries (Yao, et al., 2014).

Fly ash as SCM will develop secondary C–S–H when reactive silica present in ash reacts with the $Ca(OH)_2$. Depending upon the availability of Ca ions in the fly ash, it is classified as Class F and Class C (Thomas, 2007). The development of strength while using SCMs will depend on the Ca and Si ions and their ratios. Several kinds of research were done on the usage of low volume and high-volume fly ash based on its enhancement of strength and durability of ordinary and special concretes (Babu & Nageswara Rao, 1993; Guru Jawahar et al., 2018). The formation of ettringite and the significant hydration product density is high when compared with conventional concrete. In some concrete grades, water demand declined, and other capillary voids were also reduced with the help of fly ash (Saha, 2018).

Fine aggregate is the most common material used in the construction industry. River sand is used as fine aggregate in the concrete manufacturing industry. In the SCC, fine aggregate utilisation is more than 50% of total aggregate content, which is relatively higher than standard vibrated concrete (Cunha et al., 2010). Due to the higher requirement of fine aggregate, river sand utilisation has been increased, and the depletion of natural resources significantly river sand increased the construction cost. In addition to super plasticiser, fine aggregate also plays a crucial role in cost efficiency. To overcome this, the fine aggregate may be replaced with industrial sand or manufactured sand. Steel slag. Quarry dust, Copper slag are some of the industrial wastes (Dehwah, 2012; Kandasamy & Kothandaraman, 2020). Copper slag is an industrial waste obtained from the copper manufacturing industry. For one tonne of copper production, almost 2–3 tonnes of copper waste will be generated (Geetha & Madhavan, 2017). Copper slag may be one of the feature alternative building materials because of its properties. Due to glassy morphology, water demand for concrete for hydration is drastically stepped down. Copper waste usage in concrete enhanced the fresh properties by the very low water absorbing behaviour (Ishimaru et al., 2005; Sonule & Tayade, 2021). Generally, copper waste will be fine in nature with a particle nature of less than 4.5 mm, similar to the fine aggregate. However, industrial copper waste particle sizes are finer than the usual river sand. Previous studies stated that copper slag in concrete would improve the life of the concrete and shows promising results against corrosion and water absorption (Al-Jabri et al., 2011; Sharifi et al., 2020).

Review of literature

Esquinas et al. (2018) used fly ash from power plants as SCC filler in mixing SCC-2 and observed that it enhanced the concrete properties like hardened, water absorption, and capillary pore structures. Rafat Siddique (2011) replaced cement with fly ash in self-compacting concrete at the various levels of 15%, 20%, 25%, 30%, and 35% and achieved a maximum compressive strength of 35.19 MPa at 28 days of the test. However, the remaining levels declined the strength parameters and 25% of fly ash resisted the chloride penetration in the concrete. Mostafa Jalal et.al (2015) studied Class F fly ash effects on high-performance self-compacting concrete by taking 5%, 10%, 15% level in 400 kg/m^3 and 500 kg/m^3 cement. In both cases, 15% fly ash advanced the performance of the SCC and presented the ettringite formations in SEM observations. The capillary absorption decreased with the filling of voids with the ash particles and the formation of secondary C–S–H. Sua-iam et al. (2017) considered fly ash at high volumes, at 40% and 60%. Also, it shows better performance when combined with alumina waste. Fresh properties of SCC were improved and also helps to achieve sustainable concrete. Soleymani Ashtiani et.al (2013) investigated mechanical properties at 3, 7, 28, and 90 days with Class C fly ash. At an early age, the compressive strength is low compared with 28 days. With the help of experimental work, the strength values were predicted using an empirical formula. Anjos et al. (2020) conducted experiments on a 60% fly ash combination of metakaolin and hydrated lime and compared it with conventional SCC, normal vibrated concrete. It was observed that even at 60% of fly ash developed fresh properties. Nonetheless, compressive strength decreased with respect to normal vibrated concrete. Choudhary et al. (2019) replaced cement with fly ash at 15%, 25% and 35%. Among these, 15% have better strength and good water absorption resistance than the other percentages. Nagaratnam et al. (2019) mixed fly ash at 10%, 20%, 30%, and 40% levels and studied on availability of CaOH in the concrete mix. Results are clear that with the increase of ash content, CaOH gets decreased.

Chithra et al. (2016) combined copper slag with colloidal nano-silica and showed optimum results at 2% substitution. Copper slag enhanced the fresh, mechanical properties and durability of the concrete with colloidal nano-silica content. Arunchaitanya et al. (2019) reviewed the usage of fly ash and copper slag as fine aggregate in the SCC. The review observed that fly ash content boosts the workability of the concrete as well as copper slag reduces the usage of super plasticiser to achieve the workability of SCC. CS can improve the durability of concrete by achieving good particle packing with adjustable coarse structure and irregular morphology. Nainwal et al. (2021) utilised copper slag with 10% metakaolin, fine aggregate replaced with CS at 20%, 40%, and 60%. This combination resulted in CS 40% having good strength parameters, and durability based on initial surface water absorption and water absorption. Lori et al. (2019) studied hydraulic characteristics of pervious concrete with copper slag. Mixes having 20%, 40%, 50%, 60%, 80%, 100% replaced in dolomite stones. 60% CS had a strong gain of 31% compressive, 19% flexural, and 18% splitting tensile strength. Copper slag based pervious concrete increased the porosity. Usage of CS as fine aggregate in SCC has limited research and needs more study to have to be done. In this regard, the present study focused on effect of CS utilisation on high-strength SCC and its durability and long-term properties.

Methodology

In this experimental investigation, twelve different mixes were prepared, including conventional or control mix, 20% fly ash as secondary cementitious material. The remaining ten mixes were fine aggregate replacements with industrial copper waste at 10% increment up to 100% in 20% fly ash mix. OPC cement is mentioned as ‘O’, Fly ash as ‘A’, and Copper slag as ‘C’. Each mix is named as per the physical combinations of the materials at their levels. Control concrete is represented as O0A0C, 20% fly ash mix as O20A0C, copper slag replacements as O20A10C, O20A20C, O20A30C, O20A40C, O20A50C, O20A60C, O20A70C, O20A80C, O20A90C, and O20A100C for 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%, respectively.

Materials and mix design

Ultra Tech OPC 53 grade cement confirming to IS 12269 was procured, and locally available fly ash was collected from an RMC plant. Coming to the aggregate, the sound quality of the crushed stone was used as coarse aggregate having a nominal size of 12.5 mm passing through the sieve. Fine aggregate as river sand was purchased and sieved to classify the zone. It was confirmed to Zone-II as per IS 383. Fine aggregate replacing material named copper slag was gathered from Chennai. The method of sieve analysis had fallen under the category of Zone-I as per IS 383.

Cement is fixed at 550 kg/m^3 for control mix with a specific gravity of 3.12, and it is replaced with 20% fly ash having 2.34 relative density with fineness retained on a 45micron sieve as 15%. River sand is a fine aggregate with a fineness modulus of 2.78 and specific gravity of 2.64. Replaceable inert material determined relative density 3.93 and fineness modulus 3.67. Coarse aggregate has physical properties of specific gravity 2.72 as well as fineness modulus 7.41 is tabulated in the Table 1 The water-cement ratio is adopted at 0.3, modified polycarboxylate ether-based super plasticiser used at 0.4% and fixed throughout all the blended mixes and mix proportions were presented in Table 2.

Table 1 Physical properties of materials

Material	Fineness modulus	Specific Gravity	Fineness % (retained on 90 μ)	Fineness % (retained on 45 μ)
Cement(O)	–	3.12	5	–
Fly ash(A)	–	2.34	–	15
Fine Aggregate(FA)	2.78	2.64	–	–
Coarse Aggregate(CA)	7.41	2.72	–	–
Copper Slag(C)	3.67	3.93	–	–

Table 2 Mix proportions

S.No	Mix Name	O (kg /m^3)	A (kg /m^3)	FA (kg /m^3)	CA (kg /m^3)	C (kg /m^3)	Water/Powder ratio	Water (l/m^3)	SP (l/ m^3)
1	O0A0C	550	–	925	779	–	0.3	165	2
2	O20A0C	440	110	908	765	–	0.3	165	2
3	O20A10C	440	110	817.2	765	90.8	0.3	165	2
4	O20A20C	440	110	726.4	765	181.6	0.3	165	2
5	O20A30C	440	110	635.6	765	272.4	0.3	165	2
6	O20A40C	440	110	544.8	765	363.2	0.3	165	2
7	O20A50C	440	110	454	765	454	0.3	165	2
8	O20A60C	440	110	363.2	765	544.8	0.3	165	2
9	O20A70C	440	110	272.4	765	635.6	0.3	165	2
10	O20A80C	440	110	181.6	765	726.4	0.3	165	2
11	O20A90C	440	110	90.8	765	817.2	0.3	165	2
12	O20A100C	440	110	–	765	908	0.3	165	2

Concrete testing

Fresh concrete properties

Every mix was tested for fresh properties before casting the specimens. Passing ability, filling ability, and flowability comes under the fresh properties of SCC. Without having these properties, self-compaction of concrete will not be formed. L-box, V-funnel, and slump flow are the methods to evaluate the fresh properties. L-box is the height ratio varies from 0.8 to 1. V-funnel test is the time taken to free the funnel from concrete with gravity flow, less than 20 s will be considered as SCC. Slump flow is the flowability indicator representing the distance travelled by the concrete after lifting the slump cone. These test methods were conducted as per the EFNARC guidelines.

Hardened concrete properties

The compressive strength of SCC cubes was determined by conducting compression testing on an average of three cubes from each of the twelve mixes. 150 mm sized cubes were cast and cured with water for the period of 28, 90, 180, and 365 days. A compression Testing Machine (CTM) of capacity 3000kN was used to perform the test as per IS:516–1959. Splitting tensile strength of SCC was evaluated by casting 150 mm × 300 mm cylinders, cured for a testing period as per the testing code IS: 5816–1999 on CTM, and three cylinders were noted from each mix. Flexural strength of SCC was tested on beams using a two-point method as per the code IS 516–1959. Three beams were used for testing from each mix at each age or curing period.

Durability properties

The quality of concrete can be determined by Ultrasonic Pulse Velocity (UPV). The durability of the concrete will depend on its quality of concrete. It is a non-destructive evaluation test, which can be conducted on any concrete specimen or existing structure. It works under the principle of an ultrasonic pulse to reach the transducer. Higher velocities show a better quality of concrete; a low velocity of pulse indicates voids, cracks, or flaws in the concrete. In general, UPV is available between 20 and 150 kHz frequencies. In this study, a 150 mm concrete cube specimen was used to conduct the experiment as per IS 13311 with a 60 kHz frequency. A pair of transducers will allow the pulse to transfer from one end to another end with the help of an electrical pulse generator. A small amount of gel is applied at both ends to make the bond strong to send the pulse. A screen is available to note the velocities of the pulse while conducting the experiment.

Sorptivity is another durability parameter related to the rate of water absorption by concrete specimens by gauging the increase in mass with the function of time when only one surface is immersed. It concentrates on initial absorption and secondary absorption. The absorption calculated from the immersion period of 1 min to 6 h comes under initial absorption, and absorption that takes place up to 7 days from the immersion is named secondary absorption after the required curing ages. The average of all the absorption values, including initial and secondary, was evaluated in this study. A cube of 150 mm was placed on a pan filled with water at the level of 10 mm specimen submerged level after oven-dried and cooled to room temperature. All sides of specimens were covered with polythene or watertight plaster to avoid evaporation or loss of water molecules except the bottom surface as per ASTM C 1585. Mass gained due to absorption was noted by weighing the concrete cube at specified time intervals in ASTM C 1585.

Durability can also be determined in the form of chloride resistance of the concrete. The rapid Chloride Permeability Test (RCPT) is one of the methods to evaluate the chloride resistance of the material. A cylindrical specimen sized 100 mm × 50 mm is required to conduct the experiment. It consists of two chambers, one for 3% NaOH solution and another for 0.3 M NaCl solution. 60 V DC potential is allowed to pass through the specimen. The charge passed through the specimen will be displayed and observed for a 6-h duration with a 30-min time interval. The total charge passed is presented in coulombs, based on the magnitude, it is classified as very low, low, moderate, and high as per ASTM C 1202. Low magnitude specimens were resistant to chloride permeability, which leads to corrosion.

Results and discussion

Fresh concrete properties

Slump flow was determined for all the SCC blends to assess the flowability and presented in Figs. 1, 2, and 3. All mix proportions were within the limits specified by EFNARC. First, conventional concrete achieved 680 mm slump flow using chemical admixture. Fly ash improved the flow property to 718 mm at 20% replacement. With 718 mm slump flow, further replacements of copper slag as fine aggregate increased to 786 mm at 100%. Second, passing ability by L-box was assessed, and the reference concrete had a blocking ratio of 0.8. Same as slump flow, the passing ability was also raised to 0.83 with 20% fly ash, and CS intensified the enhanced blocking ratio to 0.96, which represents an excellent passing ability to concrete to pass through congested reinforcement. Third, viscosity was evaluated through the V-funnel test method. Control mix took 9.35 s for V-funnel, fly ash substitution decreased the time to 8.23 s, and CS also soften the concrete mix leading to 5.16 s only to pass through V-funnel. As discussed earlier, supplementary cementitious material like fly ash improves fresh state properties and results are similar to *(*Afshoon & Sharifi, 2020*)*.In this study, it was

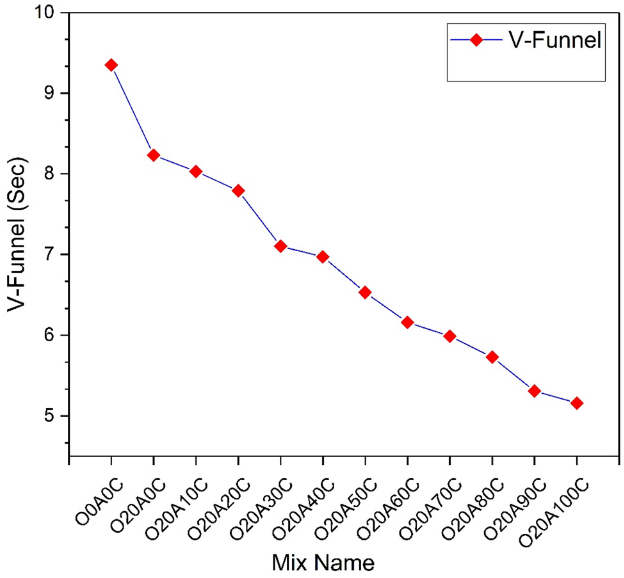

Fig. 2 V-funnel

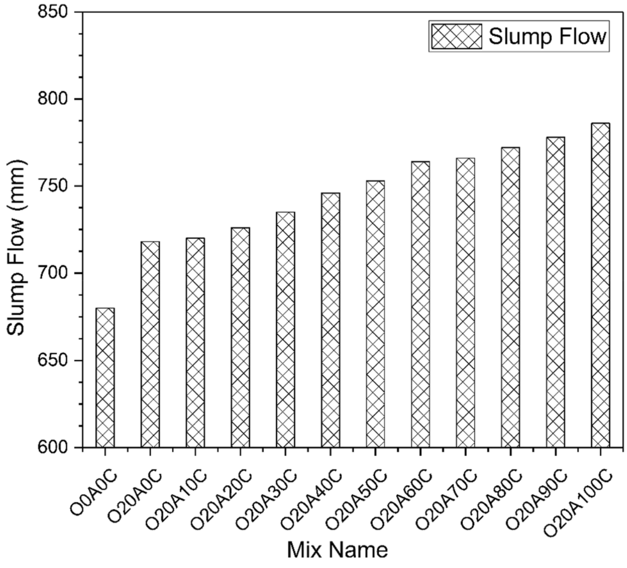

Fig. 1 Slump Flow

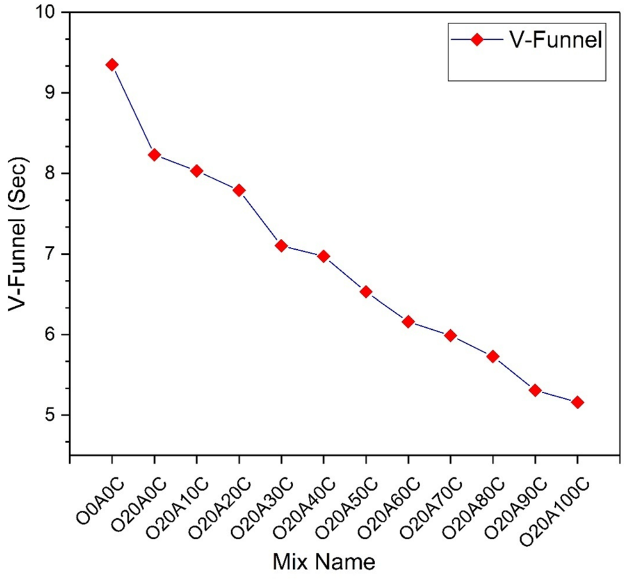

Fig. 3 L-Box

noticed that CS enhanced the fresh concrete properties with the increase of replacement in SCC.

Mechanical properties

Compressive strength

The high strength of SCC was achieved without utilising mineral admixtures of 68.5 Mpa at 28 days. Later cement was replaced at 20% fly ash noting the increment of strength to 77.26 MPa. This may be due to the formation of secondary C–S–H gel by pozzolanic action. CS enhanced the compressive strength at the level of 40% replacement, gradually from 10 to 40%. 79.25, 81.06, 83.15, and 8.53 MPa were obtained at 10, 20, 30, and 40% CS, respectively, during 28 days of curing age. Beyond 40% CS, strength got reversed gradually from 85.53 to 66.24 Mpa which is lower than conventional high-strength SCC, these were compared with the results obtained by (Sharma et al., 2020). Similarly, the same pattern was observed at 90, 180 and 365 days. However, at 365 days, compressive strength values are increased to 80.8 MPa for control mix, 97.83 for fly ash mix, and achieved 102.89 MPa, which can be considered ultra-high-strength concrete at 40% CS level shown in Fig. 4. It may be due to the good particle packing of the SCC mix obtained with the particle sizes of CS. CS entered the voids formed between the aggregates. Low-sized particles filled the gaps and formed a homogenous mix. CS not only enhanced the packing of the concrete but also developed the ettringite in the concrete matrix.

Splitting tensile strength

Splitting tensile strength of SCC for high-strength concrete is also compared to conventional concrete. All blended specimens showed a pattern similar to compressive strength at all ages. 28 days tensile strength evaluated on cylindrical specimen shows 3.9 MPa for control mix in Fig. 5. Tensile strength was increased by 17% and achieved 4.56 MPa, 23% and 4.82 MPa, 40% and 5.47 MPa at 90, 180, and 365 days, respectively. Due to the pozzolanic action, fly ash at 20% cement replacement recorded 4.2 MPa, 5.05 MPa, 5.35 MPa, and 6.08 MPa at their respective incremental curing ages, these are similar to the results of (Mithun & Narasimhan, 2015). CS replacements of 10–40% enhanced the splitting tensile strength of high-strength self-compacting concrete. However, beyond 40%, the mechanical property decreases, which may be due to an increase in voids. 40% CS achieved the maximum strength values about all the mixes, and 365-day testing period shows the highest value of 6.74 MPa.

Flexural strength

Flexural strength of high-strength SCC was achieved as 9.04 MPa at 28 days of the control mix. With the substitution of fly ash at 20%, the strength value increases from 9.04 to 9.56 MPa. It may be due to the pozzolanic action of fly ash. At every increase in curing age from 28 to 365 days, control and 20% fly ash recorded a tremendous increase in flexural strength. CS replacements from 10 to 40%, flexural values increased from 9.56 to 11.03 at 28 days, 10.51 to 11.55 at 90 days, 11.03 to 11.64 at 180 days, 11.31 to 11.82 MPa at 365 days presented in Fig. 6, these are similar to the results

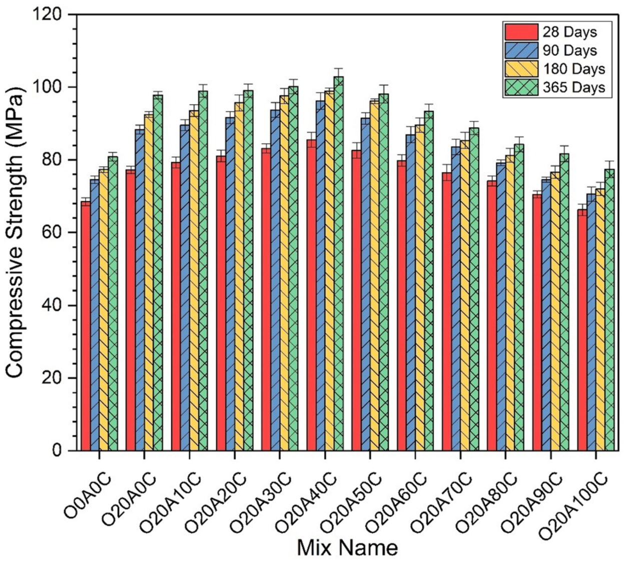

Fig. 4 Compressive Strength

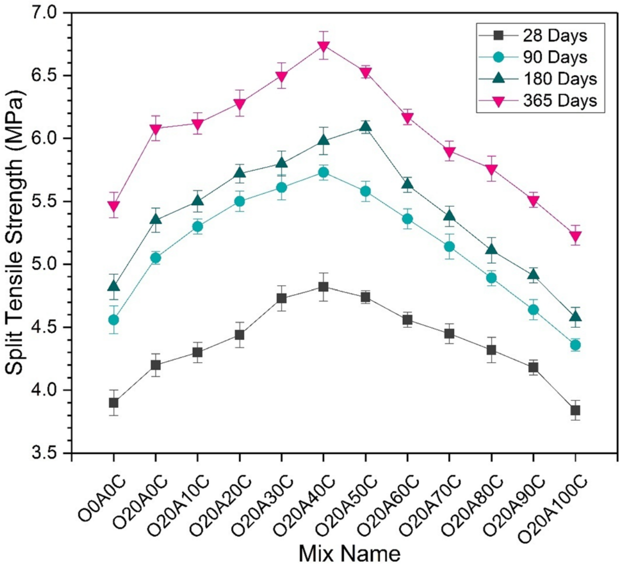

Fig. 5 Split tensile strength

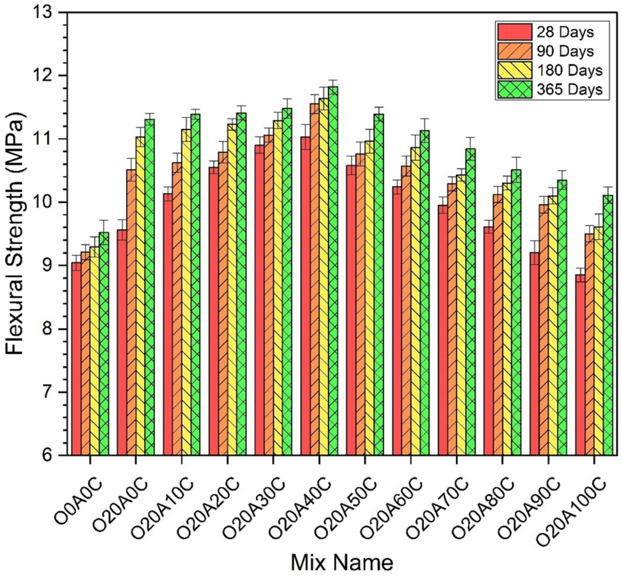

Fig. 6 Flexural Strength

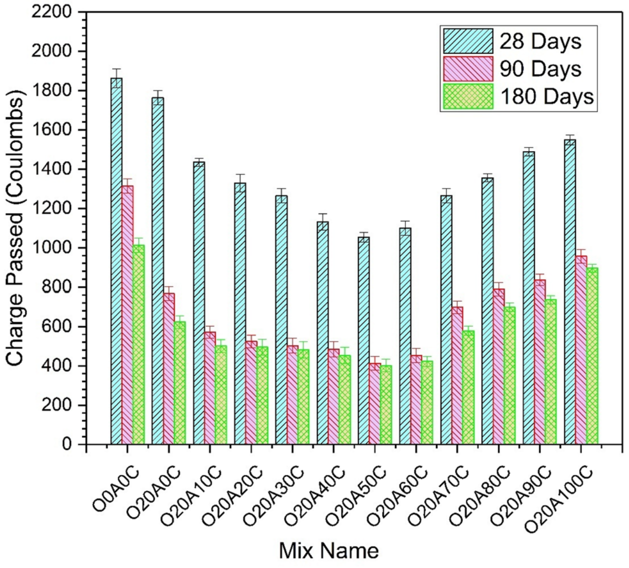

Fig. 7 RCPT

of (Mithun & Narasimhan, 2015).The enhancement of flexural strength may be due to the reduction of voids. It was achieved with the smaller particle sizes of CS, which helps to adjust the gaps of the concrete matrix. The maximum flexural strength obtained was 11.82 MPa at 365 days with 40% substitution. However, beyond 40%, similar to compression and tensile strengths, flexural also gets reduced.

Durability

Rapid chloride ion permeability test (RCPT)

Chloride ion permeability resistance of concrete is conducted on all SCC control, blended, and CS mixed samples. The charge passed through the samples are shown in Fig. 7. The control mix has passed 1863 coulombs, which is low as per recommendations of ASTM C 1202. With the substitution of 20% fly ash, the resistance of chloride ions is increased by its reduction in voids. With the rise of curing time of concrete, permeability decreases and passed 1012 coulombs at the age of 180 days. After adding fly ash at 20% constant, CS includes as fine aggregate again improved the chloride resistance of SCC. *N. Gupta. Et al. (2020)* [39] reported the similar results with the utilisation of CS as fine aggregate. CS helps to reduce the voids of concrete with its particle size adjustment. CS enhanced the resistance of chloride to 43% compared with the control mix at 28 days of age. At this age, all mix samples were recorded as low. However, at 90 and 180 days, except control mix remaining are scaled as very low chloride penetration. The maximum resistance is obtained at 50% CS substitution at all curing ages. The lowest charge passed was recorded as 401 coulombs, which is considered very low. CS as the fine aggregate replacement has better corrosion resistance, and deterioration of concrete due to chloride attack.

Ultrasonic pulse velocity

The quality of SCC was determined with the help of UPV in terms of the velocity of the pulse through the concrete. Conventional high-strength SCC at 28 days shows 4202 m/sec velocities, and by increasing the curing age from 90, 180 days, it has 4412 m/s 4574 m/s velocities. Fly ash used as supplementary cementitious material in SCC also improved the quality of concrete from 4202 to 4256 m/s, and its maximum increased to 4601 m/s at 180 days as shown in Fig. 8. River sand as fine aggregate replaced with CS gets an advantage by enhancing the quality of SCC. However, beyond 40% replacement level velocity of pulse reduced to lower than control mix at 100% level, it continued similarly for 90 days and 180 days. Sharma et al. (2017) reported the similar results. Pulse velocity decreased to above 40% levels depending on the cracks or voids available in the concrete matrix. The maximum velocity of a pulse generated for 180 days was 4920 m/s at 40% CS replacement in a 20% fly ash mix.

Sorptivity

Capillary voids of SCC were evaluated by the method of sorptivity, and initial absorption of high-strength SCC was determined. Water penetration or absorption of concrete is a key factor to know the durability of the concrete structure. For conventional high-strength SCC, sorptivity is 0.018 mm/

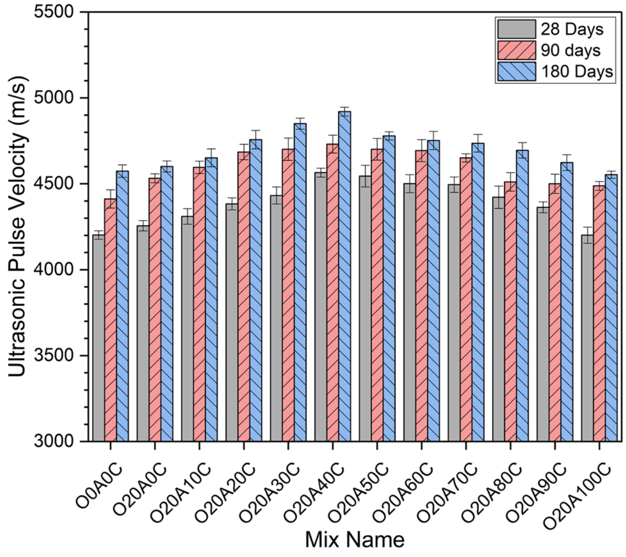

Fig. 8 UPV

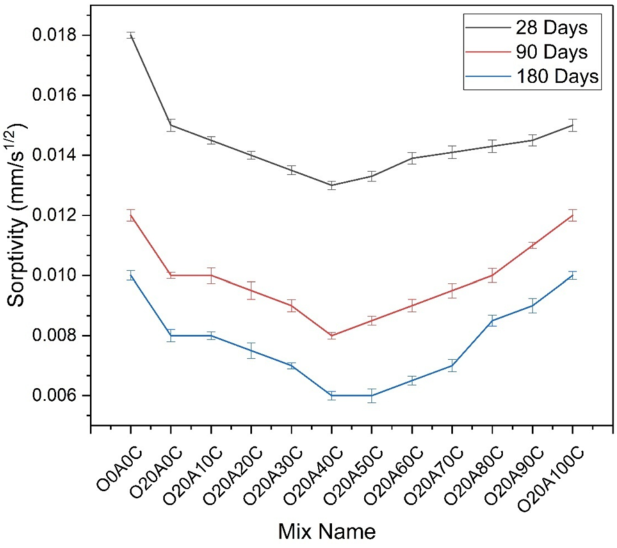

Fig. 9 Sorptivity

s$^{1/2}$ at 28 days, 0.012 mm/s$^{1/2}$ at 90 days, 0.01 mm/s$^{1/2}$ at 180 days of curing age. With the increase in the maturity period of concrete, voids are reduced with the hydration of cement particles and filled with hydrated products. After replacing cement with fly ash at 20%, sorptivity of 0.015, 0.01 and 0.008 mm/s$^{1/2}$ at 28, 90, and 180 days, respectively, presented in Fig. 9 and trends are similar to Sharma et al (2017). Using fly ash voids available in concrete matrix get occupied by secondary C–S–H formed with pozzolanic action of a mineral admixture. CS as fine aggregate also shows similar results of fly ash substitution. However, beyond 50% CS capillary voids have been increased may be due to a reduction of particle distribution across the concrete mixture. The lowest capillary voids occurred at 40% of CS level as indirectly assessed with water sorptivity of 0.013, 0.0085, and 0.006 mm/s$^{1/2}$ at 28, 90, and 180 days, respectively. But, 50% CS also presented approximately the same as of 40% CS level. From the results, it was concluded that at 40 and 50% CS has the least capillary action.

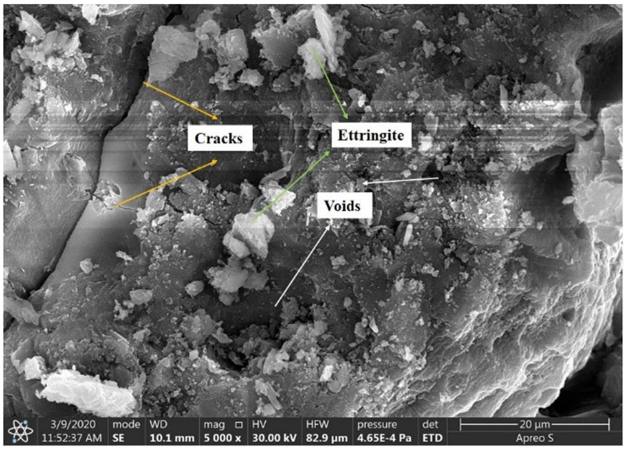

Fig. 10 O0A0C at 180 days

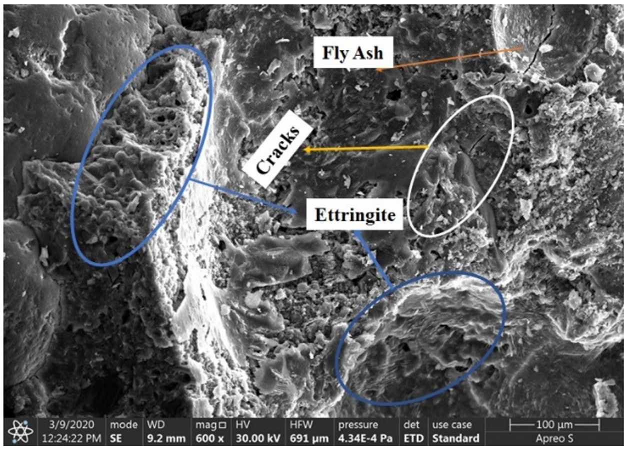

Fig. 11 O20A0C at 180 days

Microstructure

The microstructure of the high-strength SCC was observed with the help of a Scanning Electron Microscope (SEM). Samples were collected from the crushed cube of 150 × 150 × 150 mm after conducting a compressive strength test under a compression testing machine. Figures 10, 11, and 12 show the microstructure of control at the age of 180 days. It has been presenting the cracks available in the concrete, C–S–H, and ettringite formed by the hydration process. Figure 11, shows fly ash substituted high-strength

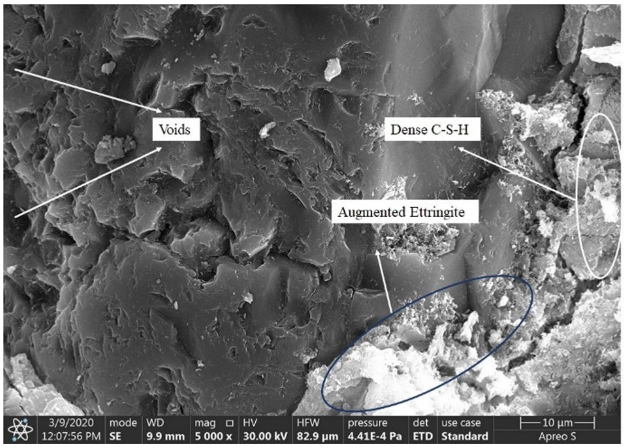

Fig. 12 O20A40C at 180 days

concrete microstructure. It contains not only spherical shaped fly ash particles but also ettringite formed with the pozzolanic action of fly ash in the concrete matrix. The hairline cracks were also observed and marked in the image, and some voids are available, which causes permeability. However, a huge quantity of hydrated products was seen in this fly ash-based high-strength SCC. Figure 12., represents fly ash 20% and 40% CS as fine aggregate mixed sample microstructure dense C–S–H than the remaining two samples. Ettringite is also enhanced with the combination of CS in SCC, which resulted in augmented ettringite in the SCC.

Conclusions

With the help of the above discussions, the following conclusions were drawn.

- All control and blended mixes satisfied the fresh properties of SCC as specified by EFNARC.
- Copper slag as fine aggregate improved the fresh properties of SCC when compared with the control mix and as well as with 20% fly ash.
- Mechanical properties of SCC with the increase in substitution of CS as fine aggregate has been enhanced up to a 40% level. Beyond this, strengths get decreased. Compressive, splitting tensile, and flexural strengths were obtained maximum at 40% CS replacement. It may be due to enhanced ettringite formation in the concrete matrix.
- The resistance against chloride ion permeability has improved with CS in SCC as fine aggregate up to 50% replacement levels. All SCC mixes show good resistance against chloride ion penetration but, 50% has the highest.
- The quality of concrete was assessed using pulse velocity, CS in SCC increased the quality by increasing CS to 40%. Control SCC also has a good quality of concrete. CS reduces the cracks and voids in the concrete matrix resulting in an improvement in the quality of concrete.
- Capillary voids in the SCC get reduced with the usage of CS. Smaller sizes of CS particles adjusted in the voids of the concrete matrix resulted from the reduction in capillary voids.

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Declarations

Competing interests The authors declare no competing interests.

Conflict of interest No conflict of interest to declare.

References

Afshoon, I., & Sharifi, Y. (2020). Utilization of micro copper slag in SCC subjected to high temperature. *J Ournal of Building Engineering*. https://doi.org/10.1016/j.jobe.2019.101128I

K. S. Al-Jabri, A. H. Al-Saidy, and R. Taha,(2011) Effect of copper slag as a fine aggregate on the properties of cement mortars and concrete,*Construction and Building Materials*., https://doi.org/10.1016/j.conbuildmat.2010.06.090.

Almohammad-albakkar, M., & Behfarnia, K. (2021). Water penetration resistance of the self-compacting concrete by the combined addition of micro and nano-silica. *Asian Journal of Civil Engineering, 22*, 1–12. https://doi.org/10.1007/s42107-020-00293-5

M. A. S. Anjos, A. Camões, P. Campos, G. A. Azeredo, and R. L. S. Ferreira,(2020) Effect of high volume fly ash and metakaolin with and without hydrated lime on the properties of self-compacting concrete, *Journal of Building Engineering*., 27, https://doi.org/10.1016/j.jobe.2019.100985.

S. Arunchaitanya and E. Arunakanthi,(2019) Usage of mineral admixtures in self compacting concrete—A review, *International Journal of Innovative Technology and Exploring Engineering*., 8(3),.

K. G. Babu and G. S. Nageswara Rao,(1993) Efficiency of fly ash in concrete, *Cement and concrete composites*., vol. 15(4), 223–229, https://doi.org/10.1016/0958-9465(93)90025-5.

Buari, T. A., Olutoge, F. A., Ayinnuola, G. M., Okeyinka, O. M., & Adeleke, J. S. (2019). Short term durability study of groundnut shell ash blended self consolidating high performance concrete in sulphate and acid environments. *Asian Journal of Civil Engineering, 20*, 649–658. https://doi.org/10.1007/s42107-019-00131-3

S. Chithra, S. R. R. Senthil Kumar, and K. Chinnaraju,(2016)The effect of Colloidal Nano-silica on workability, mechanical and durability properties of High Performance Concrete with Copper slag as partial fine aggregate, *Construction and Building Materials*., 113, 794–804, 2016, https://doi.org/10.1016/j.conbuildmat..03.119.

R. Choudhary, R. Gupta, and R. Nagar, (2019) Impact on fresh, mechanical, and microstructural properties of high strength self-compacting concrete by marble cutting slurry waste, fly ash, and silica fume, *Construction and Building Materials*, 239, 117888, 2020, https://doi.org/10.1016/j.conbuildmat..117888.

Y. T. H. Cu, M. V. Tran, C. H. Ho, and P. H. Nguyen,(2020) Relationship between workability and rheological parameters of self-compacting concrete used for vertical pump up to supertall buildings, Journal of Building Engineering, 32, 101786, https://doi.org/10.1016/j.jobe.2020.101786.

V. M. C. F. Cunha, J. A. O. Barros, and J. M. Sena-Cruz,(2010) PulloutBehavior of Steel Fibers in Self-Compacting Concrete,*Journal of Materials in Civil Engineering*., 22(1), 1–9, https://doi.org/10.1061/(asce)mt.1943-5533.0000001.

H. A. F. Dehwah,(2012) Mechanical properties of self-compacting concrete incorporating quarry dust powder, silica fume or fly ash,*Construction and Building Materials*., 26(1), pp. 547–551, https://doi.org/10.1016/j.conbuildmat.2011.06.056.

P. Dinakar, M. Kartik Reddy, and M. Sharma,(2013) Behaviour of self compacting concrete using Portland pozzolana cement with different levels of fly ash, *Materials and Design,* 46, 609–616, https://doi.org/10.1016/j.matdes.2012.11.015.

A. R. Esquinas, J. I. Álvarez, J. R. Jiménez, and J. M. Fernández,(2018) Durability of self-compacting concrete made from non-conforming fly ash from coal-fired power plants, *Construction and Building Materials*., 189, 993–1006, https://doi.org/10.1016/j.conbuildmat.2018.09.056.

L. García, M. Valcuende, S. Balasch, and J. Fernández-LLebrez,(2013) Study of Robustness of Self-Compacting Concretes Made with Low Fines Content, *Journal of Materials in Civil Engineering*. 25(4), 497–503, https://doi.org/10.1061/(asce)mt.1943-5533.0000609.

S. Geetha and S. Madhavan (2017) High Performance Concrete with Copper slag for Marine Environment, *Materials: Today Proceeding*., 4(2), 3525–3533, https://doi.org/10.1016/j.matpr.2017.02.243.

N. Gupta, Rafat Siddique (2020) Durability characteristics of self-compacting concrete made with copper slag. *Construction and Building Materials*., 247, https://doi.org/10.1016/j.conbuildmat.2020.118580

Guru Jawahar, J., Yakshareddy, B., Sashidhar, C., Sreenivasulu, C., & Ramana Reddy, I. V. (2018). Evolution of 112-day drying shrinkage equation of fly ash blended self-compacting concrete. *Asian Journal of Civil Engineering, 19*, 703–712. https://doi.org/10.1007/s42107-018-0054-z

K. Ishimaru, H. Mizuguchi, C. Hashimoto, T. Ueda, K. Fujita, and M. Ohmi,(2005) Properties of concrete using copper slag and second class fly ash as a part of fine aggregate, Zair. *Journal-Society of Materials Science Japan*, 54(8), 828–833, Aug. 2005, https://doi.org/10.2472/jsms.54.828.

M. Jalal, A. Pouladkhan, O. F. Harandi, and D. Jafari,(2015) Comparative study on effects of Class F fly ash, nano silica and silica fume on properties of high performance self compacting concrete, *Construction and Building Materials*., https://doi.org/10.1016/j.conbuildmat.2015.07.001.

Kandasamy, S., & Kothandaraman, S. (2020). The effect of formwork liner on the service life of self-compacting concrete. *Asian Journal of Civil Engineering, 21*, 1239–1247. https://doi.org/10.1007/s42107-020-00272-w

V. Kannan and K. Ganesan,(2016) Effect of Tricalcium Aluminate on Durability Properties of Self-Compacting Concrete Incorporating Rice Husk Ash and Metakaolin, *Journal of Materials in Civil Engineering*., 28(1), p 04015063, https://doi.org/10.1061/(asce)mt.1943-5533.0001330.

A. R. Lori, A. Hassani, and R. Sedghi,(2019)Investigating the mechanical and hydraulic characteristics of pervious concrete containing copper slag as coarse aggregate, *Construction and Building Materials*., 197, 130–142, https://doi.org/10.1016/j.conbuildmat.2018.11.230.

Mithun, B. M., & Narasimhan, M. C. (2015). Performance of alkali activated slag concrete mixes incorporating copper slag as fine aggregate. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2015.06.026

B. H. Nagaratnam, M. A. Mannan, M. E. Rahman, A. K. Mirasa,(2019) A. Richardson, and O. Nabinejad, Strength and microstructural characteristics of palm oil fuel ash and fly ash as binary and ternary blends in Self-Compacting concrete*, Construction and Building Materials*., 202, 103–120, https://doi.org/10.1016/j.conbuildmat.2018.12.139.

A. Nainwal, P. K. Emani, M. C. Shah, A. Negi, V. Kumar, and P. Negi,(2021) The influence of Metakaolin on the copper slag substituted concrete with the fine aggregate of Beas river, *Materials Today:Proceedings*., no. xxxx, https://doi.org/10.1016/j.matpr.2020.12.981.

A. S. Reddy, P. R. Kumar, and P. A. Raj,(2020) Development of Sustainable Performance Index (SPI) for Self-Compacting Concretes,*Journal of Building Engineering*, 27, 100974, https://doi.org/10.1016/j.jobe.2019.100974.

G.M. Sadiqul Islam, Muhammad Tanveer Raihan, Md. Mehedi hasan, Md. Rashadin (2019) Effect of retarding superplasticizers on the properties of cement paste, mortar and concrete. *Asian Journal of Civil Engineering*, 20, 591-601, https://doi.org/10.1007/s42107-019-00128-y

A. K. Saha,(2018) Effect of class F fly ash on the durability properties of concrete, *Sustainable Environment Research*., 28(1),. 25–31, https://doi.org/10.1016/j.serj.2017.09.001.

Sharifi, Y., Afshoon, I., MortezaNematollahzade, M. G., & Momeni, M.-A. (2020). Effect of copper slag on the resistance characteristics of SCC exposed to the acidic environment. *Asian Journal of Civil Engineering, 21*, 597–609. https://doi.org/10.1007/s42107-019-00218-x

R. Sharma, Riwaz A. khan (2020) Carbonation Resistance of Self-Compacting Concrete Incorporating Copper slag as Fine aggregate, *American Society of Civil Engineering*, 32, https://doi.org/10.1061/(ASCE)MT.1943-5533.0003200

Sharma, R., & Khan, R. A. (2017). Durability assessment of self compacting concrete incorporating copper slag as fine aggregate. *Construction and Building Materials., 155*, 617–629. https://doi.org/10.1016/j.conbuildmat.2017.08.074

R. Siddique, Properties of self-compacting concrete containing class F fly ash, *Materials and Design.,* 32(3), pp. 1501–1507, 2011, https://doi.org/10.1016/j.matdes.2010.08.043.

M. Soleymani Ashtiani, A. N. Scott, and R. P. Dhakal (2013) Mechanical and fresh properties of high-strength self-compacting concrete containing class C fly ash, *Construction and Building Materials*., 47, 1217–1224, 2013, https://doi.org/10.1016/j.conbuildmat..06.015.

Sandip Sonule, K.C.tayade, N.V.P.Vidyasagar, Avani Bhushan gupta (2021) A case study on performance of self-compacting concrete in highly congested reinforcement of cast in situ structure. *Asian Journal of Civil Engineering*, 22, 1423-1432, https://doi.org/10.1007/s42107-021-00378-9

G. Sua-iam and N. Makul (2017) Incorporation of high-volume fly ash waste and high-volume recycled alumina waste in the production of self-consolidating concrete, *Journal of clean Production*., https://doi.org/10.1016/j.jclepro.2017.05.075.

M. D. A. Thomas,(2007) Optimising the Use of Fly Ash in Concrete, *Portland Cement Association*., 24,.

M. Toledano-Prados, M. Lorenzo-Pesqueira, B. González-Fonteboa, and S. Seara-Paz,(2013) Effect of polycarboxylate superplasticisers on large amounts of fly ash cements, *Construction and Building Materials*., 48, 628–635, https://doi.org/10.1016/j.conbuildmat.2013.07.069.

Z. T. Yao et al. (2014) A comprehensive review on the applications of coal fly ash, *Earth-Science Reviews*. 2015, https://doi.org/10.1016/j.earscirev.11.016.