EFFECT OF SCMs ON THE DURABILITY PROPERTIES OF HIGH STRENGTH LIGHTWEIGHT AGGREGATE CONCRETE

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ABSTRACT. Lightweight aggregate concrete possess great potential bring sustainable developments in construction industry. As the demand for concrete is growing, one of the effective ways to minimize the harmful effect of concrete is to improve its structural efficiency and durability performance. Addition of supplementary cementitious materials (SCMs) is one of the way to improve the durability performance of concrete. The present study aims to identify the influence of silica fume and metakaolin on the performance of the high strength lightweight aggregate concrete. The mechanical properties, such as compressive strength, splitting tensile strength and drying shrinkage, and the durability properties like surface resistivity, chloride migration and corrosion rate were investigated. The water-binder ratios adopted in the present study was 0.25 and 0.35; and the percentage replacement of the SCMs were taken as 10 and 15 %. All the developed concretes attain the strength required to qualify them as high strength concretes. The results indicates that the improvements in strength properties are marginal by the inclusion of silica fume and metakaolin, whereas significant improvements in the durability properties were observed. It was also noticed that the mechanical and durability properties of the investigated concretes were improved with age of curing.

Keywords: Durability, Sustainability, Lightweight concrete, Sintered fly ash aggregate

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INTRODUCTION

Structural lightweight aggregate concrete is a vital and versatile material in modern construction practices. The inclusion of lightweight aggregate (LWA) in structural concrete provides a weight reduction of 25 %–35 % without sacrificing the strength [1]. In recent decades the demand of high strength lightweight aggregate concrete has been increased in areas like multi storey buildings, long span bridges, offshore oil platforms and precast structural components [2, 3]. In offshore floating structures, great efficiencies are achieved by the adoption of lightweight materials. A reduction of 25 % in weight of reinforced concrete will result in a 50 % reduction in load when it is under submerged condition [4]. Reducing the self-weight of the concrete without sacrificing the strength is one such initiative to improve the structural efficiency of the concrete. Though some European and North American codes provide certain guidelines towards the structural application of lightweight aggregate concrete (LWAC), most of the mechanical and durability characteristics are poorly categorized [5]. This may be due to lack of available data in this research area; since most of the structural lightweight aggregate concrete research is concentrated on expanded clay, shale and slate.

Sintered fly ash lightweight aggregate is one of such potential materials to make concrete lighter than the conventional aggregate concrete [6]. Sintered fly ash lightweight aggregates were produced by sintering the mixture of fly ash, semi plastic clay as binder and coke breeze at a certain proportion and sintering them at a temperature between 1200 ^{0}C and 1300 ^{0}C in a Laboratory Chain Grate Sintering System by the Down Draft Sintering Technique [7]. To develop high strength concrete, inclusion of high end pozzolanic materials like metakaolin (MK) and silica fume (SF) is essential. According to earlier studies, it was found that 10 to 15% replacement levels are the optimum dosage for metakaolin and silica fume to enhance the matured properties of the concrete [8]. Adoption of lower water-binder ratio and suitable pozzolanic material will create a stronger paste within the concrete matrix. Earlier studies proved that proper aggregate packing is highly effective in the development of high performance concretes [9].

The present investigation is an attempt to develop high strength high performance lightweight concrete using sintered fly ash aggregate in a more reliable method and also to investigate the influence of metakaolin and silica fume on the mechanical and durability properties of the developed concretes. In this study metakaolin and silica fume were replaced at 10% and 15% by weight of the Ordinary Portland cement to investigate the relative effectiveness of metakaolin and silica fume on the development and performance of the concretes. For this purpose, two groups of concrete mixtures having water-binder ratios 0.25 and 0.35 were employed and the mechanical and durability characteristics of the developed concretes were assessed through various experimental investigation at different ages. This study will envisage the potential use of sintered fly ash aggregate on the development of high-performance concretes.

EXPERIMENTAL PROGRAME

Materials

Ordinary Portland cement (53 grade) confirming to IS: 12269 was used as the primary binding material. Metakaolin and silica fume were used as supplementary cementitious materials (SCMs). Well graded river sand was used as fine aggregate. Three different size fractions of sintered fly ash aggregates 2–4, 4–8 and 8–12 mm, were used as coarse aggregates. All the coarse aggregates confirming with the requirements provided by ASTM C 330. The sintered fly ash aggregates are rounded in shape and possess a rough surface texture. The average individual aggregate crushing strength is found to be 9.5 MPa in accordance with the procedure given by Kockal and Ozturan [10]. Commercially available polycarboxylate ether based superplasticizer is employed to achieve the desired workabilities.

Mix Proportioning

The water-binder ratios adopted in this investigation are 0.35 and 0.25. The free water content is fixed at 170 kg/m^3 for both the mixes. To compensate the water absorption by the aggregate that takes place during mixing, extra water is added according to the method proposed by the authors elsewhere [11]. Different aggregate fractions were combined in accordance with the combined aggregate grading as recommended by the DIN 1045 [12]. Standard curve DIN 'A' is adopted in the present study as the reference grading curve. Actual and standard DIN 'A' curve along with different aggregate fractions is presented in Fig. 1. The detailed mix composition formulated for the current experimental investigation is presented in Table 3. The optimum dosage of the superplasticizer (SP) was determined by conducting trials in order to achieve the designed slump of 100 ± 10 mm. In the mix designation letters 'C' stands for control mix and, 'M'and 'S' indicates mix which contains metakaolin and silica fume, respectively. The numbers 10 and 15 indicate percentage replacement of SCM by mass of cement. The numbers 25 and 35 indicate water-binder ratio 0.25 and 0.35, respectively. For example mix designation M 1025 indicates that the mix contain water-binder ratio 0.25 and 10% metakaolin as SCM.

Table 1 Concrete mix composition adopted in the present investigation.

MIX ID	w/c	SCM (%)	Cement (kg/m^3)	MK (kg/m^3)	SF (kg/m^3)	WATER (kg/m^3)	FINE AGGREGATE (kg/m^3)	COARSE AGGREGATE (kg/m^3)	SP (kg/m^3)
C 25	0.25	0	680	0	0	236	326	696	4.08
M 1025	0.25	10	612	68	0	235	323	690	4.83
M 1525	0.25	15	578	102	0	235	322	688	5.44
S 1025	0.25	10	612	0	68	235	321	686	5.17
S 1525	0.25	15	578	0	102	235	319	682	6.12
C 35	0.35	0	486	0	0	243	359	767	2.72
M 1035	0.35	10	437	49	0	242	358	763	2.99
M 1535	0.35	15	413	73	0	242	357	763	3.13
S 1035	0.35	10	437	0	49	242	356	760	3.26
S 1535	0.35	15	413	0	73	242	355	757	3.4

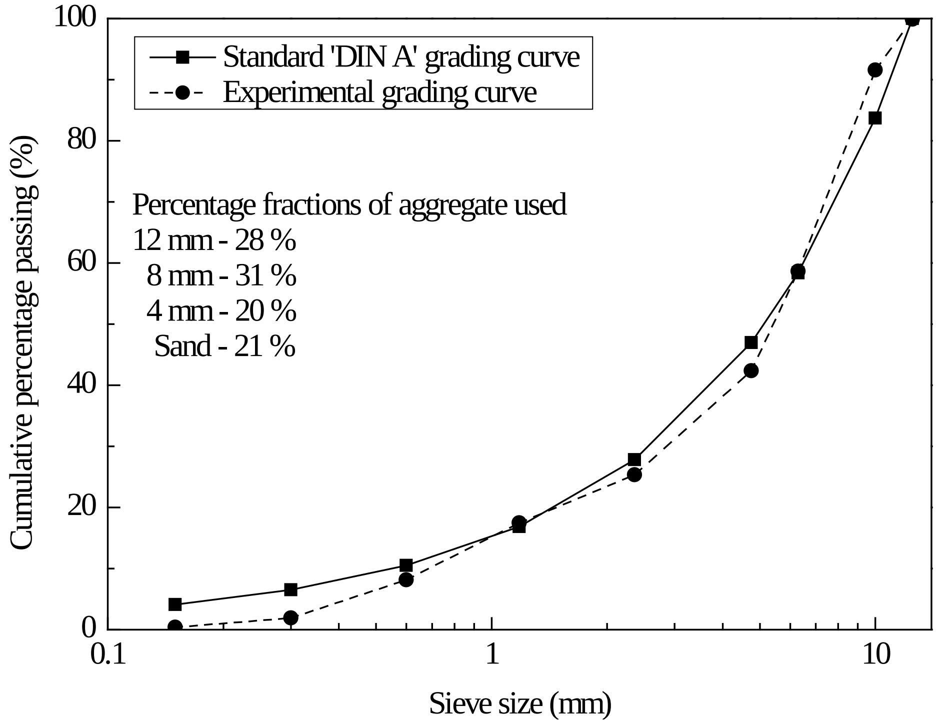

Figure 1 The actual and standard grading adopted in the study.

Experimental Methods

The experimental program was formulated in such a way that the mechanical properties were assessed by compressive strength, splitting tensile strength and drying shrinkage. The durability properties were assessed by the surface resistivity, chloride migration coefficient, and the rebar corrosion rate. The mechanical properties were determined according to the guidelines provided by ASTM. The mechanical properties and the corresponding codes can be described as follows; compressive strength (ASTM C 39), splitting tensile strength (ASTM C 496), and drying shrinkage (ASTM C 157). Compressive strength and splitting tensile strength tests were conducted on an automatic compression testing machine having a capacity of 3000 kN. To determine the ionic conductivity of the concrete, surface resistivity has been conducted using the Wenner four probe apparatus on a cylindrical sample. Chloride migration is another important permeation characteristic exhibited by the concrete. Chloride migration coefficient of the concrete was determined using rapid chloride migration test conducted on disc specimen in accordance with NT Build 492 [13]. To understand the status of the reinforcement steel embedded within the concrete, corrosion rate was monitored using potentiodynamic polarization technique (Tafel plot).

RESULTS AND DISCUSSIONS

Compressive Strength

The compressive strength test results obtained on concretes having water-binder ratio 0.35 and 0.25 are depicted in Fig. 2. It can be observed from the results that, as the SCM dosage increases the later compressive strength also increases. In the case of 0.35 water-binder ratio concretes, at 28 days 10 to 13% strength reduction was observed due to the incorporation of SCMs. This may be due to the phenomena called dilution effect, a consequence of replacing a part of cement by the same quantity of metakaolin and silica fume [14]. More precisely addition of silica fume exhibited enhanced strength results over metakaolin. Similar trends were observed earlier in case of normal aggregate concrete also [15]. The dilution effect may be absent in these category of concretes due to the higher cement content adopted in the mixes. Moreover from Fig. 2 it can be noticed that 10% replacement level is the optimum in case of silica fume whereas 15% replacement level performs superior in case of metakaolin concretes. From the results it can be seen that by employing these SCMs high strength lightweight aggregate concretes having strengths more than 60 MPa can be realized.

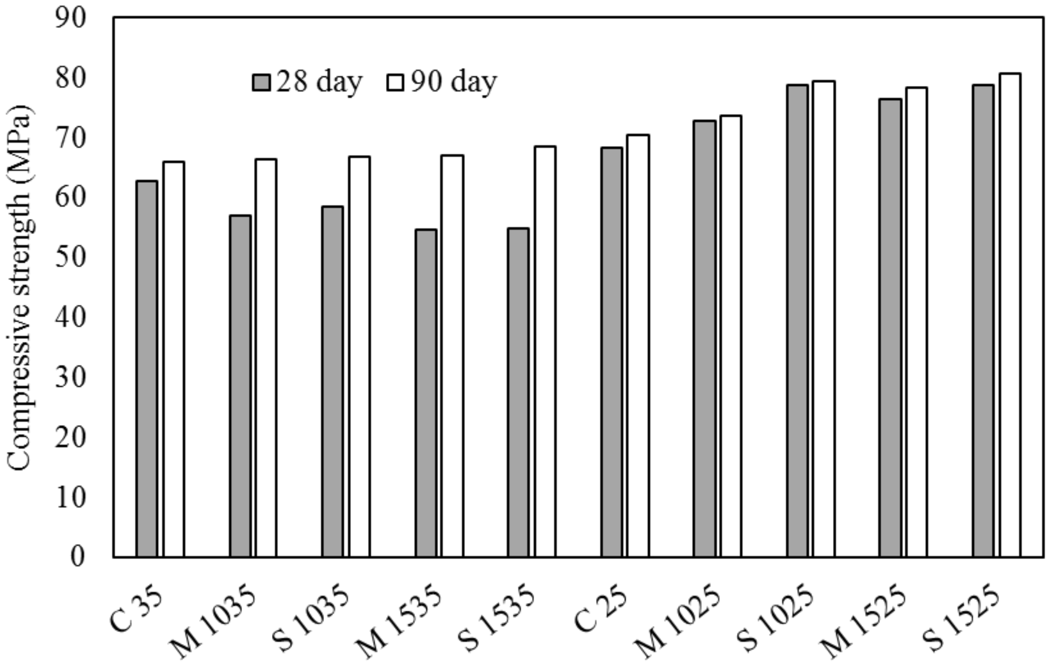

Figure 2 Compressive strength of concretes

Splitting Tensile Strength

The tensile strength results of the developed concretes were depicted in Fig. 3.The results indicate that cement replacement with silica fume is more effective compared to metakaolin in sintered fly ash aggregate concretes. It was observed that the tensile strength enhancement is limited in the case of concrete having water-binder ratio 0.35, even by the addition of SCMs. A slight decrement in tensile strength is observed in case of 15% replacement of both silica fume and metakaolin at 28 days, but the variation in tensile strength becomes marginal at 90 days. Among this only concrete containing silica fume shows superior results at 90 days. In all the cases metakaolin concretes perform inferior to control mix. Though the variation in all the concretes is marginal, S1525 exhibited an exceptional performance compared to other concretes at 90 days. Earlier studies reported that 10–15% replacement of metakaolin and silica fume will have beneficial effect on the tensile properties of LWAC [16]. But in the present investigation, this trend is only visible in 0.25 water-binder ratio for silica fume replacements at 90 days of curing.

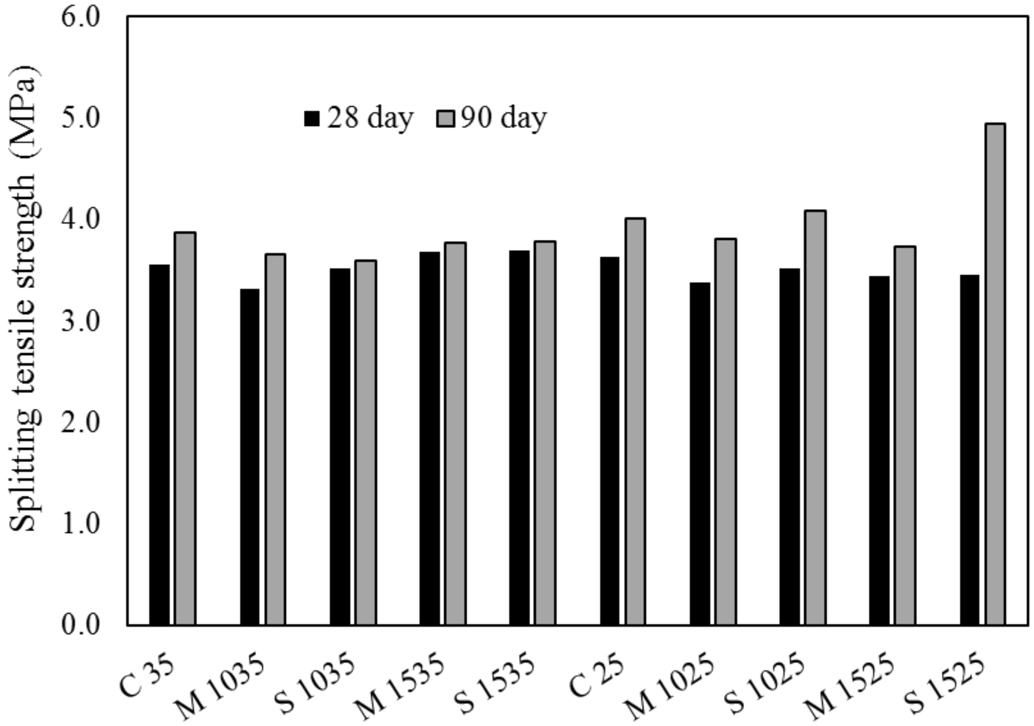

Figure 3 Splitting tensile strength of concretes

Drying Shrinkage

The drying shrinkage results of the concrete having water-binder ratios 0.35 and 0.25 were presented in Fig. 4. By analyzing the results of concretes having water-binder ratio 0.35, it can be observed that the addition of metakaolin reduces the shrinkage whereas silica fume increases the shrinkage. Up to three weeks the control mix possesses the maximum shrinkage compared to concretes containing pozzolanic materials. Concrete having 15% silica fume concretes surpasses all the other concrete from third week onwards. After 12 weeks, S 1035 also attained second highest shrinkage. Meanwhile, concretes containing 15% metakaolin showed the least shrinkage after 9 weeks, till then M 1035 exhibited the least shrinkage. Also, it is noticed that the shrinkage occurred in control mix gets stabilized by 10 weeks, while the concrete containing pozzolanic material took 13 weeks. This may be due to the extended pozzolanic reactivity occurred in the concretes contains SCMs. The increase in drying shrinkage by the addition of silica fume was also observed earlier in case of normal aggregate concrete. This may be due to the increment in the capillary stress due to the refined micro pore structure of the paste matrix [14]. Also, Zhang et al., [17] observed that the autogeneous shrinkage of the concrete increases with increase in the silica fume content within the concrete mix. Whereas, in the case of metakaolin the long term autogeneous shrinkage is found to decrease with the increase in the dosage [18]. In case of concretes having water-binder ratio 0.25, from ninth week onwards S 1525 possess the highest shrinkage among all the concrete. Meanwhile, M1525 possess minimum shrinkage.M1025 and control concrete shows similar shrinkage values from tenth week onwards. Compared to water-binder ratio 0.35, concrete having water-binder ratio 0.25 stabilizes against shrinkage at the earliest. It can also be noticed that 10% and 15% replacement of metakaolin has no effect on the final shrinkage of the concrete up to 6 weeks. Almost all concretes have attained stability against shrinkage from 11 weeks onwards.

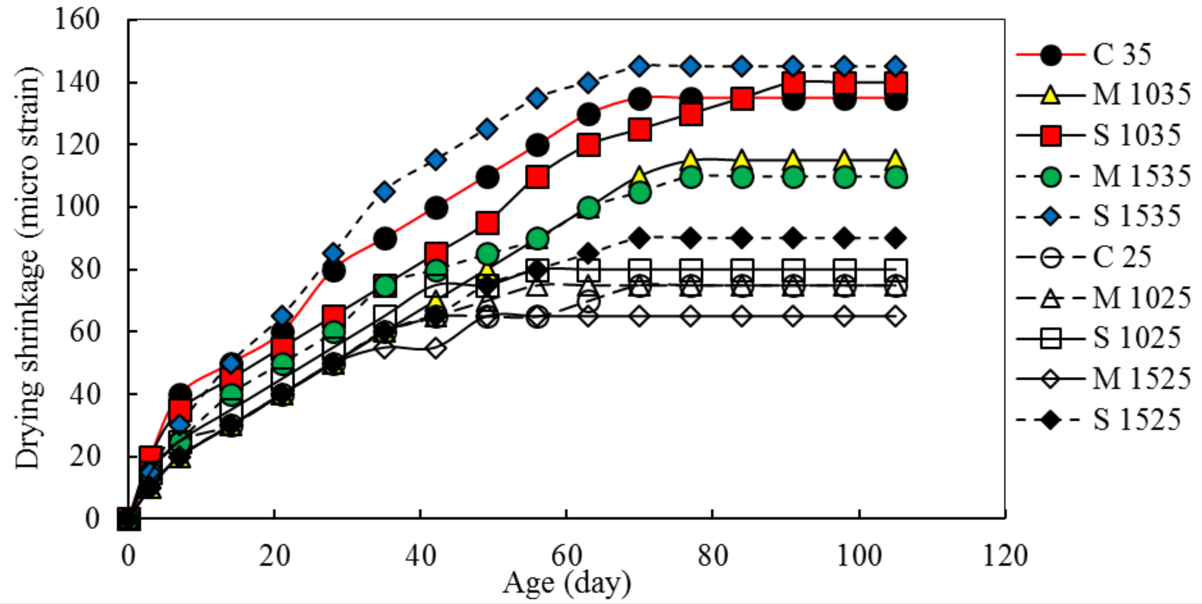

Figure 4 Drying shrinkage of concretes at different ages

Surface Resistivity

The ionic resistance offered by the concrete was assessed through surface resistivity test. The surface resistivity results indicate that the incorporation of SCMs has significant impact on the performance characteristics of the LWAC (Fig. 5). Also, it can be observed that significant improvement has taken place in all the concretes with age. This may be the result of prolonged hydration due to internal curing [19] and pozzolanic reaction [20] that may have taken place within the matrix. Incorporation of both the metakaolin and silica fume in LWACs resulted in enormous increase in the resistivities of the concretes. The inclusion of silica fume has dominant outcome than the metakaolin at both 28 and 90 days. This may be due to higher fineness of silica fume, which enhances the micro filling ability than the metakaolin. Also, higher specific surface area may aid towards the maximum participation in the secondary hydration.

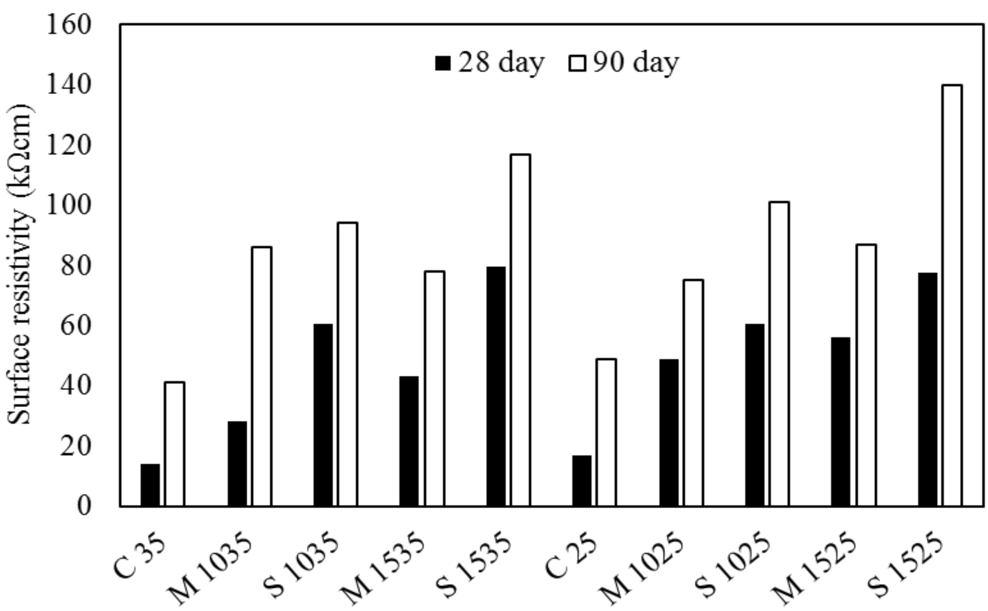

Figure 5 Surface resistivities of concretes

Chloride Migration

The rapid chloride migration test results are depicted in Fig. 6 and according to that, addition of mineral admixtures having beneficial effects on the coefficient of chloride migration in water-binder ratios 0.35 and 0.25. In water-binder ratio 0.35 addition of mineral admixtures causes the increase in chloride diffusion. This may be due to the dilution effect of the SCMs, but in water-binder ratio 0.25 this effect may absent. Previous studies have shown that the coefficient of chloride migration lies in the range of 3.4 -10.3 $\times 10^{-12}$ m^2/s for w/b ratio 0.35 in the case of lightweight aggregate concretes [21]. And the present study on the sintered fly ash aggregates also lies within the similar range. In an earlier investigation Real et al. [21] observed that the due to more accessible porosity 'Lytag' (sintered fly ash aggregate) exhibited higher chloride migration than the other type of aggregates.

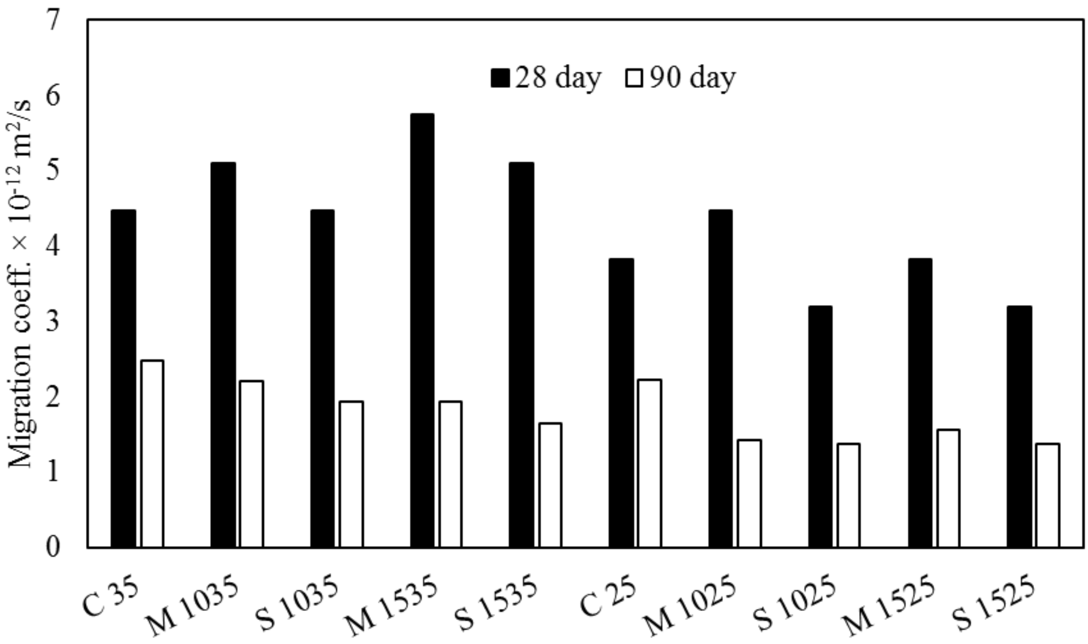

Figure 6 Chloride migration coefficient of different concretes

Corrosion Rate

The reinforcement corrosion in concrete is partially governed by the permeation of ions through the concrete matrix. The corrosion rate results of the concrete specimen cured in chloride water is shown in Fig. 7. Corrosion rate results of concretes having water binder ratio 0.35 indicate that after two years all the concretes possess 'low 'corrosion rate according to the assessment criteria provided by Bertolini et al., [22]. The concretes having water binder ratio 0.25 possess a lower corrosion rate than water binder ratio 0.35. Also all the concretes except control concretes shows 'low' corrosion rate from 56 days of curing. At water binder ratio 0.25, it is observed that metakaolin concretes exhibited similar or better performance than silica fume concretes. Especially, concrete having 15% metakaolin replacement shows superior performance even in chloride environment. This may be due to the formation of stable 'Friedel salt' in these concretes [23]. Previous studies also concluded that 15% replacement of metakaolin, reduced the reinforcement corrosion in LWAC significantly [24]. These observations indicate that to produce a high-performance concrete in the aggressive environment combination of sintered fly ash aggregate and mineral admixtures can be recommended.

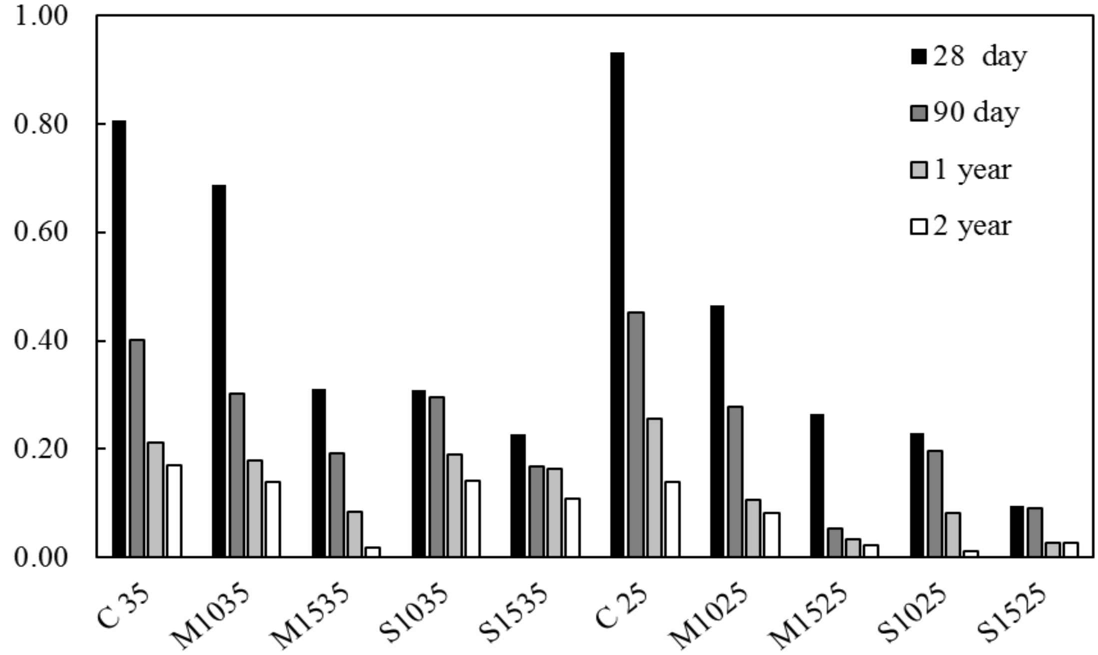

Figure 7 Corrosion rate of specimens at different ages

CONCLUDING REMARKS

Due to the inclusion of both metakaolin and silica fume the superplasticizer demand of the concrete mix getting increased. And the demand increases as the replacement level increases. Among this silica fume concretes exhibited higher superplasticizer demand compared to metakaolin concretes. Strength enhancement is possible by the replacements of silica fume and metakaolin, among them silica fume offers superior results compared to metakaolin. The improvement of tensile strength of the concrete due to the addition of silica fume and metakaolin is marginal. Drying shrinkage results indicate that the addition of silica fume will increase the drying shrinkage of the concrete, whereas metakaolin reduces the same. Surface resistivity results show that addition of both metakaolin and silica fume improves the resistivity significantly. Rapid chloride migration test results indicates that the use of sintered fly ash aggregate at lower water-binder ratio possess 'good' quality concrete in general. The corrosion rate study of the developed concretes reveals that the addition of the SCMs into the concrete matrix facilitates good corrosion resistance even in the aggressive environment also. The effectiveness of the SCMs is more profound in concrete having water-binder ratio 0.25 than 0.35.

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