Durability of Concrete with Different Mineral Admixtures: A Review

Tehmina Ayub, Nasir Shafiq, Sadaqat Ullah Khan

Abstract—Several review papers exist in literature related to the concrete containing mineral admixtures; however, this paper reviews the durability characteristics of the concrete containing fly ash (*FA*), silica fume (*SF*), ground granulated blast furnace slag (*GGBS*), metakaolin (*MK*) and rice husk ash (*RHA*). Durability related properties reviewed include permeability, resistance to sulfate attack, alkali-silica reaction (*ASR*), carbonation, chloride ion penetration, freezing and thawing, abrasion, fire, acid, and efflorescence. From review of existing literature, it is found that permeability of concrete depends upon the content of alumina in mineral admixtures, i.e. higher the alumina content, lesser the permeability which results higher resistance to sulfate and chloride ion penetration. Highly reactive mineral admixtures prevent more *ASR* and reduce efflorescence. The carbonation increases with the mineral admixtures because higher water binder ratio and lesser content of portlandite in concrete due to pozzolanic reaction. Mineral admixtures require air entrainment except *MK* and *RHA* for better resistance to freezing and thawing.

Keywords—Alkali silica reaction, carbonation, durability, mineral admixture, permeability.

I. INTRODUCTION

CONCRETE is supposed to last for decades and/or centuries due to its excellent durability characteristics. Term 'durability' has been described as an ability to resist against environmental risks and maintaining desired engineering properties [1]. Environmental risks may involve weathering action, chemical attack, alkalinity, carbonation, freezing and thawing and abrasion. It is reported in literature that not only placement, curing and service environment influence the durability characteristics of concrete but proportioning and interaction between concrete ingredients significantly control the durability and life of the concrete. Different mineral admixtures are often added in concrete to improve the durability, rheology of fresh concrete, and mechanical properties of hardened concrete.

It is well known that changes and deterioration in concrete limit service life of the concrete structures. Addition of mineral admixtures to concrete not only reduces the cement content thereby reducing heat of hydration, but also inhibits deterioration of concrete making it durable and better quality concrete by reducing pore size or permeability and improving resistance against sulfate attack, alkali-silica reaction (*ASR*), carbonation, chloride attack on reinforcement, freezing and thawing, abrasion, fire, and acid.

Numbers of examples in the literature are evidence of the positive impact of mineral admixtures on the durability properties of the concrete. Thomas et al. [2] proved that use of *FA* reduces concrete permeability or in other words improves durability by reporting the results of cores taken from 30-year-old structures which had been performing well at that time. Maage and Sellevold [3] presented the 20-year results which indicated that concrete containing *SF* performed approximately same as those as made with sulfate-resisting cement. Resistance of concrete against sulfate attack is improved by the use of *MK* and *RHA* [1]. Comparison of the mechanical properties [4] and properties of fresh concrete [5], [6] containing mineral admixtures exist in literature, but only few mineral admixtures have been compared. The comparison of durability characteristics of hardened concrete incorporating mineral admixtures including *FA*, *GGBS*, *SF*, *MK,* and *RHA* is the theme of this paper.

II. DURABILITY OF CONCRETE

In concrete technology, durability refers to the resistance against degradation. The primary factor determining durability is a good-quality concrete with low porosity i.e. low permeability. The other advantages of durable concrete include resistance to alkali-silica reaction and sulfates, increased corrosion protection, and reduced heat of hydration. The utilization of wastes and industrial by-product led the researchers to partially replace the cement. Thomas et al. [2] and Thomas [7] reported that the use of mineral admixtures is highly beneficial in order to reduce the environmental damage, along with the improvement of durability of concrete. This improvement is caused by the alteration of pore structure of concrete to reduce its permeability, thus increasing its resistance to water penetration and water-related deterioration such as frost damage, reinforcement corrosion, sulfate and acid attack [8], [9]. Keck and Riggs [10] discussed the benefits of the addition of Class C and Class F *FA*. Use of *FA* in concrete provides many advantages related to durability such as reduced permeability [10], resistance to alkali-silica reaction (*ASR*) [10], [11] and sulfates [8], increased corrosion protection, and reduced heat of hydration. *GGBS* in concrete is beneficial in terms of long-term durability due to smaller pore size, overall finer pore size distribution [8], resistance to

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sulfate attack [12], resistance to *ASR* [12] and resistance to chloride attack [12]. Similarly, *SF* produces very dense microstructure concrete [8] which features high impermeable, sulfate resistant [13] and resistance to chloride ion diffusion [14]. *MK* as a partial replacement of cement has been reported as an effective solution of improving the pore structure and hence exhibits greater resistance against harmful environmental attack. Generally, well-cured slag concrete is likely to be more durable than similar Portland cement concrete [8]. *RHA* concrete reduces the permeability of concrete [15] and it is better sulfate resistant than *SF* concrete [16]. The detail of durability properties of these mineral admixtures has been discussed as under:

A. Permeability

Benefits of using *FA* in terms of low permeability are listed in literature and it is also identified that the addition of *FA* is good in terms of improving durability of concrete [10]. Inclusion of *FA* increases the small diameter pore in a cement matrix. Because of the change in pore size distribution, concrete become less permeable and resistance to penetration of media is improved [17]. Fig. 1 shows the permeability of concrete with and without incorporating *FA* and it can be seen that due to addition of *FA*, considerable reduction in the permeability is observed. This reduction in the permeability is due to the increase of cementitious compounds and the density of concrete, and thereby minimizing voids, which makes concrete to better resist freeze/thaw damage or fragmentation from attack by acids, salts or sulfates [18].
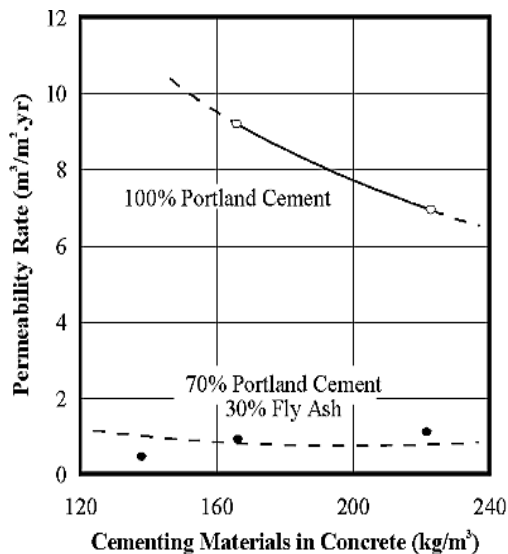

Fig. 1 Permeability of concrete with and without *FA* [18]

Inclusion of *GGBS* in well-cured concrete, particularly at higher temperatures has been reported as beneficial in terms of long-term durability due to continuous hydration, which takes place well beyond 28 days. With the increase in slag content, number of smaller pores increases and the overall pore size distribution become finer [8]. Similar to *GGBS*, very dense

concrete develops due to addition of *SF* which results very little permeable to impermeable *SF* concrete due to the virtual absence of weak layer normally surrounding the aggregates [8]. Cheng et al. [19] reported the influence of 0, 40 and 60% replacement of cement with *GGBS* on the permeability of the concrete and reported results were 2.56×10^{-13}, 1.52×10^{-13}, and 1.32×10^{-13} m/s, respectively. This shows that use of higher *GGBS* content causes denser structure and protects concrete from water penetration.

The interaction of *MK* by replacing 20% cement content in the presence of about 27% water forms additional calcium silicate hydrate (*CSH*) and calcium silicate aluminum hydrate (*CSAH*) through which pore size is reduced to about one tenth of the diameter during the initial days to reduce water uptake. *MK* concrete is less porous that reduce overall pore size lead to more strength, higher density and more acid resistance [1]. Pradip and Ajay [20]reported the results of water permeability of concrete in which 4, 6, and 8% volume of cement was replaced by metakaolin and reported lowest permeability with 8% cement replacement (Refer Fig. 2).
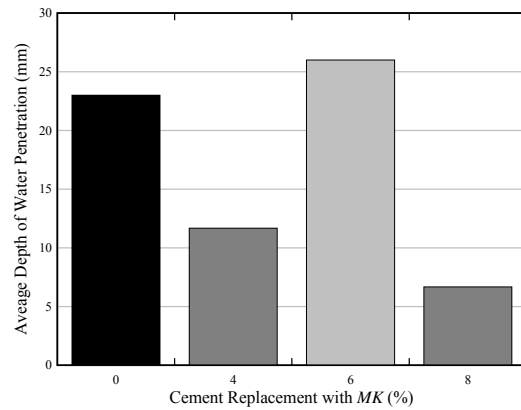

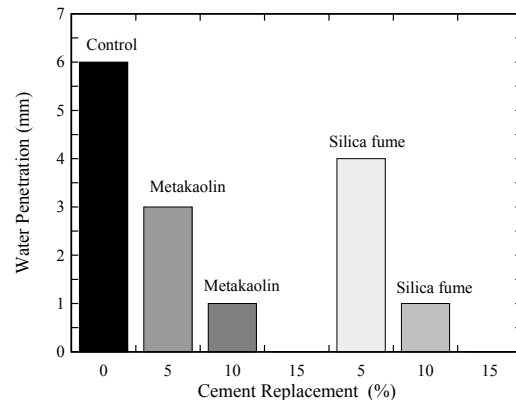Fig. 2 Average depth of water penetration of *MK* concrete with 4, 6 and 8% cement replacements (w/b=0.29) [20]

Fig. 3 Water penetration of *MK* and *SF* concretes (w/b =0.26) [21]

Bonakdar et al. [21] compared the depth of water penetration of metakaolin and silica fume concretes by replacing 5, 10, and 15% of cement content with each of the

both mineral admixture and reported that at 5% replacement level, permeability of metakaolin concrete was lower than silica fume concrete. While at 10% level, similar results of water penetration were observed while at 15% replacement level, both concretes were reported as impermeable (Refer Fig. 3).

Kartini et al. [15] through experimental results suggested that replacement of ordinary Portland cement (OPC) with *RHA* reduces the permeability of concrete and found that OPC concrete was about 3 and 7 times more permeable than concrete containing *RHA* up to 20% and 30%, respectively. Dakroury and Gasser [22] determined the effect of *RHA* content on the total porosity of cement paste and found that when the volume percentage of *RHA* increased, then total porosity is decreased (Refer Fig. 4).
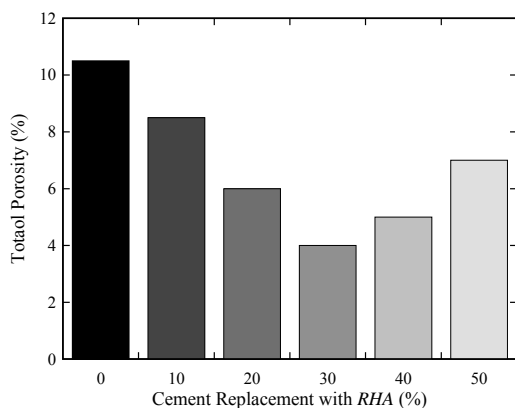

Fig. 4 Effect of cement replacement with *RHA* on the total porosity of the cement pastes [22]

On the other side, Givi et al. [23]investigated the effect of particle size of the *RHA* on the water absorption of the concrete and found that use of ultrafine *RHA* better reduces the water absorption (Refer Fig. 5).
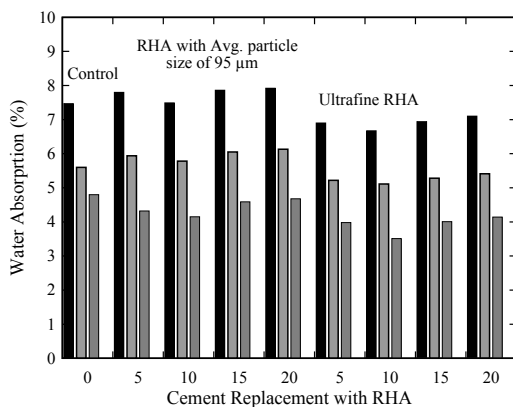

Fig. 5 Effect of particle size of *RHA* on the water absorption of concrete [23]

Hooton [17] carried out an experimental investigation on the sulfate resisting cement pastes by blending *FA*, slag and *SF*; and reported the experimental results of strength development, permeability to water and pore size distribution at 7, 28, 91, and 182 days after moist curing. According to results reported, *SF* was most effective in reducing permeability at early ages and reducing calcium hydroxide content of the cement pastes and slag was the least effective. Fig. 6 shows the reduction in the permeability due to various levels of replacement of cement by silica fume varying w/b ratios. It can be seen that there is direct relation between the permeability and w/b ratio and replacement of 6% of cement with silica fume at w/b=0.35 and 0.4 makes concrete impermeable but replacement of more than 10% of cement again starts increasing permeability [24]. Song et al. [24] associated the reason of discontinuous and impermeable pore structure of silica fume concrete to the refined pore size and denser matrix, reduced content of $Ca(OH)_2$ and refined paste and aggregate interfacial zone resulted due to pozzolanic reaction between silica fume and calcium hydroxide during hydration process.
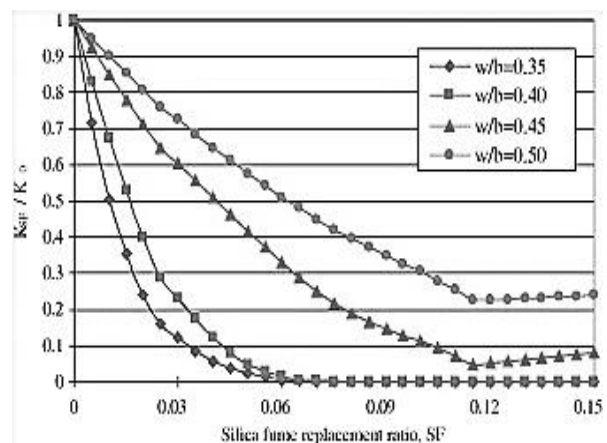

Fig. 6 Reduction in permeability due to partial replacement of cement with *SF* for different w/b ratio [24]

B. Resistance to Sulfate Attack

Sulfate attack occurs when calcium hydroxide and aluminates in the cement reacts with the sulfates contained in soil and seawater. Crystallization of seawater salts in the pores of the concrete may cause disruption, but this particular problem between tidemarks is subjected to alternate wetting and drying. The presence of a large quantity of chlorides in seawater inhibits the expansion experienced by concrete where groundwater sulfates have constituted the attack [8]. Deterioration of concrete in environments containing chloride has led to improve the resistance/performance of concrete against sulfate attack. Two basic forms of sulfate attack are as follows:
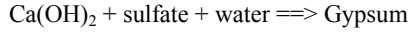1) Reaction between aluminates and gypsum in cement, and
2) Acid interaction of sulfate ions and calcium hydroxide (causing gypsum formation).

If the quantity of reactive aluminates in the cement is too high, then excessive reactive aluminates in hydrated form will be available to react with sulfates after hardening of cement.

This is harmful, as it will produce expansive ettringite and cracking of the concrete. This process has been summarized as:

$$Aluminate\ Hydrate + Ca(OH)_2 + sulfate + H_2O$$
$$==>Ettringite$$
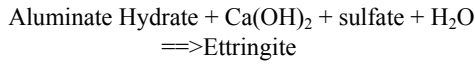
The second principle of gypsum formation has been shown below:

$$Ca(OH)_2 + sulfate + water ==> Gypsum$$

Calcium, Magnesium, Aluminium, and Ammonium of the sulfate salt affects the type and the severity of the attack. Therefore, use of supplementary cementitious materials together with cement results in the improvement of sulfate resistance of concrete.

It is reported by Newman and Choo [8] that the resistance of *FA* concrete against sulfate attack is comparatively higher than ordinary Portland cement concrete of similar grade due to reduced pore size which slows down the penetration of sulfate ions. Tricalcium aluminate (C_3A), which is the major constituent of cement and is prone to sulfate attack, gets diluted after reaction with sulfates within the *FA* at an early age. Concrete made with combinations of Portland cement and BS 3892: Part 1 Pulverized *FA*(*PFA*) where the *FA* content varies between 25-40 % has good sulfate resisting properties [8].United States Bureau of Reclamation (USBR) conducted a study on *FA* and showed that properly use of 35 % Class F fly ash in concrete will better resist sulfate attack than Plain concrete. Plain and fly ash concrete mixes using Type I cement, moderate sulfate resisting Type II and Type V cements were compared under standardized conditions of exposure to sodium sulfate. Test results revealed that Type II cement with Class F fly ash was more resistant to sulfate attack than Type V. Anantharaman [25] compared the test results of linear expansion of mortar samples exposed to Sodium Sulfate Solution at room temperature. The samples were prepared by 0, 10, 20, 30 & 40% cement content with Class C and Class F *FA* respectively. Results of the linear expansion due to ASR are shown in Fig. 7. Anantharaman [25] reported that use of both Class C and F lowered the expansion as compared to the control mortar specimens. During initial period of 0-14 weeks, initial expansions were observed to be increased as the replacement level increased.
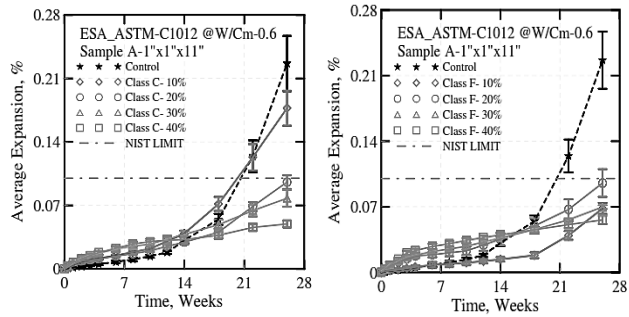

Fig. 7 Average expansion of Class C and Class F *FA* [25]

Similar to *FA* concrete, concrete containing *GGBS* exhibits higher resistance to attack from sulfates than those made with only Portland cements due to an overall reduction in the C_3A content in blended cement (*GGBS* contains no C_3A) and reduction in permeability. It is generally accepted that provided Al_2O_3 content of the slag is less than 15% than cements containing at least 70 % *GGBS* can be considered comparable to sulfate-resisting Portland cement [8]. Higgins and Uren [12] also confirmed the increase in the resistance of concrete to sulfate attack if Portland cement is partially substituted by *GGBS*.

Alongside *FA* and *GGBS* concrete, performance of *SF* concrete is same as that of concrete containing sulfate - resisting cement. Maage and Sellevold [3] presented the 20-year results which indicated that concrete containing *SF* performed approximately same as concrete made with sulfate-resisting cement. Thomas et al. [13] reported that together use of relatively small levels of *SF* (e.g. 3 to 6%) and moderate levels of high CaO *FA* (20 to 30%) produces a high level of sulfate resistance as shown in Fig. 8.
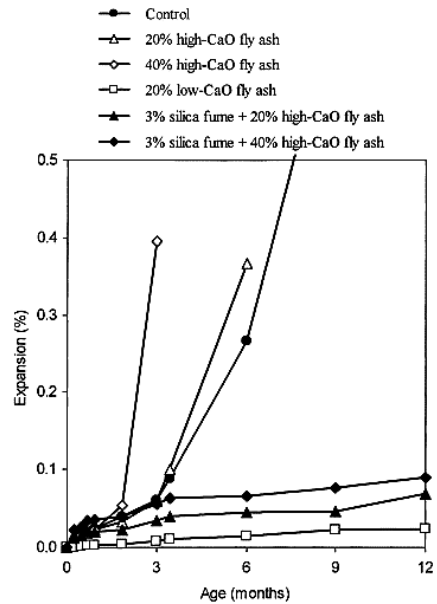

Fig. 8 Effect of *SF* and *FA* on sulfate resistance [13]

Use of *MK* and *RHA* also improves the resistance of concrete against sulfate attack. Addition of *MK* up to 15%, has been reported to increase sulfate resistance in a sodium sulfate solution [1]; similarly concrete mixed with *RHA* has been reported as better sulfate resistant than *SF* [16].

Al-Akhras [26] determined the sulfate resistance of *MK* concrete considering the effect of sulfate exposure period on sulfate expansion of *MK* concrete in which 5%, 10%, and 15% of cement was replaced with MK by weight of cement and water to binder ratio of 0.5 and 0.6 (Refer Fig. 9). From Fig. 9, it is evaluated that with the increasing *MK* replacement of cement sulfate resistance of concrete. Other than this, Al-Akhras [26] also determined the effect of water to binder ratio (w/b=0.5 and 0.6), curing type (moist and autoclaving) and air content (1.5% and 5%). Effects of these three parameters on 18 months sulfate expansion are shown in Fig. 10, which show that:

(1) The sulfate resistance of concrete is influenced by the w/bratio and at w/b ratio of 0.5; this resistance was found to be higher than that at w/b ratio of 0.6

(2) Autoclaved cured *MK* concrete exhibited higher sulfate resistance compared to moist cured due to lowering of the pore volume of autoclaved *MK* concrete, and

(3) As compared to the non-air entrained *MK* concrete, the air entrained *MK* concrete showed higher improvement in the sulfate resistance.
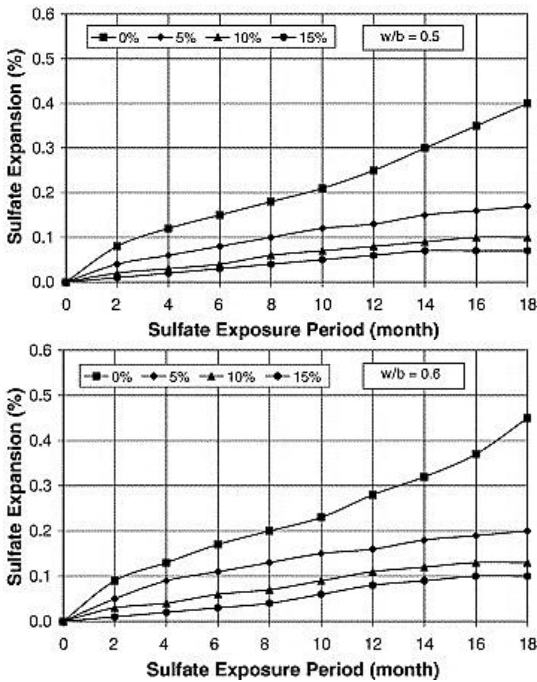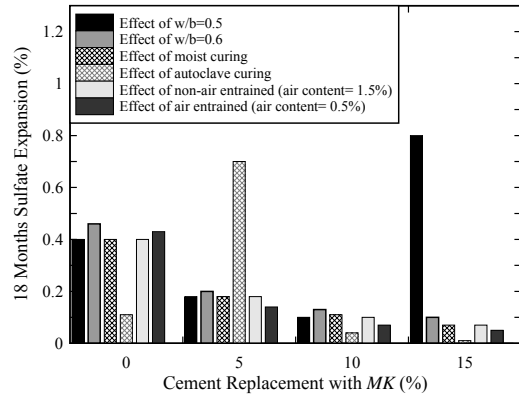

Fig. 10 Effect of water to binder ratio, curing type and air content on 18 months sulfate expansion [26]

Justice et al. [27] compared the results sulfate resistance of two types of *MK* concretes with *SF* concretes using w/b ratio of 0.485. The first *MK* concrete "MK235" was prepared from Kaorock Metakaolin while second type of *MK* concrete "MK349" was prepared from Kaorock F Metakaolin. The ASTM C 1012 test results of sulfate resistance are shown in Fig. 11, which indicate that the resistant to sodium sulfate attack can be produced using any of the two metakaolins or silica fume at either 8% or 15% weight replacement.

Fig. 9 Effect of sulfate exposure period on the sulfate expansion of *MK* concrete (for w/b= 0.5 and 0.6) [26]
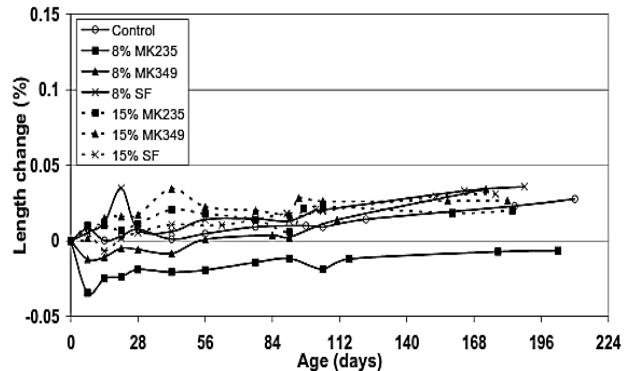

Fig. 11 Mortar bar expansion due to sulfate exposure [27]

Mangat and Khatib [28] presented the results of sulfate resistance of concrete containing various levels of *FA*, *SF*, or *GGBS* by partially replacing *OPC* and reported that cement replacement by 22 and 32 percent weight of *FA* produced maximum sulfate resistance. However, replacement by 5 to 15 percent also showed great sulfate resistance in spite of the increasing intruded pore volume and the proportion of large pores of diameter > 0.1μm. Moreover, it has been reported that higher level of sulfate resistance in the initially air-cured specimens in comparison with initially wet/air-cured specimens [28]. On the other hand, an increase was observed in the sulfate resistance of concrete in which 80 percent cement had been replaced by *GGBS* [28]. Whereas, 40 percent replacement showed disagreement in spite of the lower pore volume and the finer pore structure, under initial wet/air-

curing at 45°C and 25 percent relative humidity did not result in higher sulfate resistance. In another study to investigate the recycled concrete aggregates, conducted by Berndt [29]; it has been determined that replacement of cement by 50 percent slag gives best performance in terms of compressive and tensile strengths, elastic modulus, coefficient of permeability and durability in chloride and sulfate solutions. Contrarily, concrete with 50% *FA* had a relatively poor performance for the materials and mix proportions used in the study. Therefore, in authors view, such mixes must be tested in detail prior to use in construction projects. It can also be inferred that sulfate resistance of concrete incorporating mineral admixtures depends upon the content of alumina in mineral admixtures, higher the alumina content higher the resistance.

C. Alkali-Silica Reaction

Alkali–silica reaction (ASR) is a very trouble making reaction within concrete involving higher pH alkalis such as sodium and potassium hydroxide, which react with silica (usually exist within the aggregates) and produce gel. This gel has a high capacity of absorbing water from the pore solution causing expansion and disruption of the concrete. The main source of the alkalis is the Portland cement itself or external sources [8]. According to ASTM C 1260, expansion due to ASR of less than 0.1% at 14 days of age indicates acceptable performance, while expansion of greater than 0.20% indicates unacceptable performance [27].

Research shows that the addition of *FA* is a preventive source of ASR as glass present in *FA* is a highly reactive fine form of silica [10], [11]. To prevent ASR, coarse *FA* may be required; however use of small quantity of fine *FA* with low-reactivity aggregates is more susceptible to *ASR* [11]. Coarse *FA* has been found effective to prevent ASR when total alkalis within the concrete were as high as 5 kg/m3 and coarser *FA* was minimum 30%. Klieger and Gebler [30] reported that as compared to Class C, Class F *FA* more effectively resist the alkali-silica reaction expansion in mortar.

Thomas et al. [13] reported that with some *FA*, replacement levels to control expansion due to ASR may be required up to 60%; however, combined use of relatively small levels of *SF* (e.g. 3 to 6%) and moderate levels of high CaO *FA* (20 to 30%) is very effective in reducing expansion due to ASR. Anantharaman [25] compared the test results of ASR of mortar samples exposed to Sodium Sulfate Solution at room temperature. The samples were prepared by 0, 10, 20, 30 & 40% cement content with Class C and Class F *FA* respectively. Results of the linear expansion due to ASR are shown in Fig. 12, which show that use of both Class C and F lowered the average expansion due to ASR compared to the control mortar specimens. During initial period of 0-6 weeks, initial expansions were observed to be increased as the replacement level increased.
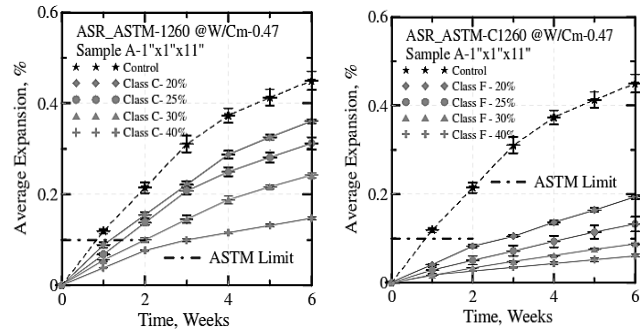

Fig. 12 Average *ASR* expansion of Class C and Class F *FA* [25]

Higgins and Uren [12] suggested that the use of a minimum 50% *GGBS* in concrete suitably prevents alkali-silica reaction, if the alkalis are only contributed by cementitious materials. Beside this, Ahmad and Shah [31] studied the effect of *GGBS* on the alkali aggregate reaction for various types of aggregates and found that aggregates from different locations exhibited different *ASR* potential and hence should be investigated individually. Results of *ASR* investigated by Ahmad and Shah [31] for two different sources of the aggregates up to 28 days are plotted in the Fig. 13 which further revealed that highest *ASR*, irrespective of the aggregate sources, were observed at 28 days.
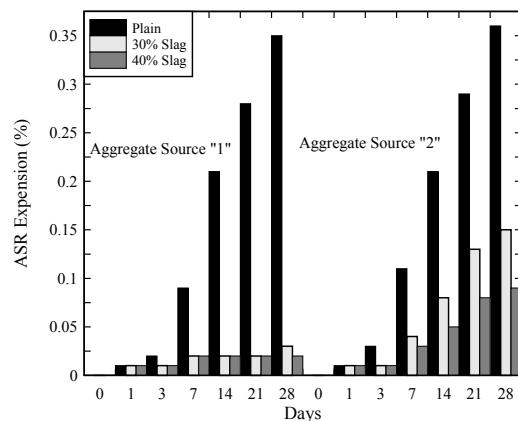

Fig. 13 Effect of *GGBS* replacement on the ASR for various types of aggregates [31]

Justice et al. [27] compared the ASR resistance of the *OPC* concrete and the concrete containing two types of *MK* and *SF* at w/b=0.47 (Refer Fig. 14). Based on the criterion of ASTM 1260 as described earlier, the 15% MK235 concrete (prepared from Kaorock *MK*) passed, while 8% MK235and 15% MK349 (prepared from Kaorock F *MK*) specimens fell into the intermediate range (showing between 0.10% and 0.20% expansion at 14 days), and all other concretes failed. These results show that both *MK* concretes reduce expansion due to *ASR* much higher than the *SF* concrete. Moreover, at 15% replacement with any of the two *MK*, concretes produced greater reductions in expansion than 8% replacement, and MK235 was more effective than MK349 in mitigating

expansion due to ASR. Replacement of cement between 10 and 15% with *MK* may be adequate to overcome the harmful expansion caused by *ASR* in concrete; however, it depends on the nature of the aggregates [27].
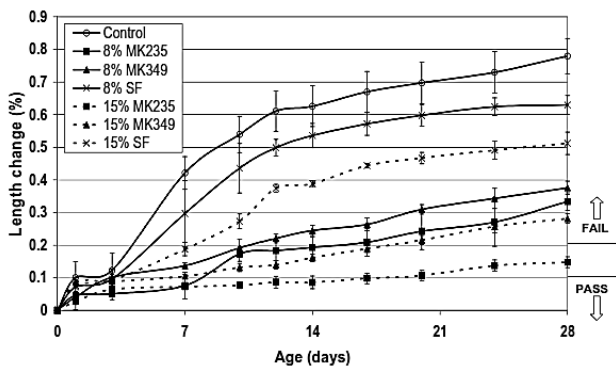

Fig. 14 ASR resistance of two *MK* concretes (MK235and MK349) and *SF* concretes [27]

RHA suppresses the expansion due to alkali-silica reaction by trapping the alkalis through supplementary hydrates [33]. Based on the literature cited it may infer that highly reactive mineral admixtures are more effective in preventing *ASR* as *MK* is giving more prevention against *ASR* due to highly reactive nature.

D. Carbonation

Carbonation is associated with the steel reinforcement corrosion and with the shrinkage of concrete. In other words, it is the ability of concrete to protect steel from corrosion depending upon the extent to which the concrete of the cover zone is carbonated. Carbonation is a complex function of permeability and available lime.

Khunthongkeaw et al. [34] studied carbonation of *FA* concrete using two types of *FA* containing different CaO contents and found that the carbonation rate is the highest when specimens are exposed to the natural exposure conditions. Moreover, by decreasing water to binder ratio and *FA* content, better carbonation resistance can be obtained. Similarly, concrete containing high-CaO *FA* better resists carbonation than those of low CaO *FA*; however concrete strength will be equal showing that the effect of the type of *FA* on carbonation is not influencing the mechanical properties of concrete.

Contradicted results were observed when the influence of the additions of *GGBS* on carbonation has studied based on relevant test procedures and conditions used [8]. Collepardi et al. [35] compared the effect of the addition of mineral admixtures (*FA*, slag and ground limestone) as partial replacement of Portland cement on the CO_2 penetration rate and found that addition of mineral admixture increases the carbonation rate in concretes, except when the amount of cement replacement is as lower as 15% (Refer Fig. 15).
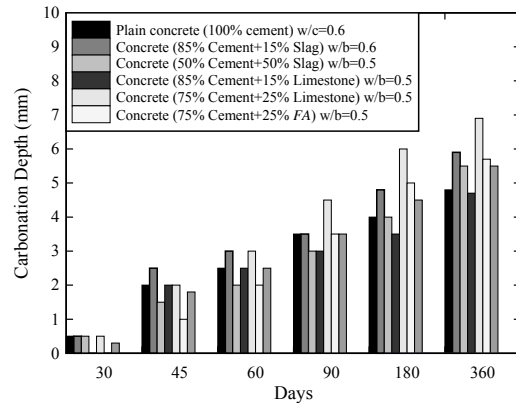

Fig. 15 Carbonation of partially replaced *FA*, slag and limestone concretes [35]

Similar to *GGBS*, the test results on the carbonation rate of *SF* concrete are somewhat varied in literature and contradictory; perhaps due to viewpoint taken when analyzing the findings [8]. However, the results, which have been described in literature, indicate that increase in the carbonation rate for concrete above 40 MPa if there is reinforcement present. As *SF* concrete is normally used where the compressive strengths are above 40 MPa, therefore carbonation is a serious risk. However, correct curing procedures and water binder ratio are essential to ensure optimum performance of the *SF* concrete [8].

Kim et al. [36] studied durability of concrete using *MK* at various replacements of *SF* and *MK* and rapid chloride permeability test, immersion test in acid solution, repeated freezing and thawing test and accelerated carbonation test have been performed. The results of accelerated carbonation depths are shown in Fig. 16 by age of concrete for nine mixtures measured at 7, 14, 28 and 56 days according to the phenolphthalein indicator method. It has been observed that the carbonation depth of concrete is bigger than the control mix in the case of *SF* or *MK*. The carbonation depth of *MK* concrete is 20 to 30% more than the control mix at 28 days for replacement level of 5% and 10%, however, 40% and 70% more carbonation depth at 56 days for replacement level of 5% and 10% has been observed as shown in Fig. 16. Similarly, large carbonation depths observed in *SF* concrete irrespective of the age and replacement level. Concrete mixed with *MK* and *SF* together, also demonstrated an increase in the carbonation depth with the increase of the replacement level. The reason for this increase in carbonation depth is that the *MK* or *SF* concrete possesses lesser content of portlandite in hydrate products due to pozzolanic reaction.
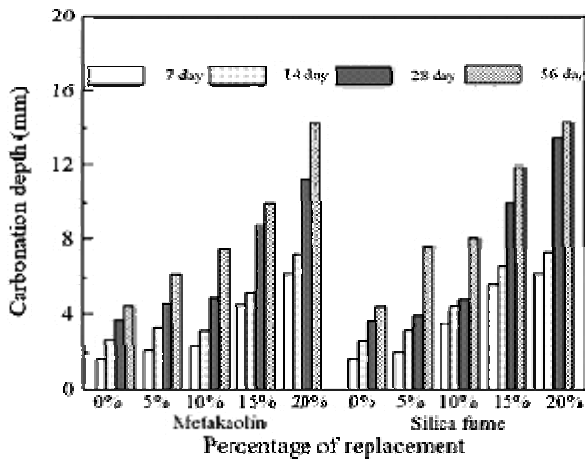
Fig. 16 Carbonation depth versus replacement level with *MK* or *SF* [36]

Fig. 17 Chloride ion permeability of *FA* Concrete (w/b=0.5) [38]

The amount of Ca(OH)$_2$ in the paste with 30% *RHA* begins to decrease after 3 days, and after 91 days it reaches nearly zero, whereas in the control mix it is increasing with hydration time. Based on this experience, Yu et al. [37] discovered that in comparison to the concrete without *RHA*, there will be more C-S-H gel and less portlandite in the concrete with *RHA* and will give to improvement in resistance to carbonation, and penetration [38]. This discovery seems conflicting with the findings of Kim et al. [36] in which he stated that the *MK* or *SF* concrete possesses lesser content of portlandite in hydrate products due to pozzolanic reaction causes an increase in carbonation depth. In authors view, mineral admixture that requires more water binder ratio causes more carbonation as in case of *MK* or *SF*, whereas *RHA* requires less water binder ratio in comparison with *MK* or *SF* and that is the main reason *RHA* concrete is less susceptible in carbonation than *MK* or *SF* concrete.

E. Resistance to Chloride Ion Penetration

Diffusion of chlorides in concrete may be from external sources or already exist in the mix constituents causing the steel to be unprotected. Various sources of chlorides are possible such as seawater and de-icing salts; in order to reduce the chloride ingress, the permeability of the concrete should be reduced. Klieger and Gebler [30] mentioned that the chloride-ion permeability of concrete incorporating *FA* does not significantly affected by the class of *FA*. Recently, Horsakulthai and Paopongpaiboon [38] reported the 7, 28 and 90 days test results of chloride ion permeability of concrete by replacing 20, 40 and 60% of the cement content with coarse *FA* and found that in order to reduce the chloride ion permeability, 40% is the optimum replacement level of the cement (Refer Fig. 17).
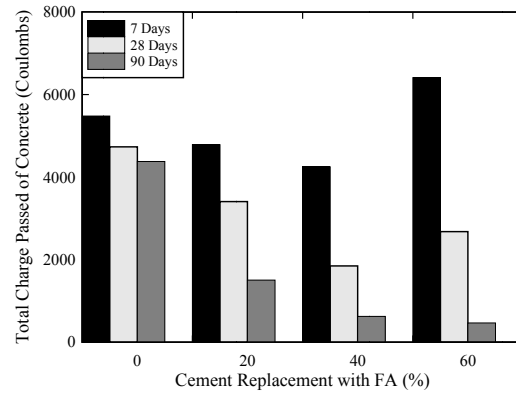
Thomas et al. [13] reported the diffusion test results of concrete containing *SF* up to 3 to 6% and moderate levels of high CaO *FA* (20 to 30%) which indicated a very high resistance to the penetration of chloride ions. Similarly, Higgins and Uren [12] suggested that by partially replacing the cement with *GGBS*, resistance of concrete to chloride attack can be increased.

Cheng et al. [20] reported the influence of 0, 40 and 60% replacement of cement with *GGBS* on the total charge passed and reported that use of higher volume of *GGBS* as partial replacement of cement reduces the chloride ion penetration (Refer Fig. 18).

In a study by Hooton et al. [14], a series of concrete slab elements were cast by replacing 0.7 and 12% of cement content by *SF* at various water-cement ratios which showed that use of properly distributed *SF* improves the resistance of concrete against chloride ion diffusion.

The use of *MK* is of major importance to concrete in seawater environment and sea side constructions [1]. Chloride ion diffusion is dependent on the permeability of concrete and it is mentioned that use of *MK* reduces the pore diameter; therefore, diffusion of chloride ions is hindered. Chloride penetrability of the concrete with *MK* at w/b ratios of 0.3 and 0.5 were reported by Poon et al. [39]. Both *MK* concrete showed lower total ion penetration than the control. At w/b of 0.3, concrete with a 10% *MK* showed the best performance, while at w/b of 0.5, 20% replacement was the best. Study of Justice et al. [27] revealed that *MK* concrete better reduces rapid chloride ion permeability than *SF* mixtures. Caldarone et al. [40] compared the rapid chloride permeability results of high reactive metakaolin with silica fume and control concrete after 56 days of moist-curing and reported the lowest chloride ion permeability with metakaolin (Refer Fig. 19).
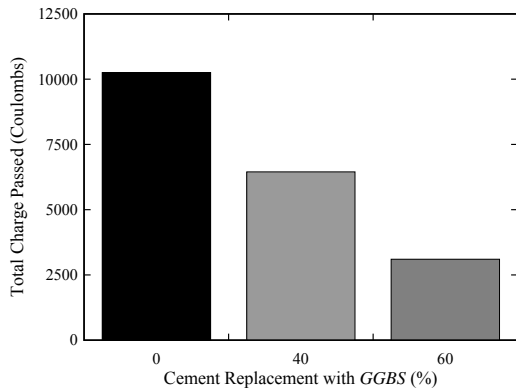
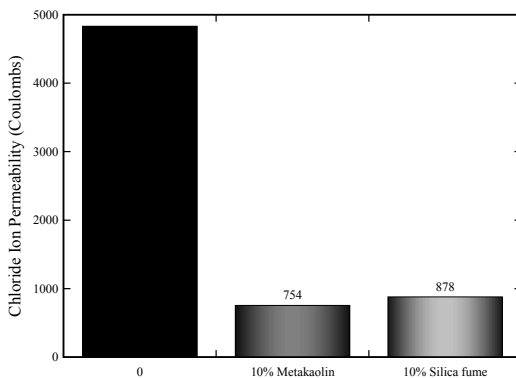Fig. 18 Effect of *GGBS* replacement on the chloride ion resistance [20]

Fig. 19 Rapid Chloride ion permeability results of *MK* and *SF* concrete after 56 days of moist-curing [40]
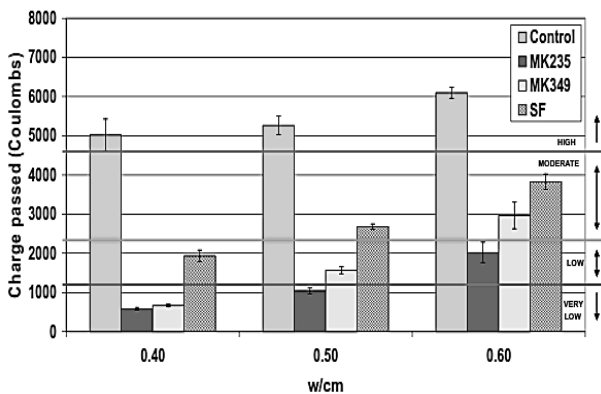

Fig. 20 Chloride ion permeability results of *MK* and *SF* concrete [27]

Justice et al. [27] also measured the chloride ion resistance of the concretes made from two different *MK* and compared with the plain and *SF* concretes. The concrete manufactured with Kaorock *MK* is named as MK235, while concrete manufactured from Kaorock F *MK* is named as MK439. Results of all concretes are shown in Fig. 20 and it can be seen that with either of the *MK*, chloride ion permeability reduces compared to control and *SF* concrete.

Kartini et al. [15] related to the durability performance of normal strength concrete specimens of 30 N/mm^2 containing 20% or 30% *RHA* by cement weight, with or without the addition of superplasticizer showed an increase in the resistance of concrete to chloride ion penetration in comparison with the ordinary concrete.

F. Resistance to Freezing and Thawing

Freeze and thaw is a natural phenomenon that causes deterioration of concrete in cold areas, when water enters in the voids and get frozen. Voids are generally produced during the hydration of Portland cement, when calcium hydroxide leaches. Since concrete is a porous material and due to freezing of water to ice, increased volume of water in the pores of concrete causes distress. This distress initiates with the first freeze-thaw cycle and continues throughout successive winter seasons resulting in repeated loss of concrete surface.

Freeze–thaw properties of concrete containing *FA* using the ultrasonic pulse velocity (UPV) have been conducted for the assessment of freeze–thaw performance and found that adding *FA* reduces freeze–thaw resistance unless air entrainment is used but only 1% air entrainment gave superior performance when compared with plain concrete irrespective of the cement type [8].

There is little difference between the freeze–thaw resistance of ordinary Portland cement concrete and *GGBS* concrete of a similar strength and air content. However, concrete having no air-entertainment and high slag levels greater than 60% are likely to show an inferior resistance to attack than equivalent Portland cement concrete. Use of *GGBS* also does not normally harm the effectiveness of air-entraining admixtures to entrain air [8].

Addition of *SF* does not make concrete to resist to freezing and thawing; therefore, it may be said that *SF* concrete of the same strength as ordinary Portland cement concrete has a similar resistance to freeze–thaw attack [8]. Use of *SF* with air entrainment is considered to be the best option with the micro-silica maintaining good stability and uniform bubble spacing of the air which gives maximum frost protection, based around a mix design guideline for a concrete of 30–50 MPa, utilizing 8 % micro-silica and 5 % air entrainment as an optimum [8].

Use of *MK* in concrete significantly alters the pore system and permeability of the paste, therefore well-designed *MK* concrete exhibits increased resistance to the damaging effects of freezing and thawing. Zhang and Malhotra [41] reported that *MK* concrete showed excellent performance after 300 cycles of freezing and thawing in the ASTM C666 test. The results of experiment by Caldarone et al. [40] confirmed that *MK* concrete exhibited high freeze–thaw durability.

As reported by Zhang and Malhotra [41], *RHA* and *SF* concrete demonstrated very good performance in the freezing and thawing test. The *RHA* concrete showed durability factor of 98.3 and small changes in length, mass, pulse velocity, and resonant frequency after 300 cycles of freezing and thawing [8].

G. Resistance to Abrasion

Atis [42] investigated the abrasion resistance of high volume *FA* concrete. Concrete containing *FA* in mass basis at 50 and 70% were prepared with various water binder ratios. The abrasion value was measured using a Dorry abrasion machine. Examination results have shown that the abrasion resistance is increased as compressive strength increases. Concrete with 70% *FA* gave more abrasion resistance than that of ordinary concrete and concrete with 50% *FA*. However, there is an insignificant effect of superplasticizer and curing conditions on the abrasion of concrete.

If concrete is adequately cured then there is a slight advantage of using *GGBS* in terms of abrasion resistance than ordinary Portland cement concrete of equal grade; whereas, in case of inadequate curing, concrete containing *GGBS* will be more affected than ordinary concrete [8]. Use of high-strength *SF* concrete shows great improvement in resistance to abrasion and erosion [8].

In authors view, there is no literature available related to resistance to abrasion of *MK* concrete and *RHA* concrete.

H. Resistance to Fire

Xu et al. [43] heated the pulverized fly ash (*PFA*) concrete and investigated the mechanical and durable properties of concrete. Different water binder ratios and *PFA* contents were used. It was found that compressive strength rises after exposure to 250°C, which may be due to the hardening of cement paste caused by drying and the further hydration of cementitious materials, however, loss of durability was observed which may be due to a weak transition zone between hardened cement paste and aggregate. The addition of *PFA* improved fire resistance due to residual compressive strength on high temperature and this further pronounce at maximum exposure temperatures of 450°C and 650°C.

In authors view, there is no literature available related to fire resistance of *GGBS* concrete and *RHA* concrete. Under normal fire conditions *SF* concrete behaves similar to normal concrete; however Ultra-high-strength *SF* concrete may be susceptible to failure due to increased brittleness [8].

Poon et al. [44] conducted an experimental investigation to evaluate the performance of *MK* concrete at elevated temperatures up to 800°C. 0%, 5%, 10% and 20% *MK* content were used in normal and high strength concrete. The residual compressive strength, chloride-ion penetration, porosity and average pore sizes were considered and compared to *SF*, *FA* and *OPC* concrete. At 200°C increase in compressive strength was observed. But, more loss of compressive strength and loss in permeability-related durability were observed in *MK* concrete than *SF*, *FA* and *OPC* concrete at higher temperatures.

I. Resistance to Acid

Cement containing lime is vulnerable to attack by acid. The pure water by melting ice and condensation contain carbon dioxide and will dissolve calcium hydroxide present in concrete causing erosion [8]. Since *FA*, *GGBS* and *SF* causes more strengthening gel and less content of calcium hydroxide,

it may infer that addition of mineral admixtures provides more endurance to concrete against Acid attack. Addition of *MK* as a partial replacement for cement will prolong the service life of concrete subjected to attack by acidic substances [8]. Concrete containing 10% *MK* as a partial replacement for cement resists comparatively more against the attack of organic and mineral acids as compared to ordinary Portland cement concrete of otherwise similar composition [8]. Concrete containing *MK* (10% replacement of Portland cement) was more resistant to the effects of lactic, formic, citric and humic acids and to mineral acids of pH 3.5 [8]. Experiments by Martin [45] showed that concrete containing *MK* was more resistant than plain concrete to the acids that result from the storage of silage. To complement his laboratory work, a working silage bay was constructed using plain concrete and concrete containing *MK*. After some 10 years in use, no adverse effects were apparent on the surface of the area constructed with *MK* concrete. As depicted by Yu et al. [37], in comparison to the concrete without *RHA*, there will be more C-S-H gel and less portlandite in the concrete with *RHA* and will give to improvement in resistance to acid attack.

J. Efflorescence

Efflorescence is a white deposit that appears on concrete surfaces detracting the aesthetic properties but not affecting the durability of the concrete. There are two forms of efflorescence: Primary efflorescence occurs in the early life of the structure during curing due to deposition of insoluble lime/calcium carbonate on concrete surface as a result of reaction between lime and atmospheric carbon dioxide. The second form is secondary efflorescence, which occurs when hardened concrete is wet and water penetrates the surface to dissolve some of the lime remaining in the concrete. During subsequent drying, the salt-laden solution moves to the surface depositing the salts at the surface [8].

Smith and Osborne [46] investigated the cement made by combining fine *GGBS* with untreated *FA* using a sodium hydroxide solution as an activator. Using a combination of 60% slag and 40% fly ash with 7% sodium hydroxide solution, concrete has been prepared and tested for compressive strength and it was found that early strength properties are good but very little gain in strength beyond 28 days, however, the risk of alkaline-aggregate reaction and the possibility of efflorescence has been reduced.

Addition of *SF* reduces efflorescence due to the refined pore structure and increased consumption of the calcium hydroxide; however, more efficient and longer curing is required for better resistance [8].

Addition of *MK* is supposed to control the formation of efflorescence by reducing the alkali content of the concrete; therefore, CO_2 is absorbed less rapidly. Also, it controls efflorescence by removing a proportion of the $Ca(OH)_2$ and refining the pore structure so that the absorption of water and the diffusion of salt-laden water to the surface is reduced [8], [32].

Weng et al. [47] investigated the resistance to efflorescence of cement mortar at various replacement levels of metakaolin by partially replacing the cement content as 0, 5, 10, 15, 20, and 25% and by exposing to various environments. They [47] found that mortar specimens exhibited greater resistance to efflorescence; however, the addition of more than 20% metakaolin has a detrimental effect on the efflorescence, whereas the best effectiveness of replacing cement with metakaolin at a 15% replacement.

Similarly, the use of *RHA* in concrete has been associated to reduce potential for efflorescence as calcium hydroxide is reduced due to cement replacement by mineral admixtures [48].

III. CONCLUSION

The conclusions of this review are as follows:

1) Permeability of concrete depends upon the content of alumina in mineral admixtures, higher the alumina content lesser the permeability causes higher resistance to sulfate and chloride ion penetration.

2) Tricalcium aluminates (C_3A), which is the major constituent of cement and is prone to sulfate attack, gets diluted after reaction with sulfates within the *FA* or *GGBS* at an early age of concrete. Concrete containing *SF* performs approximately same as those as made with sulfate-resisting cement. Use of *MK* and *RHA* also improves the resistance of concrete against sulfate attack, however, concrete mixed with *RHA* has been reported as better sulfate resistant than *SF*. It may infer that sulfate resistance of concrete incorporating mineral admixtures depends upon the content of alumina in mineral admixtures, higher the alumina content higher the resistance.

3) Coarse *FA* has been found effective to prevent *ASR*. Use of a minimum 50% *GGBS* in concrete suitably prevents alkali-silica reaction, if the alkalis are only contributed by cementitious materials. *MK* reduces rapid expansion due to alkali-silica reaction when compared to control and *SF* concrete. Replacement of cement between 10 and 15% with *MK* may be adequate to overcome the harmful expansion caused by *ASR* in concrete; however it depends on the nature of the aggregates. *RHA* suppresses the expansion due to alkali-silica reaction by trapping the alkalis through supplementary hydrates. Combined use of relatively small levels of *SF* (e.g., 3 to 6%) and moderate levels of high CaO *FA* (20 to 30%) is very effective in reducing expansion due to *ASR*.

4) The carbonation is increasing with the addition of mineral admixtures because higher water binder ratio and lesser content of portlandite in hydrate products due to pozzolanic reaction. Chloride ion diffusion is dependent on the permeability of concrete, therefore inclusion of *FA*, *GGBS*, *SF*, *MK* or *RHA* in concrete generally increase the resistance against chloride ion diffusion.

5) Inclusion of *FA* or *GGBS* in concrete requires air entraining admixture to increase the resistance against freeze and thaw. Conversely, there is no increase in resistance against freeze and thaw due to inclusion of *SF*. Use of *MK* or *RHA* in concrete give very good resistance against freeze and thaw and does not necessarily requires air entraining admixture.

6) The abrasion resistance increases as compressive strength increase so it may infer that inclusion of *FA*, *GGBS*, *SF*, *MK* or *RHA* in concrete generally increase the abrasion resistance.

7) *FA*, *GGBS, SF, MK* and *RHA* cause more strengthening gel and less content of calcium hydroxide, it may infer that addition of mineral admixtures provides more endurance to concrete against Acid attack.

8) The use of *FA*, *GGBS, SF, MK* and *RHA* in concrete has been associated to reduce potential for efflorescence as calcium hydroxide is reduced due to cement replacement by mineral admixtures.

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