ABSTRACT

Though being an ancient trend, usage of the homogeneous material cement in the construction industry is steadily getting eradicated with the springing up of supplementary cementing materials (SCM). Metakaolin is an imminent mineral admixture extracted from the mineral ore kaolinite, which enhances the interfacial zone by more efficient packing at the cement paste-aggregate particle interface, thus reducing the bleeding and producing a denser, more homogeneous transition zone microstructure. This paper depicts the various repercussions of the pozzolanic material metakaolin in the fresh and hardened properties of concrete when replaced with cement in finite amount. Also, it states the behavior of high-performance concrete and self-compacting concrete with metakaolin.

KEYWORDS

metakaolin, kaolinite, pozzolanic materials, self compacting concrete, high performance concrete

1. INTRODUCTION

Metakaolin (MK) is the anhydrous calcined form from the clay mineral kaolinite. It is a manufactured product rather than a by-product. It is formed when china clay (mineral kaolin) is heated to a temperature between 600 and 800°C. Its quality is controlled during manufacture, resulting in a much less variable material than industrial pozzolans that are by-products. In the 1960s, metakaolin was first used in Brazil for construction of large dams. The original intention was to suppress the damage due to the alkali-silica reaction, which induces swelling of concrete by adsorbing water from the surrounding. The particle size of metakaolin is smaller than that of the cement particles but not as fine as silica fume.

2. IMMINENT MINERAL-METAKAOLIN

Being the most effective pozzolanic material, it is available in many different qualities and varieties. It is a well known admixture even in the ‘90s, nevertheless, is very commonly used in the present decade by many researchers throughout the globe. Metakaolin inhibits a high equivalent quality of cement, and hence it is often referred to as High Reactivity Metakaolin (HRM). The non-reactive impurities in metakaolin are removed by water processing leaving the 100% reactive pozzolan behind [56]. Apparently, the kaolinite mineral (china clay) ores are spread throughout the continents and most of the sources were seemingly in China, which incites the Chinese people for the vast usage in vessel making and architectural works.

2.1. Metakaolin in mid ’90s

Though few formulations were flourishing in the ‘80s on metakaolin, an exaggerated analysis unfolded steadily in the pop up of 1990s. Wild et al. [59] detailed the portlandite content at different ages through thermogravimetric analysis relating it to the relative strength, keeping
the cement mortars and pastes with 0, 5, 10 and 15% replacement of cement with MK and with a water/binder (w/b) ratio of 0.55. The removal of portlandite by pozzolanic reaction reached a maximum at about 14 days, along with a hike in relative strength in the MK mortars and pastes. Wild et al. [59] stated three primary factors that influence the contribution of MK to the concrete strength when it is partially replaced for cement in concrete. They are listed as the filler effect, acceleration of the OPC hydration and the pozzolanic reaction of MK along with Calcium Hydroxide (CH). Thus, the obtained results exhibit 20% wt of MK as the optimum Ordinary Portland Cement (OPC) replacement level and the enhancement of strength are limited to 14 days. Khatib and Wild [30] determined the pore structure and the intruded pore volume by conducting mercury intrusion porosimetry. Metakaolin in cement paste further refines the pore structure; the refinement process appears to wind up at 14 days, which in turn shows a maximum relative strength and a minimal rise in the total pore volume along with the CH level. Palomo et al. [46] studied the alkali activation of MK and it is with the aggressive solutions. Sand and alkali-activated MK is cast into prisms immersed in sodium sulfate solution (4.4% wt), deionized water, ASTM sea water, and sulfuric acid solution (0.0014%). At 7, 28, 56, 90, 180, and 270 days, the prisms were removed from the solution. For physical, mechanical and microstructural analysis, the porosity, flexural strength, and X-ray diffraction tests were conducted. Good stability is recorded for the resultant hydroceramic for up to 270 days when submerged in various types of aggressive liquids. Faujasite crystals tend to act as a reinforcement of the cement mortar. Curcio et al. [14] compared and studied four commercially available MK samples with silica fume. Three among the four samples developed an elevation in compressive strength that of silica fume at early ages. The plotted results from the thermal analysis depict that water loss is due to the variation of the hydration products obtained and on the permeability of the materials, which can be related to the fineness of the micro-filler in the casted specimens with MK. Bai et al. [5] combined pulverized fly ash and MK to partially replace it for PC and study the workability of concrete. Vee Bee time, Slump, and compaction factor tests were performed for measuring workability. With an increase in MK content Workability of MK-PC concrete is eventually reduced. When superplasticizer is used at low w/b ratio (=0.4), there is a critical MK/PFA ratio (~0.4) above which workability declines and below which workability tends to increase with high replacement level. Terrence [52] evaluated the efficacy of metakaolin in minimizing the expansion due to alkali-silica reaction (ASR). When HRM is used to replace up to 20% of OPC the alkali concentration of the pore solutions from pastes is significantly low.

2.2. The analogy between the properties of cement and metakaolin

The rogue chemical composition (Table 1) of metakaolin enables the material to behave itself as the ideal supplementary cementitious material among other minerals and byproducts that are in practice at present. Metakaolin is produced by thermally activating high purity kaolin clay within a specific temperature. The heating process spills out water from the kaolin (Al$_2$O$_3$2SiO$_2$2H$_2$O) and alters the material structure resulting in an amorphous aluminosilicate (Al$_2$O$_3$2SiO$_2$), metakaolin.

Metakaolin, when combined with Portland cement, reacts rapidly with CaOH that is released from the hydration of cement to develop various hydrates namely C–S–H, C$_2$ASH$_4$ – strätlingate and C$_3$AH$_6$ – hydrogarnet [23].

2.3. How metakaolin outbalance other SCM’s

Amidst many mineral admixtures accessible, metakaolin is a mineral admixture whose prospects have not yet been fully tested and only finite studies have been carried out in India on the use of MK for the development of high strength concrete [49] [42]. It is obtained from natural deposits of kaolin by thermal treatment. Due to high surface area and amorphous structure (Table 2) MK shows high pozzolanic reactivity. Incorporation of MK in concrete has improved the performance of concrete under various conditions. Also, the ultrafine MK enhanced substantially the pore structure of the concretes and reduced the content of the harmful large pores, hence making concrete more impervious, especially at the replacement level of 20% [24].

2.4. Metakaolin ores in India

Kaolinite, the mineral ore for metakaolin in India as per United Nations Framework Classification for Resources (UNFC) system is mentioned at 2,705.21 million tonnes. 70% out of the total reserves are under proved type, and about 53 million tonnes (30%) reserves categorized as probable type. The resources are scattered in a number of

---

**Table 1. Chemical composition of cement and metakaolin**

| Chemical composition | Cement (%) | Metakaolin (%) |
|----------------------|------------|----------------|
| Silica (SiO$_2$)     | 17–25      | 50–60          |
| Alumina (Al$_2$O$_3$)| 3–8        | 30–40          |
| Magnesium oxide (MgO)| 1–3      | 0–2            |
| Potassium oxide (K$_2$O)| 0–1     | 0.5–1.5        |
| Sulfuric anhydride (SO$_4$)| 1–3       | 1–3            |
| Calcium oxide (CaO) | 60–65      | 0–0.5          |
| Ferric oxide calcium oxide (Fe$_2$O$_4$)| 0.5–6| 0.5–5 |

**Table 2. Physical properties of cement and metakaolin**

| Physical parameter | Cement | Metakaolin |
|--------------------|--------|------------|
| Color              | Grey   | Off white  |
| Physical form      | Fine powder | Powder     |
| Loss on ignition   | 1.3    | 0.68       |
| Specific gravity   | 3.15   | 2.5        |
states, out of which about 25% is found under Kerala, followed by Rajasthan and West Bengal (16% each) and Karnataka and Odisha (10% each). Out of total resources, about 608 million tonnes (22%) are categorized as ceramic pottery grade, 4% falls under chemical, paper filler and cement grades, and about 1,980 million tonnes (73%) resources are classified as mixed grade, unclassified, others & not-known categories [27] (Part-III: Mineral Reviews).

3. FRESH CONCRETE PROPERTIES WITH METAKAOLIN

Metakaolin is one among the artificial pozzolanic admixtures that are presently used in a variety of mortar and concrete mixes. Its effect and its behavior are highly dependent on its activity and also on formulation features like workability and the method of mixing in the formulation [45].

3.1. Workability

In pursuance of good dissipation of the MK, the definite amount of MK and super-plasticizer were mixed with water to produce slurry which is then added to the coarse aggregate and mixed for a minute [20]. The fine aggregate was then combined and mixed for a couple of minutes followed by the cement and mixed for further two more minutes. For the lower workability control mix, additional vibration was used to make it fully compacted [59].

The workability of MK-PC concrete is considerably diminished with inflation in MK content. The high chemical activity and high specific surface lower the workability which in turn elevates the water uptake and thus there is a higher water requirement. The influence of MK on flow and compaction is ceased by the incorporation of superplasticizer. This is ascribed to the thixotropic nature of clay suspensions and lower void space due to the higher dispersion of MK particles [5]. Workability was observed to cease with 15% of MK for which finite amount of super plasticizer is much needed to counterbalance it [47].

3.2. Setting time

Replacement of OPC by MK up to 20% prolong the initial and final setting time of cement mortar since the MK particles develop a coating on the cement grains. Furthermore, it initiates the development of ettringite and the dilution of Ordinary Portland cement. The initial and final setting time is quickened up with the increase (15–20 wt%) in MK content, which is attributed to the decline of water of consistency of cement mortar and filling effect caused by MK [19]. Badogiannise et al. [4] and Moulin et al. [40] reported dawdling in initial and final setting time in a range of 0–95% and 14–64%, respectively, when replaced with 20% of different types of MK. These remissions could be imputed to the fineness of different MK and the quantity and behavior of different plasticizers in each test.

3.3. Shrinkage

It is vital to slacken off the rate of shrinkage to maintain a durable structure since shrinkage initiates cracks in concrete. Guneyisi et al. [24] intensively studied the shrinkage properties of concrete. Shh et al. [57] conducted free shrinkage and restrained Shrinkage tests by incorporating SRA (shrinkage reducing admixture). The addition of SRA significantly declined the crack width of the restrained samples along with reduced free shrinkage. Kinuthia et al. [32] noted inflation in autogenous shrinkage of cement pastes at 5% and 10% replacement levels with MK. At the same time declination of autogenous shrinkage is observed at elevated replacement levels of 15% and 20%. Caldarone et al. [11] co-related the replacement of cement with 10% HRM to the shrinkage of concrete and thus 33% reduction in shrinkage was noted after 156 days. The test method for autogenous shrinkage was explained in detail in The Japan Concrete Institute 1988. Later on Brooks et al., [10] elaborated a most reliable method for the same and concluded that MK at higher replacement level dented the basic creep, drying creep, and the total creep of concrete.

3.4. Water/Binder ratio

The water/binder ratio influence the major parameters of concrete like compressive strength, pore size distribution, and capillary pores refinement. Concrete incorporated with MK is expected to refine the pore structure and limit permeability due to its filler effect. The chemically combined amount of water increases with elevated MK content up to 10% [60], which is attributed to the high specific surface area and the rise of water of consistency of cement paste. Furthermore permeability, porosity and sulfate attack found to decline at low w/b ratio [16]. More ettringite formation causes severe decay to concrete as well as more %wt loss caused by magnesium sulfate attack with the elevated w/b ratio [8]. Intense durability towards sulfate attack was observed in metakaolin concrete with a w/b ratio of 0.6, which developed more deterioration due to sulfate attack in a comparative study for MK concrete for a duration of 18 months [2]. Thus the permeability and porosity tend to decrease at low w/b ratio, which in turn lowers the sulfate attack minimizing the intrusion of sulfate ions. However, optimum w/b ratio for highest compressive strength was determined as 0.4 with 10% replacement level of MK [17]. The water-soluble (1.76 g/L at 10 °C) portlandite (CH), which is linked with the changes in relative strength, varies with the w/b ratio. The higher consumption of CH marks more formation of C–S–H, thus improving the strength of concrete. A w/b ratio of 0.5 is adopted for 30 and 40% metakaolin replacement when cured for 28 days in lime-saturated water for the complete removal of portlandite from the OPC [44]. Whereas another study reported 20% replacement of cement with MK is necessary to eradicate CH in a standard concrete at 28 days [33].
4. HARDENED CONCRETE

Strength, durability, and dimensional stability parameters are studied to replicate the hardened properties of concrete. Amidst compressive strength and tensile strength is the well-adapted common parameter for experimenting with the hardened concrete. Thermal and acoustic properties are considered under unique contingencies.

4.1. Compressive strength

The cardinal motif of introducing supplementary cementitious materials, fibers, and other admixtures are to enhance the compressive strength as well as to make the concrete economical by de-emphasizing the use of cement, which in succession taper off the CO₂ emission. Khatib et al. [29] limited the addition of MK up to 20% for which maximum refinement of pore structure and compressive strength is achieved, furthermore, the study concluded that beyond 30% the compressive strength decreases with the addition of MK. Wild et al. [59] suggested that irrespective of the replacement level of MK, the benefitance of MK in the intensification of concrete is restricted beyond 14 days. Whereas in silica fume it promotes strength enhancement at extended ages of at least 28% replacement levels [18].

For 15% of cement replacement similar strength development at 90 days and 180 days with MK and silica fume, respectively, were noticed, which can be related to the fineness of the micro-filler of MK specimens [14]. MK concrete under heat curing of 50 °C exhibits higher early strength at 7 days than the specimens which were cured at 20 °C. However, the enhancement of strength decelerates in the long term for 365 days [55]. Aishwarya et al. [1] analyzed the behavior of nano-metakaolin with concrete and concluded a higher increase in compressive strength for M20 grade concrete up to 37% compared with the other grades of concrete such as M30, M40, and M50.

4.2. Tensile strength

Development of strength for splitting tensile strength is rather a replica of compressive strength. For 20% wt of MK, the maximum tensile strength was observed for 0.35 and 0.55 w/b ratio in a comparative study [26]. Thus, splitting tensile strength was observed to increase along with the MK content in all ages. Compared to the compressive strength, the increase in split tensile strength was less. In another study, it was showcased that both split tensile strength and compressive strength are closely related. And technically both parameters are related to the strength of the concrete. It was also noted that the rise in tensile strength was low compared to that of compressive strength [43].

The variation in tensile strength was studied at 0, 5, 10, and 15% replacement of MK with cement. With the increasing MK replacement level, the tensile of concrete was found to increase mutually. Also, the bending strength showed high variations with a gain of 32 and 38% at 10 and 15% replacement, respectively [51]. In another study, the bending strength attained a maximum at 14 and 28 days in MK concrete [13]. The bonding strength capacity is found to increase by 35% when MK concrete is developed with steel fibers [25]. In another studies [6, 7] it was stated that by controlling the crack growth inside the concrete, the pull out resistance was enhanced when steel fibers were introduced.

4.3. Chloride resistivity

In order to determine the chloride resistivity of concrete, the electrical conductance of concrete is performed by allowing the chloride ions to penetrate into it. The resistance of chloride ions of concrete is directly proportional to the internal pore structure and permeability since highly permeable concrete allows a huge flow of current in it. For a period of 6 h, the amount of electrical current passing through in a 100 mm nominal diameter and 50 mm thick slice is monitored. A 60 V DC potential difference is maintained at both ends of the specimen, out of which one is immersed in sodium hydroxide solution and then other one in a solution of sodium chloride. The total amount of charge in coulombs is noted, which can be related to the resistivity of concrete specimens towards chloride ion penetration. This test is performed as per the [3]. Poon et al. [50] conducted rapid chloride diffusion test on specimens which were preheated to 600 and 800 °C since extreme damage occurs at high temperature and also to limit the long testing time of concrete. A high amount of charge is passed through indicating loss of impermeability at high temperatures. These results are accounted to the coarsening of the pore structure of concrete and internal cracking [12]. Nevertheless, concrete with 5% cement replacement for MK and SF performed better than the pure OPC because of the low CH content, which inhibits internal cracking when subjected to heating and disintegration on cooling [35]. An apparatus set up by McGrath [37] was used in another study to experiment with the HRM [9].

4.4. Alkali silica reaction

The alkaline component in cement tends to react with the silica component in aggregate at suitable moisture conditions causing the formation of sodium silicate gel which is soluble and viscous in nature. The hygroscopic gel further starts swelling absorbing the water due to the expansive pressure, which in turn promotes spalling and strength loss of concrete. These reactions are often referred as “concrete cancer” and even promote demolition of the particular structure.

Incorporating 15% of MK in standard Portland cement completely eliminates the expansion of concrete caused by ASR, by limiting the freely available CH/SiO₂ (active) ratio and CH intercepting the swelling gel formation [33]. The C–S–H crystal obtained when MK reacts with the portlandite is much of a replica of the composition and structure of that of Portland cement [15]. Terrence et al. [52] conducted an extensive study on the ASR and found the alkali concentration of pore structure to be significantly low when 20% of MK is incorporated. For both moderate alkali
cement and high alkali cement, the concentration of long
term hydroxyl ion was lowered below 0.2 mol/L. They also
concluded that the supplementary hydrates entrapped the
alkalis as well as reduced the pH of pore solutions.

4.5. Fire resistance
It is mandatory to safeguard human life from fire accidents
in structures as well as from structures (oil, gas, and power
industries) which are exposed to elevated temperatures. An
absolute analysis of each component of concrete is essential
before introducing them in concrete structures for the better
behavior of structures. Reduction of CH content, less
permeability, dense pore structure, and constituent materials
(pozzolans) alter the thermal behavior of concrete. For the
complete elimination of CH, the amount required depends
on Portland cement composition, curing condition, porosity
of MK, and w/b ratio [44]. Reduced CH content develops
high strength and durability to concrete even at a higher
temperature [35]. Experimental analysis on MK concrete at
high temperature was initiated by [50], in which the speci-
mens were tested after 60 days. Specimens were heated up to
200, 400, 600 and 800 °C after 28 days water curing un-
stressed compressive strength test, permeability, resistance
to chloride ion penetration, rapid chloride diffusion test,
porosity, average pore size, and spalling frequency were
tested after bringing down the specimen to room tempera-
ture. Compressive strength tends to increase at 200 °C fol-
lowed by a sharp decline after 400 °C causing severe cracks
and explosive spalling. Lower porosity and dense micro-
structure are responsible for the poor behavior of MK
concrete at elevated temperatures. Due to the vapor pressure
in dense pore structure, explosive spalling was observed
between 450 and 500 °C. At all temperatures, MK concrete
with 5% replacement performed better with no spalling.
Morsy and El-Nouhy [39] analyzed the effect of high tem-
perature on the physical–mechanical properties of MK
mortar. In MK20 mix, a marginal gain of 1% is noted for
compressive strength. In another study [38] by the same
author, it was concluded that poor microstructure along
with increased cracking and development of inappropriate
configuration of C–S–H crystals are responsible for the
strength loss in MK cement mortar. The sorptivity values
increased with rise in temperature thus developing more
resistance to penetration by water by capillary action [41].

4.6. Sulfate resistance
The intrusion of sulfate ions to concrete can cause severe
damage by the weakening of the bond between cement paste
and aggregate, extensive cracking and expansion. Reduced
expansion of the mortar was noted with an increase in MK
content (5–20%) when included in high and intermediate
C₃A content cement [29]. At higher MK replacement levels,
sulfate resistance of concrete was observed better. MK
concrete with both 0.5 and 0.6 w/b ratio showed maximum
sulfate expansion values of 0.4 and 0.45%, respectively for 10
and 15% MK replacement at 18 months [2]. In another
study, MK concrete developed better chemical resistance
than the PPC [54]. The resistance of MK concrete to sulfate
attack was found higher at low w/b ratio, high air content
(1.5–5%) and when autoclaved [2].

4.7. Pore structure and permeability
Cement mortar with metakaolin leads to refinement of the
pore structure. High MK content increased the proportion
of pores with radii less than 20 μm and also decreased the
threshold value for paste [30]. Below 20% of MK content,
the total porosity of cement mortar tends to decrease [60].
However, filler effect and increased w/b ratio caused high
porosity beyond 30% of MK content along with decreased
pore volume and threshold diameter [34]. The effect of MK
on the pore size distribution of cement mortar is further
detailed in another study. Total porosity was found to be
about 16% more than the OPC paste along with pore size
reduction, which can be attributed to the fineness of cement
and MK used and also nature and composition [21].

4.8. Resistance to freezing and thawing cycles
A comparative study [31] was conducted for MK and SF
when mixed with high strength concrete. Incorporating 5
and 10% of MK and SF, respectively, with 25% of w/b ratio
on five mixtures, the freezing and thawing characteristics
were studied. The relative dynamic modulus of elasticity was
observed to remain quasi-constant for all the 5 types of
cement up to 300 cycles, which are attributed to the lower
w/b ratio of entrained air content and HPC. This study thus
depicts the resistance of MK concrete to freezing and
thawing when compared with SF. In another case [22], when
under three-point loading, freeze-thaw resistance of the
specimens are studied. MK showed improved durability
than SF which is attributed to the refining of the pore
structure.

4.9. Resistance to aggressive agricultural environment
and sea water
The resistance of concrete towards aggressive solutions and
seawater is a crucial factor since it can cause further spalling
of concrete which provokes the reinforcement to get exposed
to the corrosive environment triggering the damage to the
structure. Denser concrete and increased concrete cover can
usually limit the reactivity of concrete to aggressive solutions
and environment. The resistance of concrete to ammonium
sulfate and solution of lactic acid reciprocating an aggressive
agricultural environment is studied. 10% of MK content
minimized the damage caused by lactic acid and found to be
more pozzolanic than SF which was less reactive in more
aggressive ammonium sulfate solution [28]. Another study
[36] concluded MK can be incorporated to improve the
durability of concrete subjected to aggressive action of silage
effluents containing organic acids. In addition to that mass
loss of concrete is reduced by 30% with 15% MK replace-
ment when exposed to silage effluent.
5. METAKAOLIN IN SPECIAL CONCRETE

The high pozzolanic nature of metakaolin makes it more suitable when involved with special concretes. It further enhances the required parameter to a higher extent. The filler effect and fineness nature of MK makes it more flexible and aids in improving the physical and mechanical properties. The white color of the metakaolin is further an upper hand which enables to use it for decorative purposes too, unlike other pozzolanic materials.

5.1. Metakaolin in self-compacting concrete

Being a durable and flowable concrete, self compacting concrete (SCC) plays a key role in the recent construction era. Though it does not need manual compaction, it shows no bleeding and segregation. With less time and manpower SCC always heads off the other types of concrete. The highly pozzolanic material, metakaolin, when introduced in SCC, resulted in much better consistency and durability.

Rahmat et al. [61] attempted a thoroughgoing study on SCC with metakaolin. Slump value being the vital factor for SCC, when metakaolin was introduced, the values ranged between 660 and 715 mm. The range of slump throws light on the practical feasibility of the same. Adequate stability (Stability Index = 0 or 1) can be achieved in SCC with MK, without the usage of VMA. Though the passing ability was ceased, no blockage effects were noted in the L-Box test. Maximum compressive strength was obtained at 14 days (up to 27%) with improvement in both early age strength as well as compressive strength, and almost the same results were replicated in the tensile strength. The low absorption value (less than 3% at 30 min) indicating good quality of concrete even at lower w/b ratio is consequential. In the long range, 10% replacement of MK is considered as optimal value for concrete in view of net comfort.

5.2. Metakaolin in high performance concrete

High performance concrete was usually adopted in special cases in which durability parameters are bounded under particular environmental and structural requirements. Patil and Kumbhar [48] experimented on HPC with high reactivity MK and optimized 7.5% of the replacement for high compressive strength, after which the same seem to decline due to the decrease in w/b ratio and delayed pozzolanic activity. The chloride attack and sulfate attack resistivity were also enhanced for HPC with MK. Eva et al. [58] extensively studied the Czech MK in HPC and highlighted 10% of replacement as effective range for which excellent durability properties and chloride binding capacity were observed, while [23] optimized 8–12% replacement level for the improved durability performance and 15–20% replacement level for minimizing the expansion caused by ASR. Further, the increase in compressive strength was higher when high performance metakaolin concrete were developed with glass fibers of 12 mm length and 14 μm diameter [53].

6. CONCLUSION

With the aerial perspective from the literatures studied, a few conclusions were acquired as follows:

- The high specific surface and reactivity of MK lowers the workability
- 10% of replacement of MK with 0.4 w/b ratio developed maximum compressive strength
- The finer nature of MK lowers the porosity and thus a much permeable concrete is developed, which in turn provides resistance to chloride attack, sulfate attack, and acid attack
- The less CH content in the MK concrete tends to introduce high strength and durability to withstand the elevated temperatures
- Good gain in compressive strength was noted in MK concrete for up to a replacement level of 20% along with the inflation in tensile strength, which is comparatively lower than the former one
- Workability gets affected at higher MK replacement levels

REFERENCES

[1] S. Aiswarya, A. G. Prince, and A. Narendran, “Experimental investigation on concrete containing nano-metakaolin,” IRACST. Eng. Sci. Technol., vol. 3, no. 1, pp. 180–187, 2013.
[2] M. Nabil Al-Akhras, “Durability of metakaolin concrete to sulfate attack,” Cement Concr. Res., vol. 36, no. 9, pp. 1727–1734, 2006 September.
[3] ASTM-C1202-97, Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration, Philadelphi: American Society for Testing and Materials, Annual Book of ASTM Standards, 1994.
[4] S. Badogiannis Tsivilis, V. Papadakis, and E. Chaniotakis, The effect of metakaolin on concrete properties, International Congress on Challenges of Concrete Construction In Innovation and Development In Concrete Materials and Construction. Sept, Edition Dundee, pp. 81–89, 2002.
[5] S. Bai, J. Wild, B. B. Sabir, and J. M. Kinuthia, “Workability of concrete incorporating pulverized fuel ash and metakaolin,” Mag. Conc. Res., vol. 51, no. 3, pp. 207–216, June 1999.
[6] N. Banthia and C. Yan, “Bond-slip characteristics of steel fibers in high reactivity metakaolin (HRM) modified cement-based matrices,” Cement Concres. Res., vol. 26, no. 5, pp. 657–662, May 1996.
[7] E. Baran, T. Akis, and S. Yesilmen, “Pull-out behavior of prestressing strands in steel fiber reinforced concrete,” Construct. Build. Mater., vol. 28, no. 1, pp. 362–371, 2012.
[8] M. Beulah and M. C. Prahallada, “Effect of replacement of cement by metakalioin on the properties of high performance concrete subjected to magnesium sulphate attack,” Int. J. IT. Eng. Appl. Sci. Res. (IJIEASR), ISSN: 2319-4413 February, vol. 2, no. 2, pp. 16–22, 2013.
[9] A. Boddy, R. D. Hooton, and K. A. Gruber, “Long-term testing of the chloride-penetration resistance of concrete containing high-reactivity metakaolin,” Cement Concres. Res., vol. 31, no. 5, pp. 759–765, 2001.
[10] J. J. Brooks and M. M. Johari, “Effect of metakaolin on creep and shrinkage of concrete,” Cement Concr. Compos., vol. 23, no. 6, pp. 495–502, 2001.

[11] M. A. Caldarone, A. G. Karen, and G. B. Ronald, “High reactivity metakaolin (hrm): a new generation mineral admixture for high performance concrete,” Concr. Int., vol. 16, no. 11, pp. 37–41, 1994.

[12] Y. N. Chan, G. F. Peng, and M. Anson, “Residual strength and pore structure of high-strength concrete and normal strength concrete after exposure to high temperatures,” Cement Concr. Compos., vol. 21, no. 1, pp. 23–29, 1999.

[13] L. Courard, A. Darimont, M. Schouteden, F. Ferauche, X. Willem, and R. Degremont, “Durability of mortars modified with metakaolin,” Cement Concr. Res., vol. 33, no. 9, pp. 1473–1479, September 2003.

[14] F. Curcio, B. A. De Angelis, and S. Pagliolico, “Metakaolin as pozzolanic microfiller for high-performance mortars,” Cement Concr. Res., vol. 28, no. 6, pp. 803–809, June 1998.

[15] P. S. De Silva, and F. P. Glasser, “Pozzolanic activation of metakaolin,” Adv. Cement Res., vol. 4, no. 16, pp. 167–178, 1992.

[16] J. D. Tong and Z. Li, “Effects of metakaolin and silica fume on properties of concrete,” ACI Mater. J., vol. 99, no. 4, pp. 393–398, 2002 Title no. 99-M39 July–August.

[17] G. Dhinakaran, S. Thilaguvaithi, and J. Venkataramana, “Compressive strength and chloride resistance of concrete made with metakaolin,” KSCE J. Civ. Eng., vol. 16, no. 7, pp. 1209–1217, November 2012.

[18] P. Duan, Z. Shui, W. Chen, and Chunhua Shui, “Effects of metakaolin, silica fume and slag on pore structure, interfacial transition zone and compressive strength of concrete,” Construct. Build. Mater., vol. 44, 1–6, July 2013.

[19] H. El-Diadamony, A. A. Amera, T. M. Sokkary, and S. El-Hoseiny, “Mechanical performance of high strength concrete made from high volume of Metakaolin and hybrid fibers,” Construct. Build. Mater., vol. 140, no. 1, pp. 203–209, June 2017.

[20] F. Massaza, “Pozzolanic cements,” Cement Concr. Compos., vol. 15, no. 4, pp. 185–214, 1993.

[21] M. Frias and J. Cabrera, “Pore size distribution and degree of hydration of metakaolin–cement pastes,” Cement Concr. Res., vol. 30, no. 4, pp. 561–569, 2000.

[22] C. Girodet, M. Chabanne, J. L. Bosc, and J. Pera, “Influence of the type of cement on the freeze–thaw resistance of the mortar phase of concrete,” in RILEM Proceedings, Chapman & Hall, pp. 31–40, 1997.

[23] K. A. Gruber, T. Ramlochan, A. Boddy, R. D. Hooton, and M. D. A. Thomas, “Increasing concrete durability with high-reactivity metakaolin,” Cement Concr. Compos., vol. 23, no. 6, pp. 479–484, December 2001.

[24] E. Güneyisi, M. Gesoglu, and K. Mermerdas, “Improving strength, drying shrinkage, and pore structure of concrete using meta-
kaolin,” Mater. Struct., vol. 41, no. 5, pp. 937–949, June 2008.

[25] E. Güneyisi, M. Gesoglu, A. Omer, M. Ako, and K. Mermerdaş, “Combined effect of steel fiber and metakaolin incorporation on mechanical properties of concrete,” Compos. B Eng, vol. 56, pp. 83–91, 2014.

[26] E. Güneyisi and K. Mermerdas, “Comparative study on strength, sorptivity, and chloride ingress characteristics of air-cured and water-cured concretes modified with metakaolin,” Mater. Struct., vol. 40, pp. 1161, December 2007.

[27] Indian Minerals Yearbook 2013 (Part-III: Mineral Reviews).

[28] A. Jean Pera and A. chène Amrouz, “Development of highly reactive metakaolin from paper sludge,” Adv. Cement Base Mater., vol. 7, no. 2, pp. 49–56, March 1998.

[29] J. M. Khatib, and S. Wild, “Sulphate resistance of metakaolin mortar,” Cement Concr. Res., vol. 28, no. 1, pp. 83–92, 1998.

[30] J. M. Khatib and S. Wild, “Pore size distribution of metakaolin paste,” Cement Concr. Res., vol. 26, no. 10, pp. 1545–1553, October 1996.

[31] H. S. Kim, S. H. Lee, and H. Y. Moon, “Strength properties and durability aspects of high strength concrete using Korean meta-
kaolin,” Construct. Build. Mater., vol. 21, no. 6, pp. 1229–1237, June 2007.

[32] J. M. Kinuthia, S. Wild, B. B. Sabir, and J. Bai, “No Access Self-
compensating autogenous shrinkage in Portland cement—meta-
kaolin—fly ash pastes,” Adv. Cement Res., vol. 12, no. 1, pp. 35–43, January 2000.

[33] J. A. Kostuch, G. V. Walters, and T. R. Jones, “High performance concretes incorporating metakaolin: a review,” Concrete, vol. 2, pp. 1799–1811, 2000.

[34] J. A. Larbi and J. M. Bijen, “Influence of pozzolans on the Portland cement paste–aggregate interface in relation to diffusion of ions and water absorption in concrete,” Cement Concr. Res., vol. 22, no. 5, pp. 551–562, 1992.

[35] D. C. Lin, X. W. Xu, F. Zuo, and Y. C. Longa, “Crystallization of JBW, CAN, SOD and ABW type zeolite from transformation of metakaolin,” Microporous Mesoporous Mater., vol. 70, no. 1–3, pp. 63–70, May 2004.

[36] S. Martin, Metakaolin and its contribution to the acid resistance of concrete, International Symposium on Concrete for a Sustainable Agriculture, Stavanger, Norway, 1997, pp. 21–29.

[37] P. F. Mc Grath and R. D. Hooton, “Influence of voltage on chloride diffusion coefficients from chloride migration tests,” Cement Concr. Res., vol. 26, no. 8, pp. 1239–1244, 1996.

[38] Y. Morsy, A. Al-Salloun, H. Abbas, and S. H. Al sayed, “Behavior of blended cement mortars containing nano-metakaolin at elevated temperatures,” Construct. Build. Mater., vol. 35, pp. 900–905, October 2012.

[39] R. M. S. Morsy and El-Nouhy A. M., “Effect of elevated temperature on physico-mechanical properties of metakaolin blended cement mortar,” Struct. Engin. Mech., vol. 31, no. 1, pp. 1–10, 2009.

[40] E. Moulin, P. Blanc, and D. Sorrentino, “Influence of key cement chemical parameters on the properties of metakaolin blended cements,” Cement Concr. Compos., vol. 23, no. 6, pp. 463–469, December 2001.

[41] A. Nadeem, S. A. Memon, and T. Y. Lo, “The performance of fly ash and metakaolin concrete at elevated temperatures,” Construct. Build. Mater., vol. 62, pp. 67–76, 2014.

[42] M. Narmatha and T. Felixkala, “Analyse the mechanical properties of metakaolin using as a partial replacement of cement in concrete. Int. J. Adv. Res. Ideas Innovat Tech., vol. 3, no. 1, pp. 25–30, 2017.

[43] A. M. Neville, Properties of concrete, 4th ed., Essex, England: Prentice Hall, 2006.

[44] M. Oriol and J. Pera, “Pozzolanic activity of metakaolin under microwave treatment,” Cement Concr. Res., vol. 25, no. 2, pp. 265–270, 1995.
H. Paiva, A. Velosa, P. Cachim, and V. M. Ferreira, “Effect of metakaolin dispersion on the fresh and hardened state properties of concrete,” *Cement Concr. Res.*, vol. 42, no. 4, 607–612, April 2012.

A. Palomo, M. T. Blanco Varela, M. L. Granizo, F. Puertas, T. Vazqueza, and M. W. Grutzeck, “Chemical stability of cementitious materials based on metakaolin,” *Cement Concr. Res.*, vol. 29, no. 7, 997–1004, July 1999.

N. Sanjay Patil, K. Anil Gupta, and S. Subhash Deshpande, “Metakaolin-Pozzolanic material for cement in high strength concrete,” *J. Mech. Civ. Eng.* vol. 2, pp. 46–49, 2011.

B. B. Patil and P. D. Kumbhar, “Strength and durability properties of high performance concrete incorporating high reactivity metakaolin,” *Int. J. Mod. Eng. Res. (IJMER)*, vol. 2, no. 3, 1099–1104, May–June 2012.

C. H. Shen, P. Duan, Z. H. Shui, and W. Chen, “Effects of metakaolin, silica fume and slag on pore structure, interfacial transition zone and compressive strength of concrete,” *Construct. Build. Mater.*, vol. 44, 1–6, July 2013.

C. S. Poon, S. Azhar, M. Anson, and Y. L. Wong, “Performance of metakaolin concrete at elevated temperatures,” *Cement Concr. Compos.*, vol. 25, no. 1, 83–89, January 2003.

X. Qian and Z. Li, “The relationships between stress and strain for high-performance concrete with metakaolin,” *Cement Concr. Res.*, vol. 31, no. 11, 1607–1611, November 2001.

T. Ramlochan, M. Thomas, and K. A. Gruber, “The effect of metakaolin on alkali–silica reaction in concrete,” *Cement Concr. Res.*, vol. 30, no. 3, 339–344, March 2000.

S. Rao, V. G. Ghoparde, and H. M. Somasekharaiah, “Durability studies on metakaolin based glass fibre reinforced high performance concrete,” *Int. J. Adv. Sci. Res. Technol.*, vol. 2, no. 2, 204–211, 2012.

C. S. Roy, P. Arjunan, and M. R. Silhbee, “Effect of silica fume, metakaolin, and low-calcium fly ash on chemical resistance of concrete,” *Cement Concr. Res.*, vol. 31, no. 12, 1809–1813, December 2001.

B. B. Sabir, “The effects of curing temperature and water/binder ratio on the strength of metakaolin concrete,” 6th International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Bangkok, Thailand: American Concrete Institute, pp. 493–506, 1998.

M. S. Shetty, *Concrete technology*, New Delhi: S. Chand and Co. Ltd., 2004.

S. P. Shh, M. E. Krguller, and M. Sarigaphutti, “Effects of shrinkage-reducing admixtures on restrained shrinkage cracking of concrete,” *Mater. J.*, 89, no. 3, 289–295, January 1992.

E. Vejmelková, M. Pavlíková, M. Keppert, Z. Keršner, P. Rovnaníková, M. Ondráček, et al., “High performance concrete with Czech metakaolin: experimental analysis of strength, toughness and durability characteristics,” *Construct. Build. Mater.*, 24, no. 8, 1404–1411, August 2010.

S. Wild, J. M. Khatib, and A. Jones, “Relative strength, pozzolanic activity and cement hydration in superplasticised metakaolin concrete,” *Cement Concr. Res.*, 26, no. 10, 1537–1544, October 1996.

P. Bredy, M. Chabannet, and J. Pera, “Pore structure and permeability of cementitious materials,” *Materials Research Society Symposia Proceedings*, vol. 137, p. 43, 1989.

M. Rahmat and S. M. Yasin, “Fresh and hardened properties of self-compacting concrete containing metakaolin,” *Construct. Build. Mat.* vol. 35, pp. 752–760, 2012.