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A Dissertation Project Report on

"EFFECT OF PARAMETERS ON SELF-COMPACTING CONCRETE USYING TAGUCHI METHOD"

Submitted in partial fulfilment for the award of the degree of

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BY

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Certificate

This is to certify that the project work entitled **"EFFECT OF PARAMETERS ON SELF-COMPACTING CONCRETE USYING TAGUCHI METHOD"** has been successfully completed by *Mr. SUBHASH N REDDY* (USN 1CR16CV064), *Mr. SAMPATH LAMANI* (USN 1CR16CV054), *Mr. ROHIT C N* (USN 1CR15CV053) *, Mr. YAMANESH (USN 1CR15CV107), bonafide students of CMR Institute of technology in partial fulfilment of the requirement for the award of degree of Bachelor of Engineering in Civil Engineering of the* ***"VISVESVARYA TECHNOLOGICAL UNIVERSITY",*** *Belgaum during the academic year 2017-18. It is certified that all corrections indicated for internal assessment has been incorporated in the Report. The project report has been approved as it satisfies the academic requirements in respect of project work prescribed for the said Degree.*

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DECLARATION

We, **Mr. Subhash N Reddy, Mr. Sampath Lamani, Mr. Rohit C N, Mr. Yamanesh** bonafide students of CMR Institute of Technology, Bangalore, hereby declare that dissertation entitled **"EFFECT OF PARAMETERS ON SELF-COMPACTING CONCRETE USYING TAGUCHI METHOD"** has been carried out by us under the guidance of **Mr. Jithendra Reddy C** Department of Civil Engineering, CMR Institute of Technology, Bangalore, in partial fulfilment of the requirement for the award of degree of Bachelor of Engineering in **Civil Engineering** of the Visvesvaraya Technological University, Belgaum during the academic year 2017-2018. The work done in this dissertation report is original and it has not been submitted for any other degree in any university.

ABSTRACT

Self-compacting concrete is a special kind of concrete that can permeate and fill the gaps of reinforcement and the corners of moulds without any desideratum of vibration and compaction during the placing process. The highly fluid nature of SCC makes it suitable for placing in difficult conditions and in sections with congested reinforcement. Development of self-compacted concrete is a desirable achievement in the construction company in order to resolve the issues associated with casting the concrete in place. Considering lack of uniformity and complete compaction of concrete by vibration, researchers at the University of Tokyo, Japan, started developing SSC in the late 1980's and by 1990's they have develop and start to use the SCC that does not require vibration to achieve full compaction. In 1996, a large consortium of European countries embarks on a project aimed at developing SSC for practical applications, as these countries were interested in exploring the significance and potentials of SCC developed by Japan.

The amount of reinforcement bars or the arrangement of structures does not affect self-compacting concrete because of its high fluidity and resistance to segregation it can also be pumped to longer distance. The elimination of vibration leads to an improved concrete quality, decreased skilled labour and shortens the time needed for construction. On the other hand, vibrating the concrete creates noise that has a noxious physical impact on workers and affects the surrounding neighbourhood. The self-compacting concrete is widely used in post or pretension concrete sections. It possesses the ability to moulded into any shape with the help of mould. It is used in congested areas were compaction equipment's cannot be used. Thus reducing the cost of the structure to about one tenth of the total cost of structure.

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Chapter 1

INTRODUCTION

Self-compacting concrete is a special kind of concrete that can permeate and fill the gaps of reinforcement and the corners of moulds without any desideratum of vibration and compaction during the placing process. The highly fluid nature of SCC makes it suitable for placing in difficult conditions and in sections with congested reinforcement. Development of self-compacted concrete is a desirable achievement in the construction company in order to resolve the issues associated with casting the concrete in place. Considering lack of uniformity and complete compaction of concrete by vibration, researchers at the University of Tokyo, Japan, started developing SSC in the late 1980's and by 1990's they have develop and start to use the SCC that does not require vibration to achieve full compaction. In 1996, a large consortium of European countries embarks on a project aimed at developing SSC for practical applications, as these countries were interested in exploring the significance and potentials of SCC developed by Japan.

The amount of reinforcement bars or the arrangement of structures does not affect self-compacting concrete because of its high fluidity and resistance to segregation it can also be pumped to longer distance. The elimination of vibration leads to an improved concrete quality, decreased skilled labour and shortens the time needed for construction. On the other hand, vibrating the concrete creates noise that has a noxious physical impact on workers and affects the surrounding neighbourhood. The self-compacting concrete is widely used in post or pretension concrete sections. It possesses the ability to moulded into any shape with the help of mould. It is used in congested areas were compaction equipment's cannot be used. Thus reducing the cost of the structure to about one tenth of the total cost of structure.

Some of the advantages of Self-compacting concrete include the following; It can be placed faster without mechanical vibration which course reduction in placement cost ,Better and more uniform structural surface finish with little or no remedial surface work, Hard to reach areas and restricted sections can be filled easily, Creating structural and architectural shapes and surfaces finish difficult to obtained usin g conventional concrete, Better consolidation around reinforcement and Better pumping ability.

Chapter 2

Literature review

Self-compacting concrete (SCC), also known as self-consol- idated flowable concrete, has the ability to consolidate under its own weight. It was introduced by Prof. Okamura at Ouchi University, Japan, in 1986. Due to flowability, SCC does not require any kind of vibration. Self-compacting concrete is commonly used in heavy reinforced sections.

According to ASTM C 125, admixture is defined as a material, other than basic raw materials, used in mortar and concrete to improve its certain properties and added immediately before or dur- ing mixing (Mehta and Monteiro 2006). Various studies have been conducted on the self-compacting concrete using com- bination of mineral admixtures such as metakaolin (MK), fly ash (FA), rice husk ash (RHA), silica fume (SF), ground- granulated blast-furnace slag (GGBFS), fibers and chemical admixtures, i.e., accelerators, retarders, water reducers and air entrainers. The admixtures are divided into two catego- ries, namely mineral admixtures and chemical admixtures (Fig. 1).

Mineral admixtures or supplementary cementitious materials (SCMs) are classified as cementitious, highly poz- zolanic, normally pozzolanic, cementitious and pozzolanic and weak pozzolanic. Pozzolanas are the siliceous and alu- minum materials having few or no cementitious properties by themselves as well as finely grounded; they react with calcium hydroxide in the presence of moisture at ordinary temperature to form compounds of cementitious properties (ASTM C595).

Chemical admixtures ensure the quality of concrete during mixing, transporting, placing and curing. Types of chemical admixtures are accelerators, retarders, water-reducing agent, superplasticizer, air-entraining agent and special purpose admixtures such as shrinkage reduc- ers, corrosion inhibitors, alkali–silica reactivity inhibitors and colouring.

The action of water-reducing admixtures or plasticizers includes dispersion, lubrication and retardation. Superplasticizers or high-range water reducers are the most effective type of water-reducing admixtures.

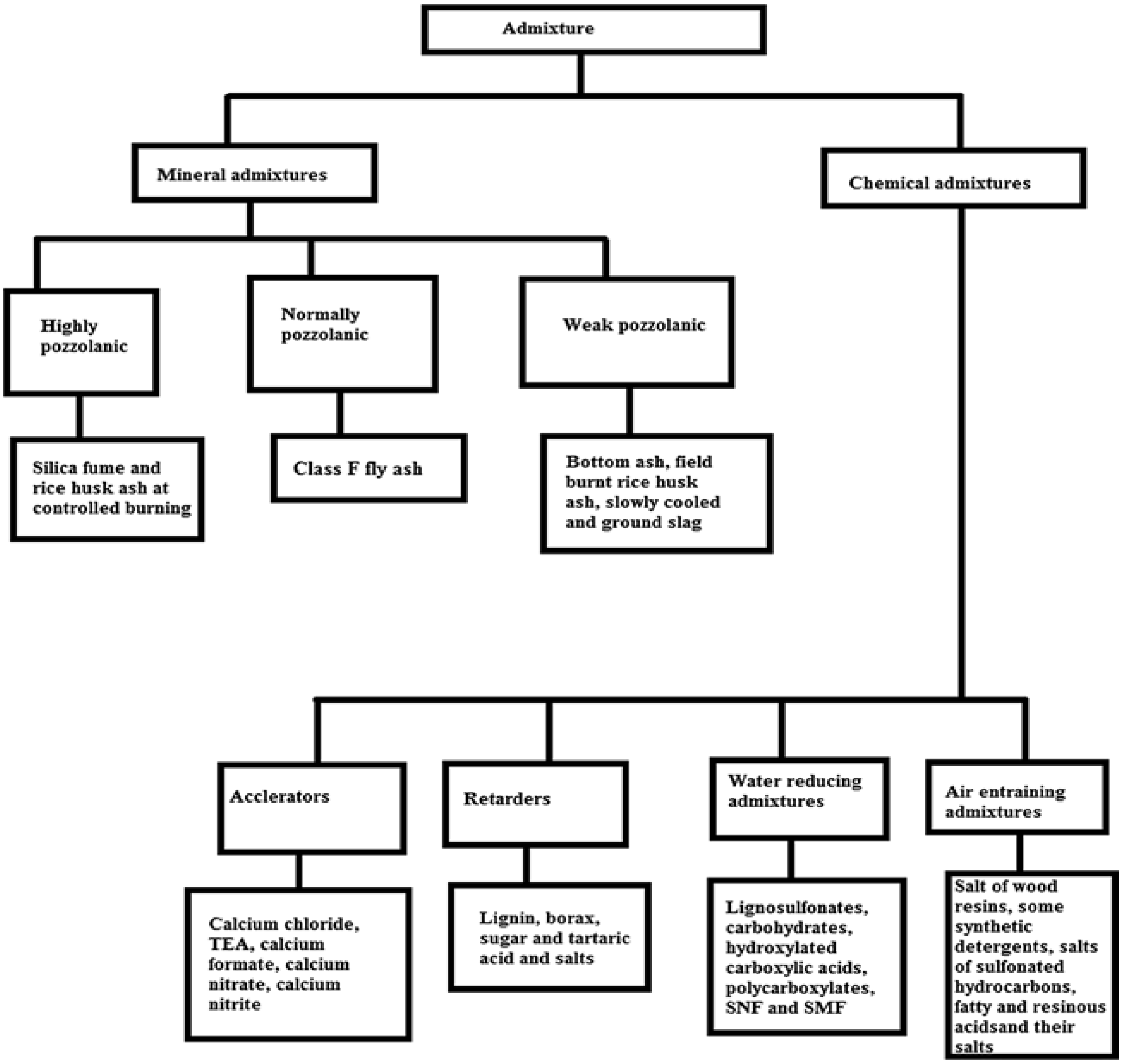

FIGURE 1: classification of Admixtures

Commonly used superplasticizers are sulfonated melamine formalde- hyde condensate (SMF), sulfonated naphthalene formalde- hyde condensates (SNF) and polycarboxylate ether-based superplasticizers (PCE).The setting accelerators and hardening accelerators are two main types of accelerators. The set retarder admixtures extend the stiffening of cement which helps in transporting long distance and place at high temperature.

The commonly used retarders are calcium lingo sulfate and carbohydrates derivatives and are used in fraction of percentage by weight of cement. Air-entraining admixtures create millions of tiny air bubbles which relieve the expansion pressure. In the pre- sent paper, mineral admixtures (SF, GGBFS, MK, RHA, FA, fiber and LP) and chemical admixtures (SMF, SNF and PCE) used in the self-compacting concrete

have been dis- cussed in detail. The classification of various rheological, mechanical resistance and durability properties of SCC is shown in Fig.

2.1. Admixtures

As each admixture has different effects on various properties of SCC, it is necessary to understand the behavior of each admixture separately and in combination. A critical review of the use and influence of mineral and chemical admixtures on distinct properties of SCC is given in the following.

2.1.1. Silica Fume

Silica fume (SF) or condensed silica fume is a volatile sil- ica or micro-silica, an artificial pozzolanic admixture used in ordinary concrete. It is an industrial by-product formed during the reduction of highly pure quartz with coal in an electric arc furnace in the manufacturing of silicon or fer-rosilicon alloy. The work done by various researchers on silica fume in self-compacting concrete (SCC) mix is listed in Table1.

2.1.1.1 FreshProperties

Table 1 shows that SF concrete mix was more cohesive than plain concrete. Change in SP dosages decreased the yield shear stress, but increased bleeding (Türkmen and Kantarcı2007). Addition of SF increased SP dosages. Combination of SF, FA and LP improved workability in comparison with individual in the mixtures (Turkel and Altuntas 2009). Zeo- lite (10% and 20%) and SF increased SP demand compared with control mix due to the presence of large amount of pores in structure and high specific area, but FA decreased SP demand due to its spherical geometry (Sabet et al. 2013). Carbon fiber affected segregation resistance, filling and pass- ing ability due to the reduction in fluidity of concrete. T50 slump flow time increased with carbon fiber content, because carbon fiber made SCC more viscous which slowed the flow of concrete (Yakhlaf et al. 2013). SF and NS decreased flowability, but improved consistency, while FA had oppo- site behavior. Nano-silica up to 2% had no effect on work- ability. An increase in FA increased slump flow diameter, but V-funnel flow time decreased.

The combination of NS and SF caused less bleeding and segregation (Jalal et al. 2015). Pumice powder degraded the workability with time. Pumice powder had good segregation resistance, flow and passing ability (Granata 2015). The increase in FA content decreased SP dosages at certain dosages. Incorporation of SF and RHA reduced mini-SLF, but increased T_{250} time and RHA were more effective than SF. Mini-SLF and T_{250} time were con- stant except FA (40%) with lower mini-SLF and higher T_{250} time. An increase in SP dosages decreased the plastic vis- cosity, but increased flowability. Dosages of SP higher than of SSD had no effect on plastic viscosity and flowability, but resulted in bleeding. The use of FA/SF decreased SSD of mortar, plastic viscosity and segregation resistance of SCHPC, but increased filling and passing ability, whereas RHA had opposite nature due to macro–mesopore structure. RHA was more efficient at higher replacement (Le and Lud- wig 2016). Self-compacting mortar (SCM) mix with FA had better rheological properties than SF and control mix. The increase in Class C, FA decreased relative slump values, because FA reduced friction between particles by dispersing cement particles. SF decreased the workability due to high surface area and finer particles size. FA increased the vis- cosity, while SF decreased the viscosity (Benli et al. 2017).

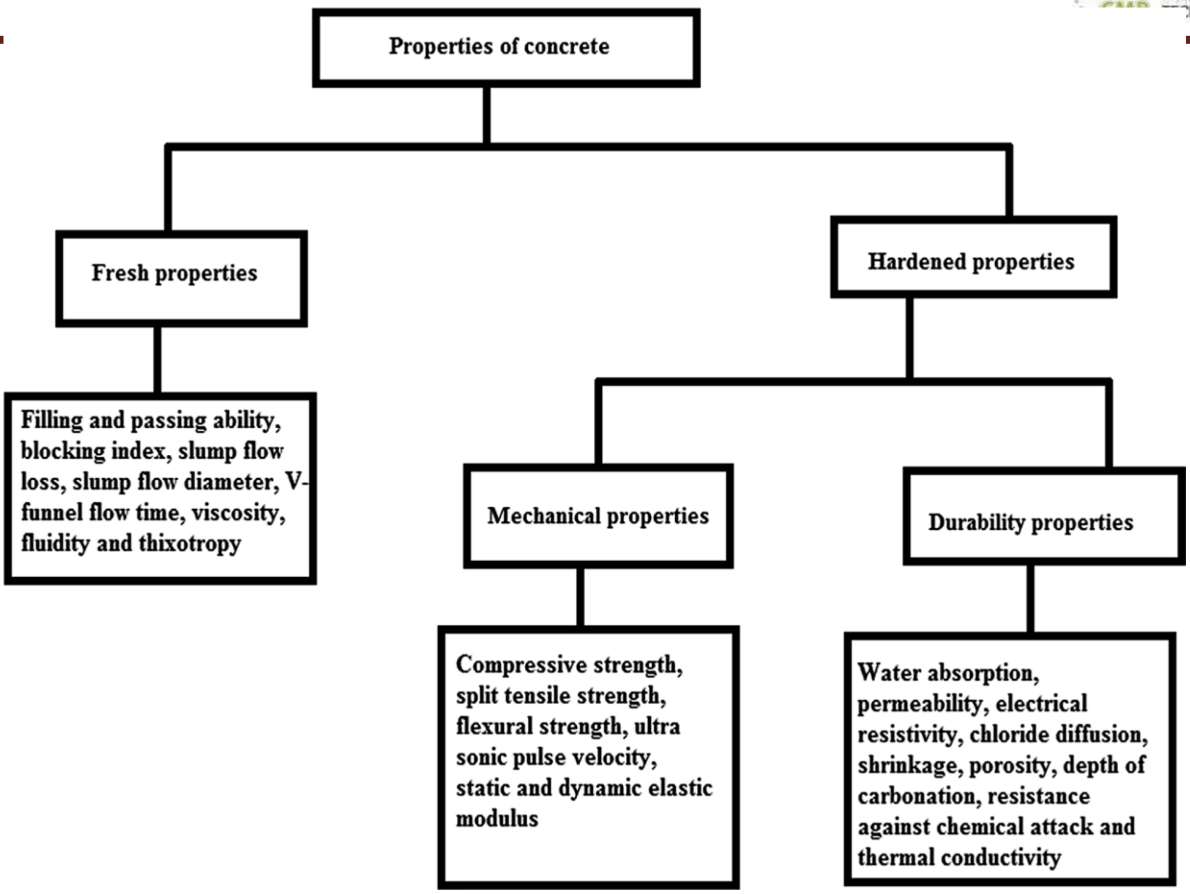

Fig.2 Properties of self-compacting concrete

Table 1 Effect of silica fume on SCC

References	Concrete mix or mortar	Replacement (%)	Mineral admixture other than SF (%)	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Türkmen and Kantarcı (2007)	SCC mixtures with expanded perlite aggregates (EPA) 0, 5, 10 and 15% and with w/cm 0.35	10%	–	PCE-based SP (2%)	Concrete with SF had more cohesiveness than plain concrete. Change in SP dosages decreased the yield shear stress, but increased bleeding	Dry unit weight decreased with the increase in EPA due to lower specific gravity of EPA. EPA reduced the compressive strength in comparison with natural aggregates due to filler effect of EPA	Concrete with EPA had higher capillarity coefficient than that of NA due to large capillary pores. Apparent viscosity at 28 days increased with the increase in EPA
Turkel and Altuntas (2009)	SCC with *w*/*b* 0.50 and sand/binder ratio 2.25	5, 10 and 30	FA 10, 15, 20, 25 and 30 and LP 5, 10 and 30	Polycarboxylic (PC) polymer-based HRWR 0–8%	Combination of FA, SF and LP improved workability compared with individual	SF at 30% had maximum C.S., but LP at 30% had the lowest C.S. and F.S. SF at 10% and FA at 20% had maximum F.S.	FA (20%) and LP (10%) had the highest water absorption for 24 h
Dahwah ((2012)	SCC with w/cm 0.38 and 0.40	5	FA 10 and quarry dust powder (QDP) 8–10	Modified PCE 1–1.8 l/100 kg and stabilizer 0.5 l/100 kg	–	SCC with QDP had higher C.S., S.T.S., F.S. and UPV than that of (QDP + SF) or FA alone	–
Sabet et al. (2013)	Self-compacting concrete with w/cm 0.33	0-20	Natural pozzolana and FA were 0–20 each	PC-based SP. 0.8–2.9%	FA and zeolite (Z) increased SP demand, while FA decreased SP demand to some extent	Z at 10% increased C.S., but decreased at 20% zeolite. SF and FA increased C.S.	Mineral admixture increased electrical resistivity at later age and reduced final absorption. Z reduced chloride diffusion compared to FA
Yakhlaf et al. (2013)	SCC with *w*/*b* 0.35 and 0.40	10	Pitch-based carbon fiber (CF) was 0, 0.25, 0.5, 0.75, 1	HRWR 1.5–8.0% and 1.0–7.0%	HRWR improved filling and passing ability, but reduced blocking index. CF increased filling ability and blocking index, but decreased stability index and fluidity	CF increased unit weight	–

Table 1 (continued)

References	Concrete mix or mortar	Replacement (%)	Mineral admixture other than SF (%)	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Jalal et al. (2015)	High-performance self-compacting concrete with *w*/*b* 0.38	10	Silica nanoparticles (NS) 2, combination of (10 SF+2 NS) and FAC 5, 10 and 15	PCE-based SP 2.5 and 3.12 kg/m^3 and VMA 2 and 2.5 kg/m^3	SF and NS decreased flowability, but improved consistency, while FA had opposite behavior	C.S., F.S. and S.T.S. increased with the decrease in FA and increase in binder content. The increase in SF, NS and their combination increased C.S. SF+NS increased S.T.S. and F.S.	NS reduced porosity. SF and NS improved pore structure. SF at 10%, NS at 2% and their combination and FA reduced capillary water absorption and chloride ion penetration
Granata (2015)	SC1 (SCC with SF and P.P.), SC2 (SCC with C.P.), SCP (SCC with P.P.) and w/c 0.45	35.4 kg/m^3	Calcareous powder (C.P.) 100 kg/m^3 and pumice powder (P.P.) 20 and 38.5%	PCE-based SP HRWR 6488, 5913, 6914 and 5000 g/m^3 and VMA 3244, 3548, 3457 kg/m^3	SCC with P.P. had good flowability, passing ability and segregation resistance	SC1, SC2 and SCP had higher C.S. and S.T.S. SC1 and SC2 had ductile behavior, but SCP had brittle behavior	SCC mixture had higher total shrinkage value than that of OPC
Leung et al. (2016)	SCC with *w*/*b* 0.38	0%, 5%, 10% and 15%	Class F fly ash (0%, 12.9, 20%, 30%, 40% and 50%)	PC polymer-based SP and liquid polymer-based VMA	–	Combination of SF and FA increased compressive strength 28 days	FA and SF reduced water absorption and sorptivity. Effect of SF was higher than of FA in case of water absorption
Ghoddousi and Saadabadi (2017)	SCC with w/cm 0.45	36 kg/m^3	Limestone powder (150 kg/m^3) and MK (90 kg/m^3)	PC-based SP with density of 1.01 g/cm^3	MK has higher pozzolanic properties and their pozzolanic reaction starts earlier than MK	–	Inclusion of SF and MK increased electrical resistivity (ER) at 28 days and MK had higher ER than SF. ER increased with the increase in curing age

Table 1 (continued)

References	Concrete mix or mortar	Replacement (%)	Mineral admixture other than SF (%)	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Benli et al. (2017)	Self-compacting mortar (SCM) in water and magnesium sulfate (10%) and *w*/*b* 0.42–0.52	6, 9, 12 and 15%	FA (10, 20 and 30) and combination FA (10%) + & SF (6, 9, 12 and 15%) and FA (20%) + SF (6& 9%)	Modified PC-based polymer type SP (8 kg/m^3)	All SCM mixes gave satisfactory results in terms of fresh properties. FA performed better than SF. The increase in SF content decreased viscosity	T.S. of SCC specimens exposed to sulfate solution had higher values than water and sea water curing for all mixes, especially at 90 days. C.S. and T.S. decreased with the increase in FA content. Ternary mix of SCM exposed to $MgSO_4$ solution performed best for flexural tensile strength. Control mix under sea water curing had the best resistance for TS	Sorptivity coefficient increased with the increase in *w*/*b*. SF (15%) had maximum sorptivity coefficient and excellent sulfate resistance as exposure duration increased. SCM with SF had higher porosity than ternary blend of SCM

2.1.2 HardenedProperties

Dry unit weight decreased with an increase in EPA due to lower specific gravity of EPA. EPA reduced the compres- sive strength in comparison with natural aggregates due to filler effect of EPA (Türkmen and Kantarcı 2007). Silica fume (30%) had maximum compressive strength, but LP at30% had the lowest compressive and flexural strength. LP was more dominant than SF and FA in strength gain at early age. SF (10%) and FA (20%) had maximum flexural strength (Turkel and Altuntas 2009). QDP had higher C.S., S.T.S., flexural strength and UPV values than those of (QDP + SF) or FA alone mixture due to its better filling ability of fine particles of QDP. QDP alone resulted as cost-effective in areas where SF and FA had to be imported from other regions, due to non-availability locally (Dahwah 2012). Nat- ural zeolite (10%) increased compressive strength, but zeo- lite (20%) reduced it due to high voids content in concrete. SF and FA increased compressive strength due to filler effect between cement grains as well as their pozzolanic activity (Sabet et al. 2013). Carbon fiber decreased unit weight due to its lightweight (Yakhlaf et al. 2013). Compressive and split tensile strength increased with a decrease in FA at early age and an increase in binder content. An increase in SF, NS and their combination increased compressive strength. Combina- tion of SF and NS increased split tensile strength and flex- ural strength. Flexural strength decreased with the increase in FA content at early age. FA (15%) increased flexural strength at 90 days. Addition of nano-silica and hybrid fiber minimized the cracking and enhanced mechanical properties of UHPFRC (Jalal et al. 2015). Total shrinkage strain tended to be more than that predicted by CEB model code 90 after 10 days because of an increase in contribution of cement paste on shrinkage strain. Total shrinkage of SCC was higher than of OPC. SC1, SC2 and SCP had higher compressive strength and split tensile strength due to high pozzolanicity of pumice powder. SC1 and SC2 had ductile behavior, but SCP had brittle behavior (Granata 2015). FA up to 12.9% increased compressive strength and afterward it decreased strength, whereas SF increased the strength, because FA had larger particles size than SF and did not completely fill the voids. Combination of SF and FA increased compressive strength at 28 days due to pozzolanic reaction (Leung et al.2016). RHA was more dominant in enhancing the compressive strength, particularly at larger replacement and later age than FA due to higher pozzolanic reactivity and amorphous silica content. Combination of FA and RHA improved com- pressive strength. The increase in FA decreased early-age strength, but at later age it increased (Le and Ludwig 2016). All binary and ternary mixes of SCM and control specimens had higher compressive and tensile strength up to 90

days and then tended to decrease at 180 days when exposed to sulfate solution. Tensile strength of SCC when specimens exposed to sulfate solution had higher values for all mixes in comparison with that of specimens subjected to simple water curing and seawater curing, especially at 90 days. All SCM mix proportions decreased the compressive strength beyond 90 days curing except SF15 which had excellent sulfate resistance as exposure duration increased. Compressive and tensile strength decreased with the increase in replacement level of FA. SCM with SF had higher porosity than ternary blend of SCM. Ternary mixes of SCM performed best in all exposure condition in case of flexural tensile strength and FA10SF6 had the greatest value at 90 days. Control mix specimens exposed to sea water had higher resistance to tensile strength. Tensile strength of ternary mixture of SF and FA had higher value than binary except FA10 and SF6. Tensile strength decreased in sea water curing in case of binary mix of SF and FA (Benli et al. 2017).

2.1.3 DurabilityProperties

Concrete with EPA had higher capillarity coefficient than that of NA due to large capillary pores. Apparent viscosity at 28 days increased with the increase in EPA (Türkmen and Kantarcı 2007). Mineral addition (30%) had higher total water absorption than control mix except 30% SF. FA (20%) and LP (10%) had the highest water absorp- tion at 24 h (Turkel and Altuntas 2009). Mineral admix- ture increased electrical resistivity at later stage because pozzolanic reaction occurs at a slower rate, but reduced final absorption because of limited pore connectivity and lower porosity. SF was most effective in reducing final absorption. Natural zeolite was more effective in reduc- ing chloride diffusion than FA. Natural zeolite enhanced durability properties of SCHPC (Sabet et al. 2013). NS reduced porosity. SF and NS improved pore structure. SF (10%), NS (2%) and their combination decreased water absorption with the increase in binder content. SF (10%), NS (2%) and their combination and FA reduced capillary water absorption and chloride ion penetration. SF and especially silica nanoparticles improved pore structure of concrete. Nanoparticles reduced porosity and formed dense matrix (Jalal et al. 2015). Total shrinkage strain tended to be more than that predicted by CEB model code90 after 10 days. Total shrinkage of SCC had higher val- ues than of OPC (Granata 2015). Replacement of FA and SF reduced water absorption and sorptivity, because their particles filled the micro-air voids inside concrete mix. SF was more effective for water absorption than FA due to smaller particles of SF (Leung et al. 2016). Paste with SF and MK decreased CH content, but increased C–S–H at peak. The peak corresponding to $Ca(OH)_2$ for paste con- sisting of SF and MK decreased as compared to control mix due to

consumption of $Ca(OH)_2$ during pozzolanic reaction. SCC with SF and MK had higher electrical resis- tivity among all the mix proportions at 28 days. Control mix of SCC had higher electrical resistivity at 1, 3 and7 days due to lesser amount of cement and higher w/c with pozzolana materials as partial replacement. SCC with MK had higher electrical resistivity than that with SF, because MK had higher pozzolanic properties and their pozzolanic reaction started at early age. Electrical resistivity increased with the increase in curing age (Ghoddousi and Saadabadi2017). Sorptivity coefficient increased with the increase in *w*/*b* ratio. SF (15%) had the highest value of sorptivity coefficient (Benli et al. 2017).

2.2 Ground-Granulated Blast-Furnace Slag

Ground-granulated blast-furnace slag (GGBFS) is a non- metallic product consisting of silicate and aluminates of calcium and other bases. GGBFS is obtained from molten iron slag produced from blast furnace in water or steam, to a produce glassy and granular product which is dried and ground into fine powder. GGBS in combination with OPC or other pozzolanic material gives a durable con- crete (Shetty 2005). It improved workability, durability to thermal cracking, resistance to sulfate and chloride attack, lowered heat of hydration, water demand and permeability and increased long-term strength. GGBFS can be used in ready-mixed concrete, precast concrete, mortar, grout, etc. The work done by the various researchers to study the dif- ferent properties of SCC with GGBFS is listed in Table 2.

2.2.1 FreshProperties

Table 2 shows that MP increased SP demand, viscosity and mini V-funnel flow time while GGBFS reduced it. Ter- nary use of GGBFS and MP decreased viscosity. Binary and ternary blend of PC, MP and GGBFS delayed set- ting time (Güneyisi et al. 2009). Slump flow diameter was670–730 mm, T50 value was less than 7 s, V-funnel flow time was 6.3–37 s, and H_2/H_1 ratio was 0.704–0.976 (Güney- isi et al. 2010). FA increased fluidity and bleeding due to its lubricating effect, smooth surface characteristics and high surface area, but MK decreased fluidity, water film thick- ness and eliminated bleeding. FA decreased resistance to segregation. Water film thickness and fluidity decreased with prolonging mixing time. An increase in water film thickness decreased the stability of mixture. SCC (FA up to 20% and *w*/*b* ratio 0.35) mixture was stable and had no significant effect on fluidity with mixing time while mixtures were prone to instability when FA content was more than 20%. Incorporation of MK with FA provided stability to mix when mixing time was prolonged. MK (10–30%) reduced segregation index with

w/*b* ratio (0.45) due to high fineness and surface area (Mehdipour et al. 2013). LLFA reduced water demand. LLFA and GBFS improved passing ability and flowability, but reduced viscosity. Flow time decreased with an increase in MC content (Beycioğlu and Aruntaş 2014). MK, SF and FAC enhanced HRWR demand than that of FAF, BFS and only PC. An increase in HRWR demand due to SF was due to its very high fineness and surface area, and MK was due to elongated shape, regular structure and high surface area. A decrease in HRWR due to BFS was attrib- uted to glassy slag particles and smooth surface. FAC, MK and VMA increased plastic viscosity because of elongated shape and irregular surface texture, but SF, FAF and BFS reduced this due to spherical shape of particles. Plastic vis- cosity decreased and yield stress increased with the increase in *w*/*b* ratio. MK, FAC and VMA increased V-funnel flow time, while SF, FAF and BFS reduced it. The increase in *w*/*b* ratio decreased thixotropy and structural breakdown. FAC, FAF and BFS increased VSI and T50 flow time after50 min. of rest. MK and FAC increased torque plastic vis- cosity with time, but BFS decreased (Ahari et al. 2015a, b). MK and GGBS increased SP dosages, while FA decreased SP dosages. All SCC mixes satisfied EFNARC requirements (Dadsetan and Bai 2017).

2.2.2 HardenedProperties

Binary blend of MP with cement decreased compressive strength. The binary system of MP and GGBFS with PC had higher strength than that of ternary blend (Güneyisi et al. 2009). SF and MK increased compressive strength, but FA decreased strength and GGBFS had comparablestrength to control mix (Güneyisi et al. 2010). Addition of chemical and mineral admixtures increased the strength in comparison with normal concrete due to low porosity and less growth of calcium hydroxide (Druta et al. 2014). LLFA and GGBFS reduced split tensile strength and static elastic modulus. High-volume LLFA and GBFS reduced compressive strength at early age, but this reduction par- tially stopped at 90 days (Beycioğlu and Aruntaş 2014). SF and MK increased thixotropy and compressive strength. FAF decreased compressive strength, while FAC increased it (Ahari et al. 2015a, b). Compressive strength increased with the increase in FA content. GGBS increased compres- sive strength at all ages with higher *w*/*b* ratio, but at lower *w*/*b* ratio GGBS increased 28 days strength, but decreased at 7 days. MK increased compressive strength attributed to quick pozzolanic reaction and large surface area. GGBS and MK increased MOE, but decreased at 10% GGBS only (Dadsetan and Bai 2017).

Table 2 Effect of ground-granulated blast-furnace slag on self-compacting concrete

References	Concrete mix or mortar	Replacement (%)	Mineral admixture other than SF (%)	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Güneyisi et al. (2009)	Self-compacting mortar with w/c 0.40	20, 40 and 60	MP 5, 10, 15 and 20 and (GGBFS + MP) was 20, 40 and 60	PCE-based SP was 4.31–7.34 kg/m^3	MP increased SP demand, viscosity and mini V-funnel flow time, while GGBFS reduced this. MP + GGBFS increased setting time	MP reduced C.S. and GGBFS had C.S. comparable to control mix. Ternary use of MP, GGBFS and cement reduced C.S.	–
Güneyisi et al. (2010)	SCC with *w/b* 0.32 and 0.44	20, 40 and 60	FA (20, 40 and 60), SF and MK (5, 10 and 15 each)	PCE-based SP 2.8–12 kg/m^3	Slump flow diameter 670–730 mm, T50 value was < 7 s, V-funnel flow time was 6.3–37 s and H2/H1 ratio was 0.704 -0.976.	SF and MK increased C.S., but FA decreased strength and GGBFS had strength comparable to control mix	The increase in FA, MK and GGBFS decreased shrinkage, but SF increased it. Ternary and quaternary blend of SF decreased drying shrinkage
Mehdipour et al. (2013)	Self consolidating mortar with *w/b* 0.35 and 0.45 and MK/FA ratio was 1:3.	5, 10, 15, 20 and 25	FA 10, 20, 30, 40 and 50) and MK 10, 20 and 30)	1% PC-based SP	FA increased fluidity and bleeding, but MK decreased fluidity, water film thickness and eliminated bleeding	–	–
Druta et al. (2014)	SCC and NVC with w/c 0.3–0.6	25	SF 15 and MK 5	HRWR 20, 50, 80, 100 and 340 ml and VMA 0, 15, 25, 50, 100 ml	–	Strength of SCC was greater than vibrated concrete	–
Beycioğlu and Aruntaş (2014)	SCC with w/cm 0.30–0.34.	20–60	Micronized calcite 5 and 10. Low lime FA (LLFA) 20–60	PC-based HRWR 6.5 kg/m^3	LLFA reduced water demand, viscosity, but improved passing and filling ability	LLFA and GGBFS reduced S.T.S. and static elastic modulus. C.S. reduced at early age, but the reduction stopped partially at 90 days	–

Table 2 (continued)

References	Concrete mix or mortar	Replacement (%)	Mineral admixture other than SF (%)	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Ahari et al. (2015a)	SCC with w/c 0.44, 0.50 and 0.56. Fine aggregates/total aggregates ratio 0.53	18	FA 18 and 36, SF 4, 8 and 12, MK 4, 8 and 18 and 36	VMA content 4.6 kg/m^3 and HRWR content 5.48, 6 and 8 kg/m^3	SF, MK and FAC increased HRWR demand. FAF, FAC and MK increased plastic viscosity, while SF and BFS reduced it. MK, FAC and VMA increased V-funnel flow time while SF, FAF and BFS reduced this	SF and MK increased thixotropy and C.S. FAF decreased C.S., while FAC increased it	–
Ahari et al. (2015b)	Fine/coarse aggregates ratio 0.53 in SCC and w/c 0.44	18	FA 18 and 36, SF 4, 8 and 12 and MK 4, 8 and 18, 36	VMA 4.6 kg/m^3 and HRWR 3.2–10 kg/m^3	FAC, FAF and BFS increased VSI and T50 flow time. MK and FAC increased torque plastic viscosity with time, but BFS decreased this	SF and MK increased C.S. and thixotropy. FAF decreased C.S., while FAC increased it	–
Altoubat et al. (2016)	SCC with *w/b* 0.36	GGBS (35, 50 and 75%)	Class F FA (35%) and combination of FA + GGBS (35% + 35%)	PC-based HRWR (6 and 6.5 L/m^3) and VEA Feyplast SUB- (0.5 and 0.6 kg/m^3)	–	–	GGBS with FA increased cracking resistance of SCC with 3 days of moist curing under high degree of restraint
Dadsetan and Bai (2017)	SCC with *w/b* 0.4–0.45	0, 20 and 30%	MK (10% and 20%), Class F FA (10%, 20% and 30%) and LS (89.4 and 121.6 kg/m^3)	ADVA flow 340 as HRWR (2.3–10.4 kg/m^3)	MK and GGBS increased SP dosages and FA decreased SP dosages. All mixes satisfied EFNARC requirements for SCC	FA decreased C.S., but enhanced with FA content. GGBS increased C.S. at all ages with higher *w/b* ratio but at lower *w/b* ratio GGBS increased 28-day strength, but decreased at 7 days	MK had a more considerable effect on microstructural strength than GGBS. From EDS analysis, lower Ca/Si ratio improved C.S.

2.2.3 DurabilityProperties

Shrinkage decreased with the increase in GGBFS, FA and MK, but SF increased it. Ternary and quaternary system of SF decreased drying shrinkage (Güneyisi et al. 2010). SCC had smaller aggregate–matrix interface micro-crack than normal concrete. SCC had smaller and rounded air voids as compared to normal vibrated concrete (Druta et al. 2014). GGBS content and curing regime had significant influ- ence on cracking potential of SCC irrespective of degree of restraint. GGBS at 50% and 70% under 7-day moist cur- ing can be used in structural members under high and low degree of restraints, respectively. Combination of FA and GGBS increased cracking resistance of SCC with 3 days of moist curing under high degree of restraint (Altoubat et al.2016). For higher *w*/*b*, MK had higher amount of C–S–H gel. MK had significant effect on microstructural strength of transition zone than GGBS. From EDS analysis, it was observed that lower Ca/Si ratio indicates the enhancement in compressive strength (Dadsetan and Bai 2017).

2.3 Metakaolin and Rice Husk Ash

Metakaolin (MK) is a dehydroxylated form of clay mineral kaolinite. MK is obtained by calcination of pure or refined clay at temperature of 650–850 °C and grinding it to achieve the required fineness. Particle size of MK is smaller than of cement but not as fine as SF. It is a highly pozzolanic material (Santhakumar 2006). Rice husk ash (RHA), highly pozzolanic, is a commonly used agricultural waste in rice- producing countries. RHA is obtained by burning rice husk in a controlled condition without causing environmental pollution (Shetty 2005). It has become a potential threat to environment due to its hazardous impact on land and surrounding areas because of direct dumping. RHA and MK were used by the various researchers in concrete to improve various properties. The work done by various researchers on RHA and MK in SCC is listed in Table 3.

2.3.1 Fresh Properties

Filling ability and air content decreased at higher RHA con- tent and lower *w*/*b* mostly due to its higher surface area. HRWR demand and AEA dosage increased at lower *w*/*b* ratio (Safiuddin et al. 2010). Flowing ability increased with the increase in HRWR dosages up to saturation point due to liquefying and dispersion action of HRWR, but beyond this, it improved the deformability of mortar. Flow of spread decreased with the increase in *w*/*b* ratio and RHA because of lower paste volume, higher sand content, surface area and volume fraction (Safiuddin et al. 2011). Filling and passing ability, Orimet and inverted slump cone flow times increased with HRWR due to its

liquefying and dispersing action. Segregation resistance, filling and passing ability increased at lower *w*/*b* ratio and high RHA content was attributed to the increase in paste volume and the decrease in aggregates content (Safiuddin et al. 2012). Metakaolin increased slump flow losses, T50 flow time, but decreased flowability due to high surface area of MK. Flowability improved with HRWR due to its liquefying and dispersion action (Madandoust and Mousavi 2012). SCC had satisfactory fresh properties for all mixes except 30% MK, 30% RHA and 20% MK + 20% RHA. Filling ability gradually reduced with the increase in MK, RHA and their combination due to high reactivity and surface area (Kannan and Ganesan 2014). The increase in MK content increased the SP dosages, T50 flow times and V-funnel time of SCC due to its high surface area (Kavi- tha et al. 2015). GF increased SP dosages due to friction between fiber and aggregates (Sivakumar et al. 2017). Addi- tion of MK reduced flowability due to layered microstructure of MK which had a strong tendency to absorb free water but enhanced the viscosity (Song et al. 2018).

2.3.2 HardenedProperties

RHA improved UPV value due to micro-filling and pozzo- lanic effect. Compressive strength increased with or with- out RHA at lower *w*/*b* credited to the reduction in porosity, air content and increase in cement content. Unit weight of concrete reduced at higher *w*/*b* and RHA content because of its lightweight (Safiuddin et al. 2010, 2012). SCC with MK had higher compressive tensile strength and UPV value at lower *w*/*b* ratio due to its pozzolanic reaction and fill- ing effect (Madandoust and Mousavi 2012). SC with PC type SP had higher compressive strength and efficiency fac- tor in comparison with naphthalene formaldehyde type SP (Dvorkin et al. 2012). SCC with RHA (15%) increased thecompressive strength but at 20% RHA decreased strength. SCC blended with MK and (MK + RHA) increased com- pressive strength as compared to unblended SCC due to its higher surface area (Kannan and Ganesan 2014). Metakaolin and steam curing increased strength (Ramezanianpour et al. 2014). MK up to 10% increased compressive and split tensile strength of SCC due to fast pozzolanic reaction, but it started to decrease beyond this due to the reduction in workability which increased the SP requirement (Kavitha et al. 2015).

GF reduced compressive strength of SCC due to the presence of tiny voids on concrete surface, but increased the split tensile and flexural strength because of bridging of diametric splitting cracks (Sivakumar et al. 2017). MK had higher activity in promoting cement hydration than that of SF.

The combination of MK and SF increased the compressive and flexural strength due to dense microstructure and lower macro-defects in internal structure of concrete (Song et al. 2018).

Table 3 Effect of metakaolin and rice husk ash on SCC

References	Concrete mix or mortar	Replacement (%) RHA	Mineral admixture other than RHA	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Safiuddin et al. (2010)	SCHPC with *w/b* 0.30, 0.40 and 0.50	0, 5, 10, 15 and 20	–	PC-based HRWR dosage was 70–80% of saturation dosages and synthetic AEA	Air content and slump flow decreased at higher RHA content and lower *w/b*. Lower *w/b* increased HRWR demand and AEA dosages	RHA increased C.S. The increase in air content decreased C.S. UPV increased with or without RHA at lower *w/b*.	Lower *w/b* and higher RHA content decreased the porosity and water absorption decreased, but increased ER
Safiuddin et al. (2011)	Self-compacting mortar with *w/b* 0.30	0, 5, 10, 15, 20, 25 and 30	–	PC-based HRWR (0.50–4.5%)	Saturation flow spread and flow spread of mortar reduced with increase in *w/b* and RHA content	–	–
Safiuddin et al. (2012)	Sand/total aggregates ratio 0.50 and *w/b* 0.30, 0.35 and 0.40	0–30	–	PC-based HRWR (0.6–2.45%) and AEA (0.011–0.080%)	At higher RHA content and lower *w/b*, AEA dosages, filling, passing ability and inverted slump cone flow times increased	Unit weight enhanced at lower *w/b*	–
Madandoust and Mousavi (2012)	SCC with *w/b* 0.32, 0.38 and 0.45	–	MK 0, 5, 10, 15 and 20.	HRWR (1.63–9.96 kg/m^3) and VMA (1.31–2.12 kg/m^3)	MK increased slump flow losses and T50 flow time, but decreased flowability	Compressive tensile strength increased and had higher UPV value at lower *w/b* ratio	Water absorption decreased, but higher electrical resistivity at lower *w/b* ratio was observed
Dvorkin et al. (2012)	SCC with w/c 0.40 and 0.42 and *w/b* 0.34, 0.37 and 0.40	–	MK 5, 10 and 15	NF type (SP1) {0.75–2.25%) and PC type (SP2) (0.16–0.51%)	–	C.S. and efficiency factor of SP2 was higher than SP1. SP2 had lower concrete cost.	–
Kannan and Ganesan (2014)	Fine-to-coarse aggregates ratio 1.1 in SCC with w/c 0.55.	(MK+RHA) 10, 20, 30 and 40 and RHA 0, 5, 10, 15, 20, 25 and 30	MK 0, 5, 10, 15, 20, 25 and 30.	Sulfonated naphthalene polymer-based superplasticizer was 2%.	Slump flow value decreased with increase in mineral additive. SCC had satisfactory fresh properties.	MK and (MK +RHA) improved the C.S.	MK and (MK+RHA) improved durability properties.
Ramezanianpour et al. (2014)	SCC with w/c 0.38	Mineral content was 20	MK, Pomis, Trass	PCE-based HRWR. 0.18–1.25%.	Slump flow time was less than 4 s, slump flow diameter 65–70 cm and slump flow loss was 61–66 cm.	C.S. increased with initial steam curing. MK had higher C.S. in comparison with other admixtures.	MK reduced depth of water penetration, permeability, but surface electrical resistivity increased.

Table 3 (continued)

References	Concrete mix or mortar	Replacement (%) RHA	Mineral admixture other than RHA	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Kavitha et al. (2015)	SCC with water/powder 0.38	5%, 10% and 15%	–	PCE-based SP (3-5 kg/m^3)	The increase in MK content increased SP dosages, T50 flow times and V-funnel time of SCC.	C.S. and S.T.S. of SCC increased up to 10% MK beyond that it decreased.	SCC blended with MK had better microstructural properties.
Kavitha et al. (2016)	SCC	5%, 10% and 15%	–	PCE-based HRWR superplasticizer (3–5 kg/m^3)	–	–	MK decreased water absorption and chloride ion penetration, but higher resistance to sulfate attack.
Le and Ludwig (2016)	Mortar and Self-compacting high-performance concrete (SCHPC) with *w*/*b* 0.26	RHA (5, 10, 15 and 20%)	SF (10%) and FA (20 and 40%)	Polycarboxylate-based SP (2 and 2.5% wt. %)	The increase in FA content decreased SP dosages at certain dosages. SF and RHA reduced mini-SLF, but increased T_{250} time. RHA was more effective than SF. The increase in SP dosages lowered plastic viscosity, but increased flowability. Incorporation of RHA, especially at higher replacement eliminated the bleeding.	RHA and SF had similar effect on C.S. RHA was more effective in improving C.S. of SCHPC, especially at higher content and later age. FA + RHA improved compressive strength.	–
Sivakumar et al. (2017)	OPC OF 53 Grade, SCC with w/p ratio 0.38	0.1–0.8% volume of Cem-FIL alkali-resistant glass fiber (GF)	10% MK	–	GF increased SP dosages.	GF reduced C.S. of SCC, but increased S.T.S. and flexural strength.	GF had very low chloride ion permeability. MK reduced water absorption, but GF increased water absorption.
Song et al. (2018)	Self-compacting ultra high-performance fiber-reinforced concrete	0, 18, 36, 54, 72 and 90 kg/m^3	FA (306 kg/m^3), SF 0, 18,36, 54, 72 and 90 kg/m^3) and steel fiber (156 kg/m^3)	PCE-based SP (33 kg/m3)	Addition of MK reduced flowability but enhanced the viscosity.	–	–

2.3.3 DurabilityProperties

Lower *w*/*b* ratio and higher content of RHA decreased the porosity. Electrical resistivity increased and water absorption of concrete decreased with the reduction in porosity (Safiuddin et al. 2010; Madandoust and Mousavi 2012). Permeability increased with the increase in steam curing temperature. SCC blended with MK improved permeability up to 30% than unblended SCC. SCC with MK gave unfa- vorable performance in an acidic environment (Kannan and Ganesan 2014). MK increased durability properties. Trass and limestone had higher permeability than Pomis and MK. Pozzolanic activity and fineness increased the resistance to permeability (Ramezanianpour et al. 2014). SCC blended with MK had better microstructural properties (Kavitha et al.2015). Incorporation of MK decreased water absorption and chloride ion penetration. MK (10%) showed higher resist- ance to sulfate attack. Mass and strength loss of control mix was higher than that of SCC with MK (Kavitha et al. 2016). Inclusion of MK reduced chloride ion penetration due to refined pore structure of concrete. SCC with GF had slightly more chloride permeability than control mix, because glass fiber bridged across the cracks which produce interconnect- ing voids. MK reduced water absorption due to high silica content but GF increased water absorption because of a good bond with cement particles (Sivakumar et al. 2017). All SCC mixtures had dense microstructure (Song et al. 2018).

2.4 Fiber

Fiber is the small piece of varied length and caliber rein- forcing material having certain characteristic properties. Fiber is generally described by aspect ratio, which is the ratio of fiber length to its diameter and varies from 30 to 150. Various types of fiber such as steel, carbon, polymeric, asbestos, glass and natural fiber are used in the concrete and fiber-reinforced concrete. Carbon fiber has the highest strength and stiffness among all the fibers, while polymeric fiber has low stiffness and moderate strength and exhibits ductile behavior. Fibers are used in concrete to control crack- ing characteristics and decrease permeability. Glass fiber- reinforced concrete is used for architectural purposes, and steel fibers are mostly used in paving and inside tunnels. Fiber-reinforced concrete consists of uniformly distributed and randomly oriented discrete fiber which enhances struc- tural integrity. Fiber reinforcement is used in shotcrete and normal concrete for ground floors, pavement, beams, piers, foundations, etc. either alone or with rebars. Concrete rein- forced with fiber (steel, glass or plastic) is less expensive than hand-tied rebars. Fibers are used to monitor plastic shrinkage cracking and drying

shrinkage cracking (http:// theconstructor.org/concrete/fiber-reinforced-concrete/150/). The types of fiber influence the strength of bond between fibers and cement paste matrix. Fibers act to bridge growing cracks, thus restricting their further growth and propagation. The work done by the various researchers on fiber is listed in Table 4.

2.4.1 FreshProperties

Straight fiber reduced viscosity, slump flow (t_{500}) and V-funnel test (Sahmaran et al. 2005). Polypropylene fiber (PPF) reduced workability, but increased SP demand (Abukhashaba et al. 2014). Steel and PP fiber improved fresh properties of SCC (Kamal et al. 2014). Steel fiber at higher volume fraction decreased workability. T50 value increased with maximum size of aggregates and mortar volume (Madandoust et al. 2015). The increase in steel fiber reduced workability; and density of fresh concrete was con- stant due to the increase in air content (Iqbal et al. 2015). All SCC mixes achieved adequate fresh properties. Syn- thetic fiber decreased the passing ability of SCC compared with steel fiber (Yehia et al. 2016). Addition of steel fiber reduced the slump flow diameter and V-funnel time due to low viscosity and its high unit weight. At 90 kg/m^3, work- ability of SCC did not satisfy the EFNARC requirements (Nehme et al. 2017). River gravel as coarse aggregates had better rheological behavior due to its quasi-spherical shape, smaller angularity and smooth texture characteristics. Steel fiber reduced the workability (Da Silva et al. 2017).

2.4.2 Hardened Properties

The increase in straight fiber increased the compressive strength due to smaller dimension in comparison with hook shape and prevented the formation and propagation of micro-cracks. UPV value was not affected by addition of fiber (Sahmaran et al. 2005). Compressive strength increased and strain value decreased with the increase in fiber content. SCFRC mixture consisting of both CKD and PPF was cost- effective and offered final concrete with distinct character- istics (Abukhashaba et al. 2014). Compressive strength and impact of resistance increased with addition of steel and PP fiber (Kamal et al. 2014).

Table 4 Effect of fiber on SCC

References	Concrete mix or mortar	Replacement ratio of fiber (%)	Mineral admixture other than Fiber	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Sahmaran et al. (2005)	Hybrid fiber-reinforced SCC with w/c 0.4	Steel fiber (total 60 kg/m^3): hook and straight (0, 18, 30, 42 and 60 kg/m^3 each)	LP (70 kg/m^3)	PCE-based SP (9.5 kg/m^3)	Straight fiber reduced viscosity, slump flow (t_{500}) and V-funnel test	Increase in straight fiber enhanced C.S. UPV value had no effect on addition of fiber	–
Abukhashaba et al. (2014)	SCC with w/c 0.45 and sand/total aggregates 0.50	PPF 0, 0.5, 1.0, 1.5%	Cement kiln dust (CKD) 20	SP 2.4%	PPF reduced workability, but increased SP demand	Fiber increased C.S. and S.T.S. F.S. enhanced at 7 days, but no improvement after 28 days	Shrinkage strain reduced with the increase in fiber content
Kamal et al. (2014)	SCC with w/p ratio 0.35–0.40.	PPF	FA 10	HRWR 2, 2.5 3 3.25 to 3.5%	Reduced bleeding and improved fresh properties	Increased C.S. and impact strength	–
Madandoust et al. (2015)	Steel fiber-reinforced SCC and w/c 0.45	Steel fiber 0, 0.38, 0.64 and 1	–	PCE-based HRWR 2.6–4.1 kg/m^3	Fiber reduced slump flow. Steel fiber at higher volume fraction decreased workability	C.S. and MOE increased with the increase in aggregates size. Fiber improved flexural behavior of concrete and tensile strength	–
Iqbal et al. (2015)	High-strength steel fiber-reinforced lightweight SCC	Micro steel fiber was 0, 0.5, 0.75, 1 and 1.25.	FA 125 kg/m^3	VMA 3 kg/m^3 and PCE-based SP 14 and 15 kg/m^3	Steel fiber reduced workability, but increased air content	The increase in steel fiber decreased C.S., but S.T.S. and F.S. increased. Steel fiber had no effect on modulus of elasticity	–
Yehia et al. (2016)	SCC with w/c 0.45 and *w/b* 0.36	SF (0–0.08 kg/m^3)	Synthetic and steel fiber of 0.5% vol. of crushed sand each and in case of hybrid 0.25% vol. of each fiber.	BASF GLENIUM Sky 504 dosages was 800–1500 ml/100 kg of cement	All SCC mixes achieved adequate fresh properties. Synthetic fiber reduced passing ability of SCC than that of steel fiber	Fiber had no observable effect on C.S. and MOE, but enhanced S.T.S and F.S. of SCC. Fiber improved post-cracking behavior. Mechanical properties of FRSCC improved when subjected to wet and dry cycle at 21 days	All SCC and FRSCC mixes had low chloride permeability in RCPT test. Steel fiber had wall effect with surrounding cement paste whereas synthetic did not

Table 4 (continued)

References	Concrete mix or mortar	Replacement ratio of fiber (%)	Mineral admixture other than Fiber	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Nehme et al. (2017)	SCC with w/c 0.51	Steel fiber (RC-65/35-BN) (0, 30, 60 and 90 kg/m^3) and steel bars	Limestone powder	Glenium 51 (3.5 kg/m^3)	Steel fiber reduced the slump flow diameter and V-funnel time. At 90 kg/m^3, workability of SCC did not satisfy the EFNARC requirements.	Addition of steel fiber reduced compressive strength.	Addition of steel reinforcement bar improved ductility and load deflection capacity of SCC.
Da Silva et al. (2017)	High-strength steel fiber river gravel self-compacting concrete (SFRG-SCC)	Hooked-end steel fiber of 35 mm length and 0.55 mm diameter.	Class C FA and SF	MASTER GLENIUM 51 PCE-based HRWR and RHEOMAC UW410 as VMA	River gravel as coarse aggregate had better rheological behavior but steel fiber reduced the workability	SCC with river gravel had higher elastic modulus than that of crushed aggregates. River gravel reduced split tensile strength	Addition of steel fiber enhanced ductile property

Compressive strength slightly increased with the aggregates size. For constant w/c ratio, compressive strength, tensile strength and modulus of elas- ticity (MOE) decreased with richer mixes. Modulus of elas- ticity was higher for larger-sized aggregates (Madandoust et al. 2015). The increase in steel fiber decreased compressive strength, but split tensile strength and flexural strength increased. Steel fiber had no effect on MOE. Fiber increased MOE and compressive strength, split tensile due to improved hydration and flexural strength of SCC, because of the ability to restrain cracks and resist internal tensile stress. Fibers improved the post-cracking behavior due to its crack bridging effect.

There was improvement in mechanical properties of FRSCC when subjected to wet and dry cycle at 21 days due to improved hydration process (Yehia et al. 2016). Fiber intrusion up to 60 kg/m^3 increased the strength, but at 90 kg/ m^3 decreased the compressive strength due to the reduction in workability. Steel reinforcement bars increased the ductil- ity as compared to plain SCC. Addition of steel reinforce- ment bar increased the ductility of SSC than that of plain SCC. Steel fiber improved the load deflection capacity of SCC due to fiber bridging effect which prevented the devel- opment of cracks (Nehme et al. 2017). Steel fiber increased the compressive strength at 28 days. Plain concrete with crushed aggregates had higher tensile strength and strain at peak load than that of river gravel aggregates, because river gravel aggregates cause premature breakage of aggregates due to weaker inter transition zone (Da Silva et al. 2017)

2.4.3 Durability properties

All SCC and FRSCC mixes had low chloride permeability in RCPT test. Steel fiber had wall effect with surrounding cement paste, whereas synthetic did not do that. Tensile micro-cracks were initiated during the hydration process due to high stiffness of steel fiber in comparison with cement paste (Yehia et al. 2016). Addition of steel fiber enhanced ductile property due to fiber bridging effect.

2.5 Fly ash

Fly ash (FA) is a finely divided residue resulting from the combustion of powdered coal and transported by flue gases and collected by electrostatic precipitator. In the UK, it is also known as pulverized fuel ash (PFA).

Class F and C are two groups in which the fly ash is classified as per ASTM. Class C fly ash had both the cementitious and pozzolanic properties, but class F fly ash has only pozzolanic properties (Shetty 2005). Fly ash is the cost-effective substitute for the cement and also environmentally friendly materials. The uses of fly ash improved the workability and durability to thermal cracking, prevented alkali–aggregates reaction and improved the strength and durability. Fly ash in concrete produces dense and smooth surfaces with sharper details. The work done by various researchers on fly ash in SCC is listed in Table 5.

2.5.1 FreshProperties

Mineral admixture improved workability of concrete. FA and GGBS had higher slump flow values, while LP, BP and MP had lower slump flow values. FA reduced slump flow values because FA particles dispersed the agglomeration of cement particles (Uysal and Sumer 2011; Uysal and Tanyildizi 2012). Lightweight aggregates improved the workability. SF increased SP demand, while FA decreased it. Lightweight FA aggregates enhanced the workability (Güneyisi et al. 2012). Workability and rheological properties of fresh SCC improved with FA due to its ball bearing-shaped particles, whereas TiO_2 nanoparticle reduced flowability due to high viscosity and improved rheological due to filling effect of finer particles (Jalal et al. 2013). NS made SCC mixture more cohesive and viscous. The increase in NS content decreased L-box height ratio. Slump flow, V-funnel flow times T20 and T40 L-box flow times, torque value and shear thickening increased by NS and decreased by FA (Güneyisi et al. 2015). Dosages of SP decreased with the increase in cement and FA (Sua-iam and Makul 2015). Loss of workability decreased with the increase in FA content. V-funnel time of SCC increased with the increase in lightweight aggregates (Kurt et al. 2015). Replacement of cement by pulverized fuel ash (PFA) and GGBS increased the viscosity of SCC (Ryan and O’Connor 2016). SCC mixtures containing pumice powder (P.P.) had better slump flow retention in comparison with other mix. SCC with P.P. had reasonable flowability, passing ability and segregation resistance. Pumice powder increased the SP dosages. Pum- ice powder required high dosages of SP in comparison with that of FA. Binary mixtures satisfied the limit of U-BOX and V-funnel test, while most of them did not satisfy EFNARC recommendation for J-ring test while ternary mixtures gave satisfactory results in all tests (Ardalan et al. 2017). Mag- netic water reduced HRWR demand and increased slump flow in comparison with tap water, because magnetic water molecules penetrate through hydration layer more easily than tap water molecules. All pozzolanic materials with magnetic water except FA increased HRWR demand except FA because of its spherical shape which reduced the friction between cement paste and aggregates. All pozzo- lanic materials improved the self-compact ability criterion of SCC in terms of flowability and viscosity. V-funnel and T50 decreased with the magnetic water. SCC with differ- ent pozzolanic materials except FA had higher viscosity and reduced passing ability of SCC mix. Magnetic water improved the passing ability of SCC in L-box test (Gholhaki et al. 2018).

2.5.2 HardenedProperties

Mineral admixtures had excellent mechanical properties of SCC. The increase in mineral admixtures decreased the compressive strength at all ages for all mixes. UPV values trend was similar to that of compressive strength. GGBS series had the highest density due to better compaction and reduction in voids. FA and GBFS increased later-age compressive strength due to filling of voids and pozzo- lanic reaction, whereas filler material increased early-age compressive strength due to better dispersion and forma- tion of denser matrix (Uysal et al. 2011). Without PP fiber, strength of mix decreased but some SCC mixtures with min- eral admixtures increased strength in small amounts due to formation of tobermorite, resulted from reaction between un-hydrated cement paste and lime. Loss in strength was observed between temperatures 400 and 600 °C due to dense microstructure which built up high internal pressure during heating. SCC with pozzolanic additives performed well in comparison with that of filler materials. Severe deterioration was observed for temperatures 600–800 °C for all SCC mix- tures due to decomposition of CSH gel. The extensive crack- ing, spalling and residual compressive strength were lower than control mix due to pozzolanic reaction and micro-filling effects of mineral admixtures used. Concrete mixture con- taining mineral admixture gave better resistance between 20 and 200 °C. From 200 to 400 °C, strength of SCC decreased without PP fiber which is due to pore structure coarsening and also loss of water from pores of hydrates temperature and FA (15%) had better resistance. Basalt powder (30%) had the lowest strength loss for the temperature 400–600 °C. Compressive strength of mixture with PPF was lower than those of without PP fiber in all replacement ratios at elevated temperature (Uysal and Tanyildizi 2012). The increase in FA content decreased the compressive strength at early ages due to the reduction of CaO content in FA but improved at90 days. FA up to 15% in concrete mix had no beneficial effect on split tensile strength, but at higher volume reduced split tensile strength. Nanoparticles up to 4% enhanced split tensile and flexural strength, but after 4% strength reduced because of defects generation in dispersion of higher compressive strength after immersion in 5% Na_2SO_4 solution after 720 days. VC had higher strength loss than SCC. The mechanical performance of SCCPZ and SCCFA was bet- ter than of VC and SCCLF (Siad et al. 2013). Compressive strength decreased with the increase in FA content. NS up to 4% increased compressive strength, but at 6% decreased the compressive strength due to balling effect of nanoparticles (Güneyisi et al. 2015). SCC mixture containing FA had lower compressive strength. The use of alumina waste and FA reduced the cost per unit of compressive strength of SCC (Suaiam and Makul 2015). Pumice and natural aggre- gates decreased unit weight and UPV. Compressive strength increased with FA (Kurt et al. 2015). Pumice powder at 30% replacement had the highest compressive strength in com- parison with control mix.

Table 5 Effect of fly ash on SCC

References	Concrete mix or mortar	Replacement ratio of FA (%)	Mineral admixture other than FA	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Uysal and Sumer (2011)	SCC with water powder ratio (0.33)	15, 25 and 35	GGBFS 20, 40 and 60 and LP, BP and MP 10, 20 and 30 each.	PC-based SP was 1.6%.	FA and GGBFS had higher slump flow, but BP, MP and LP had lower value. Mineral admixtures improved workability. GGBFS had the highest density.	FA and GBFS increased later age C.S. Increase in mineral admixture decreased C.S., UPV, static and dynamic elastic modulus.	Mineral admixtures improved resistance against sulfate attack
Uysal and Tanyildizi (2012)	Two mixes of SCC were prepared, one without PPF and the other with PPF and w/p 0.33	15, 25 and 35	PPF 2 kg/m^3 and GGBFS 20, 40 and 60, LP, BP (Basalt powder) and MP 10, 20 and 30 each	SP 7.98–9.85 kg/m^3 and 1.6%.	FA and GGBFS had larger slump flow value while MP, LP and BP had small slump flow value. T50 flow time was less than 5 s for all mixtures. Mineral admixtures improved the workability.	FA and GGBFS increased later age C.S. and UPV value. SCC without PPF reduced strength except FA15, GBFS40, BP10, BP30, Z5 and control mix at temperature 20–200 °C. Strength loss increased with increase in temperature.	Mineral admixtures improved sulfate resistance. GGBFS had higher sulfate resistance.
Güneyisi et al. (2012)	Self-compacting lightweight concrete with *w*/*b* 0.35	15 and 30	SF 5 and 10	PCE-based SP 5.3, 5.5, 5.6, 6.2 and 6.4 kg/m^3	Lightweight aggregates increased workability. SF and FA improved filling and passing ability	–	–
Jalal et al. (2013)	High-strength self-compacting concrete with *w*/*b* 0.38	5, 10, 15	TiO_2 1, 2, 3, 4 and 5	PCE-based type SP 2.5 and 2.81 kg/m^3 and VMA 2 and 2.25 kg/m^3	FA up to 15% increased slump flow diameter, but T50 and V-funnel flow time decreased. TiO_2 reduced flowability and had less bleeding and segregation.	FA improved F.S. C.S. decreased at 7 and 28 days, but improved at 90 days. TiO_2 up to 4% improved S.T.S and F.S., but beyond 4% strength reduced.	FA up to 15% and TiO_2 reduced water absorption, capillary absorption and chloride penetration. TiO_2 up to 4% increased weight loss.

than FA (Jalal et al. 2013). SCC with natural pozzolana and SCC with FA increased

Table 5 (continued)

References	Concrete mix or mortar	Replacement ratio of FA (%)	Mineral admixture other than FA	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Siad et al. (2013)	SCC and vibrated concrete (VC), SCC with LF (SCC LF), SCC with Z (SCC PZ) and SCC with FA (SCC FA).	Silico-aluminate FAF 70, 170 and 260 kg/m^3	Natural pozzolana (Z) 70, 170 and 260 kg/m^3 and limestone filler (LF) 70, 170 and 260 kg/m^3	Acrylic copolymer superplasticizer 0.9–11.50 kg/m^3	Physical and mechanical performance of SCCPZ and SCCFA were better than VC and SCCLF.	SCCPZ and SCCFA increased compressive strength after immersing for 720 days in 5% Na_2SO_4 solution.	Z had better resistance in sodium sulfate medium. VC had higher mass loss. VC and SCCLF had larger expansion in sodium sulfate solution.
Güneyisi et al. (2015)	Self-compacting concrete with *w*/*b* 0.33	0, 25, 50 and 75	Nano-silica NS 0, 2, 4 and 6	PCE type SP. 1.71–21.38 kg/m^3	NS increased slump flow and V-funnel flow times, L-box flow time, shear thickening and torque value, but FA decreased it	C.S. decreased with the increase in FA. NS up to 4% increased C.S., but at 6% decreased C.S.	–
Sua-iam and Makul (2015)	SCC with water powder ratio 0.38. Alumina waste 0, 25, 50, 75% and 100% by river sand	0 and 20	–	PCE-based HRWR.	The increase in FA content decreased SP demand. FA decreased slump flow time and V-funnel time. FA improved deformability, stability and self-compact ability	FA had lower C.S. and UPV value. AW increased C.S. and UPV value. AW and FA decreased cost per unit of compressive strength of SCC.	–
Kurt et al. (2015)	Pumice aggregates replaced with natural aggregates of 0, 20, 40, 60, 80 and 100% by volume and w/cm 0.35, 0.40 and 0.45	20, 30 and 40	–	PC-based hyper-plasticizer 11 kg/m^3 and AEA 1 kg/m^3	FA decreased loss of workability. V-funnel time increased with increase in lightweight aggregates	FA increased C.S. Pumice and natural aggregates decreased unit weight and UPV	Water absorption rate increased with FA and increase in lightweight aggregates. Pumice and natural aggregates decreased TC
Ryan and O'Connor (2016)	VC and SCC Pulverized fuel ash (PFA) and GGBS, SCC concrete with PFA and Concrete with GGBS *w*/*b* ratio 0.37 and 0.44	PFA (111 and 131 kg)	GGBS (252 and 298 kg)	Pozzolith 320 N (2.3& 2.7 kg) and Glenium 51 (1.2–3.0 L)	Replacement of cement by PFA and GGBS increased the viscosity of SCC.	–	VC had higher resistance to ingress of chloride than SCC. The durability of SCC and VC was similar to (OPC + GGBS) concrete

Table 5 (continued)

References	Concrete mix or mortar	Replacement ratio of FA (%)	Mineral admixture other than FA	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Ardalan et al. (2017)	SCC mixture with w/cm 0.38	Class F FA 0–50% @ 10%	Volcanic pumice, slag 0–50% @ 10% and SF (5 and 10%)	Polycarboxylate ether-based SP	PP had better slump flow retention than other mixes. PP required high dosages of SP than FA. Binary mixtures satisfied the requirements for U-box and V-funnel test while ternary mixtures gave satisfactory results in all test	Pumice powder (30%) had highest C.S. Replacement of FA, PP and slag after 30% reduced C.S. SCC with FA and pumice had lower C.S. in comparison with SCC with slag. Combination of PP and SF had higher C.S. than control mix	
Gholhaki et al. (2018)	SCC with 0.8 Tesla magnetic water and *w*/*b* 0.37	FA 10 and 20% by wt. of total cementitious materials	SF, MK and RHA 10 and 20% each by wt. of total cementitious materials	Carboxylate-based HRWR (2.11–7.48 kg/m^3)	All pozzolanic materials with magnetic water except FA increased HRWR demand. All pozzolanic materials improved the self-compact ability criterion of SCC in term of flowability and viscosity	FA (20%) had the highest compressive strength at 7 days and SF (20%) had the highest compressive strength at 28 days. SCC with magnetic water and SF (20%) had the highest split tensile strength in all mixes in comparison with control mix with tap water	Magnetic water decreased the water absorption in comparison with SCC with tap water.

SCC reduced compressive strength beyond replacement30% by FA, P.P. and slag. Pumice powder had pozzolanicactivity, especially with SF. SCC with FA and pumice hadlower compressive strength in comparison with SCC withslag. Combination of pumice powder and SF had highercompressive strength in comparison with control mix(Ardalan et al. 2017). FA (20%) had the highest compressive strength at 7 days because it fills the voids better andSF (20%) at 28 days due to higher pozzolanic reaction incomparison with other mixes at 28 days. MK with binaryand ternary blend enhanced the compressive strength due torapid pozzolanic reaction. SCC with magnetic water and SF(20%), MK and FA increased split tensile strength, but RHAdecreased strength in comparison with control mix with tapwater (Gholhaki et al. 2018).

2.5.3 DurabilityProperties

The increase in mineral admixture decreased the strength loss in comparison with control mix. GBFS had superior resistance against magnesium sulfate attack due to pore refinement process and FA as well as GBFS performed well against sodium sulfate due to pozzolanic reaction and reduction of total amount of tricalcium aluminate hydrate in cement paste. GBFS (40%) had better performance against magnesium sulfate attack at 400 days due to lower ettring- ite formation. Pozzolanic materials reduced chloride ions permeability than inert filler materials due to discontinu- ous pore system (Uysal and Sumer 2011). FA up to 15% reduced water absorption, capillary absorption and chloride penetration. TiO_2 nanoparticles up to 4% decreased water absorption and capillary absorption, but improved resist- ance to water permeability and weight loss of specimen (Jalal et al. 2013). VC had larger expansion and mass loss as compared to SCC mixture. SCC mixture with limestone filler had higher expansion in comparison with SCC with FA or natural pozzolana. Physical performance of SCCPZ and SCCFA was better than that of VC and SCCLF (Siad et al.2013). Pumice and natural aggregates decreased the thermal conductivity of concrete. Water absorption increased with FA (Kurt et al. 2015). VC had higher resistance to ingress of chloride than SCC. The durability of SCC and VC was similar to (OPC + GGBS) concrete (Ryan and O’Connor2016). Magnetic water decreased the water absorption in comparison with SCC with tap water due to aggregate–silica reaction in concrete which reduces the size of pores (Ghol- haki et al. 2018).

2.6 Limestone Powder

Limestone powder (LP) is produced as by-product of lime- stone crushers. Limestone is a common sedimentary rock composed primarily of calcium carbonate mineral, calcite. Limestone is formed either by direct crystallization from water or by accumulation of sea animal shells and shell frag- ment. Limestone and marble are prime building materials in the construction industry. Limestone is used as a build- ing material and to purify iron in blast furnaces. It is also used in the manufacture of glass and cement. The work done on limestone powder by the various researchers is listed in Table 6.

2.6.1 FreshProperties

SP2, FA and LP improved workability, while BP and K adversely affected workability. Both the chemical and min- eral admixture adversely affected the setting time of mor- tar. FA increased setting time of mortar (Sahmaran et al.

2006). The SP (P1) had shorter setting time and high ini- tial water-reducing capacity than P2 and P3 (Felekoglu and Sarikahya 2008). LP and FA due to spherical shape which reduce friction between aggregates and cement paste improved fluidity, but VMA reduced it. The increase in fluid- ity reduced the stability. VMA, LP and FA reduced bleeding and aggregates blockage (Libre et al. 2010). V-funnel flow time, slump retention and plastic viscosity decreased with the increase in side-chain density of SP (Mardani-Aghaba- glou et al. 2013). Slump flow, J-ring and L-box ratio values were within the range for all the mixes except T50 time and V-funnel. Ternary system satisfied the EFNARC require- ments. LS improved the workability compared to RHA due to its smooth surface characteristic. Ternary blend of RHA and LS improved the workability (Sua-iam et al. 2016).

2.6.2 HardenedProperties

SCC had higher split tensile strength and lower MOE in comparison with NVC (Felekoğlu et al. 2007). The SP (P1) had high early-age strength compared to P2 and

P3 (Fele- koglu and Sarikahya 2008). The admixture with higher slump loss caused the higher early-age concrete strength (Mardani-Aghabaglou et al. 2013). LS (15%) particles pro- duced lower strength in binary and ternary mix relative to control mix. LS (10% and 20%) had lower strength than control mixes at 7 and 28 days. Basaltic ash up to 40% due to adequate pozzolanic activity and LS up to 15% due to dilution effect increased the strength (Celik et al. 2014). RHA and LS increased the compressive strength, but LS had higher strength gain in comparison with RHA. Use of RHA and LS reduced the unit weight. Compressive strength and UPV value increased with RHA due to pozzolanic reaction as well as micro-filling ability and LS due to filling effect only (Sua-iam et al. 2016).

2.6.3 DurabilityProperties

All binary and ternary mix had high resistance to chloride penetration due to pore refinement effect. More than 55% PC replacement in ternary mix had higher value of water absorption. Basaltic ash had higher water absorption capac- ity (Celik et al. 2014). Concrete with higher w/c ratio had higher porosity and diffusion coefficient. SCC with lime- stone powder improved the durability properties due to filler effect which enhanced heterogeneous nucleation and pro- gression of hydration products, whereas VMA had lower performance in durability aspects due to its partial interference with cement hydration. Powder SCC had the high- est electrical resistivity and hybrid had intermediate value, while VMA had the lowest one, but greater than control mix. Higher electrical resistivity results in lower water absorp- tion and chloride diffusion due to lower porosity (Shadkam et al. 2017).

Table 6 Effect of limestone powder on SCC

References	Concrete mix or mortar	Replacement ratio of LP (%)	Mineral admixture other than LP	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Sahmaran et al. (2006)	Self-compacting mortar with water/powder ratio 0.40	15 and 30	High lime FA 15 and 30, Brick powder (BP) 15 and 30), kaolinite (K) 15 and 30)	PCE-based SP1 (0.5–2.5%), modified PC-based SP2 (1–2%), melamine formaldehyde-based SP3 (1.5–2.5%), microscopic silica (1–2%) and hydroxylated polymer (0.05–0.15%)	FA and LP improved workability while BP and K adversely affected workability. FA increased setting time of mortar.	SP increased strength and UPV, but mineral additives decreased it.	–
Felekoğlu et al. (2007)	Self-compacting concrete with w/c 0.37–0.60	LP 239–272 kg/m^3	–	PC acid-based SP 0.01–0.03%	Mixtures with slump flow value 65–80 cm, V-funnel flow time below 20 s were accepted and L-box ratio < 0.6 rejected	SCC had higher S.T.S and lower modulus of elasticity than NVC	–
Felekoglu and Sarikahya (2008)	SCC with Fine/coarse aggregates ratio 0.64 and w/c 0.55, 0.53, 0.50, 0.88, 0.85, 0.73, 0.80.	97 kg/m^3	High lime FAC was 158 kg/m^3	Acrylic copolymer (P1) was 1.5, 1.9, 2.2, 2.6, ter-polymer (P2) was 0.6, 1.0, 1.4, 2.3 and carboxylate–polyoxyethylene copolymer (P3) was 0.6, 1, 1.4, 1.8 and 2.3	P1 had shorter setting time and high initial water-reducing capacity than P2 and P3. Initial slump flow increased, but rate of flowability decreased with the increase in SP dosages and w/p ratio	SP1 had high early strength	–
Libre et al. (2010)	Self-compacting mortar with w/c 0.35, 0.45 and 0.55	0, 10, 30 and 50	FA 0, 10, 30 and 50	PCE and VMA was 0.5, 1, 1.5 and 2% each	LP and FA improved fluidity, while VMA reduced it. VMA, LP and FA enhanced flow properties, but reduced bleeding and aggregates blockage	–	–
Mardani-Aghabaglou et al. (2013)	SCC with w/c 0.4	LP as filler 165, 171, 172 and 173 kg/m^3	–	Four different types of polycarboxylate ether-based superplasticizer 1.42, 1.33, 1.24 and 1.67	V-funnel flow time and plastic viscosity decreased with the increase in side-chain density of superplasticizer	Admixture had higher early-age concrete strength and UPV value	–

Table 6 (continued)

References	Concrete mix or mortar	Replacement ratio of LP (%)	Mineral admixture other than LP	Chemical admixtures	Properties		
					Fresh	Hardened	Durability
Celik et al. (2014)	SCC with w/c 0.35 and total aggregates to cementing material ratio 4 to 1	15	Basaltic ash (NP) was 30–50	High-efficiency PC-based SP 1–1.50%	NP increased flowability	LS decreased C.S. at 7 and 28 days	LS increased gas permeability. All mixes had high resistance to chloride penetration. NP had higher water absorption capacity
Sua-iam et al. (2016)	SCC with *w*/*b* 0.28.	10% and 20%	RHA 10% and 20%	PC-based HRWR admixtures (2%)	Ternary system satisfied the EFNARC requirements. LS improved the workability than RHA. Ternary blend of RHA and LS improved workability	LS had higher strength gain than RHA. Addition of RHA and LS increased C.S. and UPV of SCC.	–
Shadkam et al. (2017)	SCC with *w*/*b* ratio 0.4 and 0.5	LS (40 and 80 kg/m^3)		PC-based HRWR admixture as SP (0.89–3.91 kg/m^3) and VMA(0.41–0.72 kg/m^3)	–	–	LS had lower porosity and diffusion coefficient, while VMA had higher value. LS had higher electrical resistivity than VMA, but greater than control mix

Chapter 3

Cement–Admixtures Compatibility in SCC

The cement paste with naphthalene-based admixture showed lower fluidity, while PC acid-based admixture had higher fluidity. Interaction between Portland cement and admixture affected fluidity, setting and stiffness of cement paste. Organic admixtures dispersed the cement particles through surface activating action between solid and liquid and reduced the quantity of water. The sulfonic acid-based organic admixtures contain hydrophilic group and hydro- phobic group that are adsorbed on cement particles. The sulfonic group dissociation provides negative potential to cement particles; thus, cement particles become electro- statically repulsed from each other and fluidize the cement paste (Hanehara and Yamada 1999). The performance of PC-based SP altered with the modification in backbone side-chain bond structures. SP with high slump flow loss did not retard setting time, whereas SP with better work- ability retention retarded setting time at higher dosages. The increase in admixture dosages increased strength and reduced water/powder ratio (Felekoglu and Sarikahya2008). The cement particles agglomerated in water suspension which increased the viscosity by increasing apparentparticle volume. Some amount of water entrapped in theporosity of agglomerates did not contribute to flowability.The main function of SP is to break down the agglomerates by modifying the inter-particle forces and consequentlydecrease the total pore volume and refine pore structure.The dominant pore sizes remain unaffected and thresholddiameter decreased with SP (Lazniewska-Piekarczyk 2012).

The cement–admixture compatibility is also affected withthe inclusion of mineral additive, because, admixtures interact with other components along with cement particles.The adsorption is higher with the increase in carboxylategroup content in admixture because admixture adsorptionby cement particles is mediated by its carboxylate group.The addition of PCE admixtures reduced plastic viscosityand yield stress. The zeta potential values became closeto zero with the use of admixtures. The reduction in yieldstress increased with the increase in molecular weight anddecrease in C/E (carboxylic/ester groups) of admixtures(Alonso et al. 2013). The plastic viscosity decreased withthe increase in side-chain density of carboxylic acid group.The apparent yield stress was not significantly affected withside-chain density and molecular weight. The cement and SPwere incompatible due to higher amount of side chains ofpolymer which enhanced the risk of flocculation of cementparticles (Mardani-Aghabaglou et al. 2013). The simultaneous inclusion of calcium lignosulfonate (LS) superplasticizer and tripolyphosphate type retarder (TP) accelerated thesetting time which proves the incompatibility of these twoadmixtures. The electrostatic repulsion had a major role inthe dispersion procedure of naphthalene sulfonate formal-dehyde (NSF) and LS admixture. The decrease in amountof electrostatic charge was a major factor which contributed greatly to workability loss. The mortar with naturalpozzolana (NZ) had higher adsorption values which causedloss in workability (AzariJafari et al. 2014). The increasein slump flow caused deformability and reduction in yieldstress of concrete (Blankson and Erdem 2015). The reasonfor incompatibility of PCE–cement/concrete system wasadsorbing preferences that depend on type of surface whichprovides the best steric match with molecular configurationof PCE admixture molecules. PCE had the ability to incor-porate into layer structure of clay; therefore, their dispersingability in concrete was hindered by clay impurities. Freesulfate anions occupied the positively charged anchoringsites on cement particles. PCE extended setting time andentrained more air in concrete production (Yaphary et al.2017). The addition of SCMs not only improved strength anddurability properties of SCC, but also improved the rheological properties. The dilution effect of FA and slag promotedSP consumption on the cement particles. Cement with FA, higher C_3A and less gypsum content had higher slump value, while lower value of slump was observed with lower C_3A and higher content of gypsum. A considerable amount of lime present in slag favor yields more Ca ions and results in higher adsorption. The higher value of C_2S/C_3S in cement increases compressive strength. The partial substitution of cement with FA provides limited sites for nucleation and growth of CSH product, which results in development of compressive strength. The concentration of C_3S and C_2S in cement had a major role on compressive strength. The interaction of cement with admixtures depends on physical and chemical properties of cement and SP. The small varia- tion in properties of cement and SP altered the properties of SCC (Almuwbber et al. 2018).

Chapter 4

Conclusions

The self-compacting concrete is a flow able concrete which is able to consolidate under its own weight. The self-compacting concrete improves the quality of concrete and reduction of onsite repair. It has faster construction time, reduces the overall cost and also improves health. Safety is achieved through the elimination of handling of vibrations. SCC uses various minerals such as SF, MK, fiber, GGBFS, RHA, FA and LP and chemical admixtures to improve its properties. The following findings can be drawn from this study.

- Silica fume increased the superplasticizer demand and compressive strength and improved workability. Silica fume reduced the final absorption. Silica fume along with nano-silica improved the pore structure.
- GGBFS decreased superplasticizer demand, viscosity and mini V-funnel flow time, but improved workability. GGBFS had compressive strength comparable to the con- trol mix. Sump flow and air content decreased at higher content of RHA and lower water/binder.
- Filling and passing ability, Orimet, inverted slump cone flow times and AEA dosages increased at high RHA content and lower *w*/*b* ratio. Lower water–binder ratio and increased content of RHA increased strength, UPV and electrical resistivity, but reduced porosity and water absorption.
- Metakaolin increased slump flow losses and T50 flow time, but decreased flowability. MK up to 30% in blended SCC improved strength and permeability in comparison with unblended SCC. SCC with MK gave unfavorable performance in an acidic environment. MK and steam curing increased durability properties.
- Fibers reduced the workability, but increased superplas- ticizer demand. Fiber improved fresh and strength prop- erties of SCC. Strain value decreased with the increase in fiber content. Compressive strength slightly increased with aggregates size. For a constant w/c ratio, compres- sive strength and tensile strength decreased with richer mixes. The increase in steel

fiber decreased compressive strength, but split tensile and flexural strength increased. Steel fiber had no effect on modulus of elasticity.

- FA decreased SP demand. Workability and rheological properties of fresh SCC improved with FA. FA content decreased compressive strength at 7 and 28 days, but improved at 90 days. FA up to 15% in concrete mix had no beneficial effect on split tensile strength, but at higher volume reduced split tensile strength. FA up to
- 15% reduced water absorption, capillary absorption and chloride penetration.
- Limestone powder along with FA improved the fluid- ity and VMA reduced it. Ternary system of RHA and LP satisfied EFNARC requirements. LS and RHA sepa- rately and in combination improved workability, but LS was more effective than RHA. Limestone with RHA and basaltic ash, respectively, increased the strength. It also improved the durability properties as well.
- The incorporation of mineral additive influenced the cement–admixture compatibility because admixtures react with other components too.
- The use of organic admixtures dispersed the cement particles and reduced the quantity of water. The admix- tures make cement particles electrostatically repulsive by providing negative potential which results in fluidized cement paste.

Chapter 5

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