Impact of Metakaolin on the Properties of Concrete: A Literature Review

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Abstract: The utilization of calcined clay, in the form of metakaolin (METAKAOLIN), as a pozzolanic material for mortar and concrete, has received considerable attention in recent years. This interest is part of the widely spread attention directed towards the utilization of wastes and industrial by-products to minimize Portland cement (PC) consumption, the manufacture of which being environ- mentally damaging. Another reason is that mortar and concrete, which contain pozzolanic materials, exhibit a considerable enhancement in durability properties. This paper reviews work carried out on the use of METAKAOLIN as a partial pozzolanic replacement for cement in mortar and concrete and the containment of hazardous wastes. The literature demonstrates that METAKAOLIN is an effective pozzolan which causes vast improvement in the pore structure and hence the resistance of the concrete to the action of harmful solutions.

Key words:

INTRODUCTION

Concrete is probably the most extensively used construction material in the world. It is only second to water as the most heavily consumed substance with about six billion tonnes being produced every year. This is mainly due to the abundance of raw materials for cement manufacture, relatively low cost and the versatility and adaptability of concrete in forming various structural shapes. However, environmental concerns both regarding damage caused by the extraction of raw material and CO2 emission during cement manufacture have brought about pressures to reduce cement consumption by the use of supplementary materials. These materials may be naturally occurring, industrial wastes or by-products or those that require relatively less energy to manufacture. Other concerns that have contributed to these pressures are related to the increase in the number of incidents where concrete structures have experienced serious deterioration. In addressing these concerns and other environmental problems associated with the disposal of waste industrial by- products and also because of economic advantages, mixtures of Portland cement (PC) and pozzolans are now very commonly used in concrete production by Mehta [1].

One possible source for a pozzolan is calcined clay. Natural pozzolans in the form of calcined earth blended with lime have been used to produce cementitious materials for thousands of years [2,3]. Structures such as water tanks, aqueducts, walls and bridges 4000 years old have been constructed from thermally activated clay and lime mortars [4,5]. The utilization of calcined clay in the form of metakaolin (METAKAOLIN) as a pozzolanic addition for mortar and concrete has received considerable interest in recent years. Much of this interest has focused on removal of the CH, which is produced by the hydration of cement and which is associated with poor durability. CH removal has a major influence on resistance to sulphate attack and alkali-silica reaction (ASR) and also pro- vides enhanced strength, which is derived from the additional cementitious phases generated by the reaction of CH with Metakaolin. Metakaolin is processed from high-purity kaolin clay by calcination at moderate temperatures (650- 800°C). It contains silica and alumina in an active form which will react with the CH. The principal reasons for the use of clay-based pozzolans in mortar and concrete have been materials availability and durability enhancement.

Many research works demonstrate that application of metakaolin improves properties of concrete as freeze-thaw

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resistance and resistance against de-icing salts with freeze-thaw cycles combination. A critical role in concrete performance in such severe environment is played by the porous system and the surface of the hardened concrete.

Metakaolin an Review: Metakaolin (METAKAOLIN) is a pozzolanic material. It is a dehydroxylated form of the clay mineral kaolinite. It is obtained by calcination of kaolinitic clay at a temperature between 500°C and 800°C. Between 100 and 200°C, clay minerals lose most of their adsorbed water. Between 500 and 800°C kaolinite becomes calcined by losing water through dehydroxylation. The raw material input in the manufacture of metakaolin ($Al_2Si_2O_7$) is kaolin clay. Kaolin is a fine, white, clay mineral that has been traditionally used in the production of porcelain. Kaolinite is the mineralogical term that applies to kaolin clays. Kaolinite is defined as a common mineral, hydrated aluminium disilicate, the most common constituent of kaolin. The dehydroxylation of kaolin to metakaolin is an endothermic process due to a large amount of energy required to remove the chemically bonded hydroxyl ions. Above this temperature range, kaolinite becomes Metakaolin, with a two-dimensional order in the crystal structure. In a view to producing a pozzolan (supplementary cementing material), nearly complete dehydroxylation must be reached without overheating, i.e., thoroughly roasted but not burnt. This produces an amorphous, highly pozzolanic state, whereas overheating can cause sintering, to form the dead burnt, non-reactive refractory, called mullite. Metakaolin reacts with $Ca(OH)_2$, produces calcium silicate hydrate (CSH) gel at ambient temperature. Metakaolin also contains alumina that reacts with CH to generate additional alumina-containing phases, including C_4AH_{13}, C_2ASH_8 and C_3AH_6 [6,7].

The kinetics of dehydroxylation have been studied [8]. Metakaolin can be made by flash calcining at about 1000°C or by prolonged soak calcining at lower temperatures [9]. Salvador [10] reports that the rate of calcining does not influence the pozzolanic properties, provided that dehydroxylation is complete and that the kaolin has not been over calcined. Above about 800°C, kaolin begins to convert to relatively inert ceramic materials such as spinel, silica and mullite.

Chemical Properties of Metakaolin: Cement made from alkali metal hydroxides (and/or silicates) with metakaolin are known variously as geopolymers, earth ceramics or inorganic polymers and have been used in many specialist applications.

A range of products is formed, including CSH, C_2ASH_8 (gehlenite hydrate) and hydrated calcium aluminates, C_4AH_{13} and C_3AH_6 [11,12,13]. The composition and structure of CSH are variable, as discussed in the next section. Gehlenite hydrate, also called stratlingite, is a distinct crystalline phase, but can be of variable composition. It can incorporate relatively large amounts of Na+ and K+ which displace Ca2+ in the lattice and this can affect the pore solution chemistry of cement paste which contains metakaolin.

Dunster *et al*. [14] studied the reactions of metakaolin with CH in two systems; metakaolin/lime/water and metakaolin/ PC/water, respectively. They used the trimethylsilylation technique to follow the kinetics of formation of the reaction products. They concluded that over a period of 30 days, metakaolin reacts with CH at a similar rate in both metakaolin/lime and metakaolin/PC pastes. Pure metakaolin is estimated to respond with up to 1.6 times its mass of CH. Also, they have concluded that over a period of 30 days, metakaolin reacts with CH at a similar rate in both metakaolin/ lime and metakaolin/PC pastes. However, in the metakaolin/PC mixture, metakaolin accelerates the hydration and polymerization of the low molecular weight silicate ions. This is similar to the stoichiometry proposed earlier by Murat [15].

Bauweraerts, Wastiels *et al*. [16] and Palomo *et al*. [17] have examined the properties of mortars and concrete and Davidovits [18] has described numerous applications. Palomo *et al*. [17] have investigated the chemical stability of this cement and find that they do not lose strength when immersed for 270 days in various aggressive reagents such as water, sodium sulphate solution, seawater or 0.001 m sulphuric acid. This high degree of durability, compared with the hydrated calcium silicate (CSH) phases in PC concrete, is possibly because of the three-dimensional zeolitic structure of metakaolin/alkali silicate cement.

McCarter and Tran [19] showed that electrical conductivity could be used to monitor the early hydration of pozzolana/lime mixtures. The electrical conductivity of a metakaolin: CH: water mixture (in the ratio 8:2:12) fell to about 0.2 of its initial value after 40 h. The chemistry and microstructure of hardened PC paste is complex [20]. When PC hydrates, a considerable amount of CH is formed, typically 20 percent of the paste mass; the accepted idealized reactions. Therefore, metakaolin significantly changes the chemistry of the cement paste.

NMR studies [21,22] confirmed that metakaolin increases the proportion of high molecular weight alumino silicate polymers in cured paste; Si spectra indicate a

much higher ratio compared with PC cement paste. As well as having a major effect on the chemical structure of CSH, metakaolin also modifies the nanostructure. Using high-resolution electron microscopy, Richardson [22] has suggested that the CSH phase of metakaolin/PC has a two-dimensional 'foillike' structure, rather than the linear 'needle-like' structure of standard CSH. He suggested that the foil structure is more efficient at filling space without leaving large interconnected capillary pores. This might account for the lower permeability and improved durability of concrete containing metakaolin and other pozzolans. Recent developments in high-resolution X-ray microscopy [23] should enhance our understanding of the nanostructure of cement pastes shortly.

Calcium hydroxide is a soluble and chemically reactive component of hardened cement paste. The crystals (portlandite) may be relatively large, of the order of 1–5 μm diameter and are often concentrated within the interfacial zone, which is a layer of paste a few tens of micrometres thick adjacent to the aggregate surface. According to the stoichiometry of Dunster *et al*. [14], pure metakaolin reacts with 1.6 times its weight of CH. It is difficult to measure accurately low concentrations of CH in concrete and errors can arise if the concrete is exposed to atmospheric carbon dioxide, either while curing or while preparing the sample for analysis.

The differential thermal analysis appears to be the most precise method of following the concentrations of CH in cement/metakaolin blends as they cure. Results indicate [24,25,26]; that metakaolin reacts with approximately its mass of CH and this is supported [27] by the Chapelle test [28]. Curcio *et al*. [25] found that, after 90 days' curing, 15 mass per cent replacement of PC by metakaolin reduced the portlandite content of the cured paste to between 6 and 24 mass per cent of its value for the control paste, depending on the quality and particle size of the metakaolin.

To remove all the CH substantially from cured PC paste, approximately 20–25 mass per cent of the cement should be replaced by metakaolin. Klimesch *et al*. [29,30] measured residual metakaolin in autoclaved blends of PC, metakaolin and quartz. No residual metakaolin was observed when it replaced less than 18 mass per cent of the PC. Residual metakaolin was observed when it replaced more than 18 mass per cent. In these experiments, it is possible that some of the CH had reacted with the quartz, because the mortar, after pre-curing for 24 h, was autoclaved at 180°C for 8 h.

In water desorption [31] fully saturated samples are stored in a vacuum desiccator whose internal relative humidity is controlled by a saturated salt solution. By using saturated BaCl2 solution, for example, when equilibrium is attained all pores greater than 30 nm in diameter are empty; therefore, the total pore volume and the proportion of pores below 30 nm in diameter can be calculated. The measured pore size distribution is sensitive to the exact technique employed to cast and compact the wet mixture. At low water/binder ratios, it can be difficult to achieve a flowing mixture, especially if the insufficient plasticizer is used. This might result in an inadequate mixing of the ingredients, incomplete dispersion of powder aggregates and poor compaction. Pastes at low water/binder ratios are particularly prone to errors, but mortar and concrete are less so because of the grinding effect of the aggregate. Sometimes, it is difficult to compare sets of pore size distribution measurements from different authors.

Several reports [24,31,32,33,34] indicate that with cement pastes, the addition of metakaolin decreases the proportion of pores with diameters above about 0.1 μm. There is a corresponding increase in the proportion of pores with diameters below about 0.05 μm–that is, the average pore diameter is reduced (refined). Using water desorption, Chadbourn [31] found that the total porosity of metakaolin pastes was slightly greater than that of pure pastes, indicating that metakaolin increases the volume of the fine capillary and gel pores while decreasing the volume of coarser pores.

Asbridge [35] has measured the pore diameter distributions of a series of fifteen cement pastes and mortars by MIP under standard conditions of preparation. The water/binder ratio, metakaolin content, aggregate content (glass ballotini, 1.0–1.2 mm diameter) and curing temperature were systematically varied. Some typical results comparing mortars and pastes, with and without 10 mass per cent substitution of PC by metakaolin, are

- The paste component of mortar has coarser pores (above 1.0 μm diameter) than does pure paste
- Metakaolin does not significantly change the pore diameter distribution of paste (either pure paste or the paste component of mortar) for pores above 0.2 μm diameter.
- Metakaolin refines the pore structure in the region 0.01–2 μm, for paste and the paste component of mortar. Since metakaolin does not reduce the total pore volume [31], this implies that metakaolin increases the volume of pores in the region below 0.01 μm diameter.

- Metakaolin consistently reduces the threshold pore diameter, in both pure pastes and the paste component of mortars.

Interpreting the effect of metakaolin (and other pozzolans) on the pore structure of mortars is made difficult by the presence of an interfacial zone between the paste and the aggregate. The interfacial zone is a region of low concentration of CSH, high concentrations of CH and ettringite and high porosity. It is typically 25–100 µm in thickness, but pozzolans can change the structure of the interfacial zone by reacting with the CH and generating new cementitious phases.

There is a very extensive literature [36]. Larbi and Bijen [34] found that metakaolin reduced both the amount and crystal orientation of CH in the interfacial zone. They measured the thickness of the interfacial zone to be less than 10 µm in metakaolin mortar, compared with 30 µm in the corresponding PC mortar. This resulted in increased adhesive strength between the paste and aggregate, as measured directly by pull-off tests [34].

At low replacement levels (i.e. 5 mass per cent or less), metakaolin increases the thixotropy of concrete without significantly affecting its flow properties under shear. This can reduce bleeding, improve levelling and provide an excellent surface finish. If appropriate, metakaolin can be used at up to 20 or 25 mass per cent replacement of PC. However, at high metakaolin doses and low water/binder ratios, the concrete can be difficult to work without superplasticizer [37]; Dhir [38] has shown that metakaolin concrete normally requires a smaller superplasticizer dose than does the equivalent silica fume concrete. With no superplasticizer, it may be necessary to increase the water/binder ratio to maintain the required compaction factor,

Dhir *et al*. [38] and Wild *et al*. [39] presented a report metakaolin has a lower density than PC so that replacing, say, 10 mass per cent PC by metakaolin decreases the water/binder volume ratio and slurry rheology is determined by the liquid/solid volume ratio. There have been no reports that metakaolin reacts adversely with common additions such as (super) plasticizers, air entraining agents or waterproofing aids. If waterproofing aids are used they may need to be added after the metakaolin has been fully incorporated into the mix. This will avoid the possibility of the waterproofing aid adsorbing on the high surface area of the metakaolin before the latter is properly wetted.

The viscosifying effect of metakaolin can also be overcome by using extra Superplasticizer reducing the sand content, or choosing coarser grades of sand [40].

Metakaolin is also compatible with fibrous additions such as polypropylene, glass and cellulose. The bond between the fibre and the cement matrix can be strengthened because CH in the interfacial zone is replaced by CSH and CASH phases. There is less likelihood of CH chemically attacking some fibres, such as glass [20] and cellulose.

Settling Time Properties of Metakaolin: Metakaolin slightly reduces the initial and final setting times of cement paste [24,41]. Results are shown in Table 15.4. Both investigators adjusted the water/binder ratio to give constant consistency according to BS-EN 196–3:1995. Similar trends have been found in mortar and concrete. Zhang and Malhotra [42] reported that a 10 per cent metakaolin concrete showed a final setting time of 264min, compared with 312min for the control concrete. The water/binder ratio was 0.40.

The effect of metakaolin on heat evolution in concrete has been reported by Frias *et al*. [43]. They used a semi-adiabatic method, curing mortar in a Dewar flask. The water/cement ratio was 0.5, the sand/ cement ratio was 3.0 and metakaolin was used at replacement ratios of 10 and 30 mass per cent. Both metakaolin mortars showed a maximum temperature rise of 38°C, compared with a rise of 33°C for the control. Other semi-adiabatic studies have given similar results [44].

Bajracharya *et al*. [45] report true adiabatic temperature rise experiments in which 300 mm cubes of concrete were cured under water which was maintained at the same temperature as the centre of the cube. The concrete contained 325kgm^3 cement and metakaolin was used at replacement levels of 0, 10, 15 and 20 mass per cent. All samples showed similar maximum temperature rises of 35°C. The effect of curing concrete at these relatively high temperatures on the mechanical properties of metakaolin concrete has been investigated. It is of obvious importance in large-scale engineering applications of metakaolin concrete.

Asbridge [35] showed that curing at 60°C has no deleterious effect on pore size distribution or compressive strength. In his experiments described earlier, Bajracharya initially cured the concrete for 72 h under adiabatic conditions, in which the temperature rose to about 55°C, but then continued to cure at 20°C. Compressive strength development, porosity, oxygen permeability and water permeability were measured and compared with values obtained by normal fog curing at 20°C. Results showed that adiabatic curing was no different from fog curing and metakaolin was found to have a beneficial effect on all these properties.

Early strength development Hannant [46] has developed methods for measuring the tensile strength of concrete prisms as young as 1 h. The prism is supported in a split mould on a frictionless cushion of air and the stress/strain relationship determined. Results [47] show that metakaolin significantly increases the rate at which concrete gains tensile strength during the first six hours after mixing.

Studies on chemical shrinkage, autogenous shrinkage and swelling in metakaolin/PC pastes have been reported [48]. Results indicate that metakaolin slightly elevates chemical shrinkage. It should be noted that all these shrinkage and expansion values would be considerably reduced when the binder is blended with aggregate, as in concrete. Drying shrinkage of metakaolin concrete has been measured [38]. Within the limits of experimental error, metakaolin has no deleterious effect on drying shrinkage.

Strengthening Properties of Metakaolin: Dhir *et al* [38], Ryle [40], Sabir [49] and Wild *et al* [39] made numerous studies have shown that metakaolin increases the compressive strength of concrete. The magnitude of the effect is sensitive to water/ binder ratio, being most pronounced if this ratio is less than 0.5. Best results are obtained by adjusting the superplasticizer dose to give suitable rheological properties. Since metakaolin does not increase the compressive strength of PC paste [34], it is concluded that strength improvement in concrete is due to the changes in the structure of the interfacial zone and the increased paste-aggregate bond strength. For the same reasons, metakaolin has a beneficial effect on flexural strength, although the magnitude of the effect is less than that observed for compressive strength. It has been reported that the addition of certain cationic quaternary ammonium polymers [50] and anionic polyacrylic acids [51] can significantly increase the strength of metakaolin concrete.

Creep strain has been measured [38] for a range of metakaolin substitution levels and results. The cylinders were cured in water for 28 d and then loaded to 40 per cent of their 28-day strength for 90 days. In these experiments, there was a slight upward trend of creep strain with metakaolin content, but it should be noted that superplasticizer dose was also varied, to maintain constant 75 mm slump. Using two samples of commercial metakaolin, Coleman and Page [52] found that metakaolin reduces the pH of pore water in cured cement paste. However, the reduction is relatively small, even when PC is replaced by 20 mass per cent of metakaolin.

These results confirm studies at the BRE in the UK [53] using high and low alkali cement, containing 1.38 and 0.41 mass per cent equivalent of K_2O respectively.

Coleman and Page [52] also showed that metakaolin-PC pastes could bind considerable quantities of dissolved chloride ion present in the pore water due to the formation of stable chloroaluminate such as Friedel's salt. Because metakaolin 'removes' chloride ions, as well as hydroxide ions from solution, metakaolin maintains a low $[Cl^-]/[OH^-]$ ratio; this is important concerning rebar corrosion, as discussed [54,55,56]. Chloride binding also has the effect of reducing the rate of chloride ingress in concrete, especially at low water/binder ratios [57,58].

Direct measurements of chloride diffusion in cement paste and concrete have been made by steady state and non-steady state methods.4 Results show that the diffusion rate is reduced by a factor of 3 or more when 10 mass per cent of the PC is replaced by metakaolin. Larbi [34] found that the diffusion coefficients of Cl^-, Na^+ and K^+ were all reduced by factors ranging from 40 to 60 when metakaolin replaced 20 mass per cent PC in the mortar. Ponding experiments, in which large prisms of concrete are exposed on their upper surfaces to the saturated salt solution, have been reported [31,59]. Analysis of the chloride penetration profile after 1 year typically shows that metakaolin reduces the concentration of chloride at a depth of 20 mm by factors of 2 and 17, for 10 mass per cent and 20 mass per cent metakaolin, respectively.

Gilleece compared the effectiveness of metakaolin (and blends of metakaolin with fly ash and slag) with other pozzolans and with silane treatment. Over the time scale of these experiments, the best methods of reducing chloride penetration were supplied by silane, 20 mass per cent metakaolin and 50 mass per cent slag. The movement of water through concrete plays a major role in degradation processes. Moving water can carry aggressive agents such as acids and salts and can also enhance the magnitude of corrosion currents by increasing electrical conductance.

McCarter and Watson [60] have measured the rate of drying, the rate of water absorption and electrical conductivity profiles as a function of depth of concrete. Results indicated that there was little difference between the PC concrete, the silica fume concrete and the metakaolin concrete at the higher water/binder ratio. However, at a water/ binder ratio of 0.4, the metakaolin concrete showed the lowest rates of water migration. Metakaolin decreased the equilibrium electrical conductivity, at depths of 50 mm or more, by a factor of about three.

Larbi [34] obtained comparable results for the rate of drying of wet mortars and the rate of absorption of water into dry mortars, using 20 mass per cent replacement by metakaolin and other pozzolans. Initial surface absorption tests (ISAT) have been measured [38], using the method described in BS1881: Part 5. It is seen that metakaolin reduces the rate of absorption of water, but is slightly less effective in this respect than silica fume. However, it should be noted that silica fume cannot normally be used at substitution levels of 10 or 15 mass per cent.

The rate transport of oxygen or air through concrete is a major factor in re-bar corrosion. The permeability of dry concrete to air, under a pressure differential, has been reported [61,62]. Mackechnie *et al.* showed that metakaolin significantly reduced air permeability, but Basheer found no difference between the metakaolin and control concretes. The diffusion of dissolved oxygen through water-saturated paste has also been reported [45,31]. These results indicate that metakaolin reduces the oxygen diffusion rate, but the effect is sometimes small.

Durability Properties of Metakaolin: Several published papers discuss the durability of metakaolin concrete [61,63,25,40,42]. Carbonation is sometimes a problem in reinforced concrete because it reduces the pH of the pore water and this can result in rapid re-bar corrosion. By depleting the reservoir of CH in the cement paste, it might be expected that metakaolin would increase the rate of Carbonation. Studies at the BRE [64] and the University of Dundee [65] have been carried out using a wide variety of exposure conditions.

Several laboratory studies [66,67,68,69,70,71] have shown that ASR can be prevented if 10–15 mass per cent of the PC is substituted by metakaolin. With all but the most severely reactive aggregates, 10 mass per cent is sufficient to prevent expansion, even when the concrete is immersed in 2-molar NaCl solution. Over the period 1962–79, four dams were constructed in the Amazon basin using highly reactive local aggregates. Approximately 260,000 tonnes of calcined kaolinitic clay was used, blended with PC, for the concrete [68]. It was reported later [72] that the metakaolin had inhibited the expected ASR and there were no signs of damage to the dams due to swelling.

Sulphate ions are present in sea water and many soils, especially on reclaimed industrial land. On entering the concrete, they form ettringite and gypsum, causing the concrete to swell and ultimately to disintegrate. Magnesium sulphate has a particularly damaging effect because Mg2+ ions precipitate Mg(OH)2 which has the effect of reducing pore water pH and dissolving some of the calcium silicate phases. The various chemical reactions thought to be involved in sulphate attack have been discussed [73] and there is an extensive literature [74]. It has been shown [33,75] that metakaolin can reduce or eliminate the deleterious effects of sulphate attack, but the mechanism is not clear. Possibly the reduction in the amount and crystal size of the portlandite in the cured paste is a factor. Also, it has been postulated that the (alumino) silicate phases of cured metakaolin/alkali paste are thermodynamically more stable and resistant to chemical attack [17,22].

Relatively high proportions of metakaolin are required to prevent sulphate attack. For example, Khatib and Wild [33] showed that 10 mass per cent metakaolin prevents expansion due to sulphate attack when the PC contains 7.8 mass per cent C3A; however, 20 mass per cent is required when the PC contains 11.7 mass per cent C3A.

A limited number of reports describe the effect of metakaolin on concrete subject to attack by organic and inorganic acids [63,76] and freeze-thaw cycles [38,42]. Metakaolin improves the resistance of concrete to acids. Freeze-thaw resistance is determined by methods described in ASTM C666, Procedure A and in CEN/TC51, Part 1: scaling, reference method A. All the published data indicates that metakaolin does improve freeze-thaw resistance, but the effect is relatively small. Zhang *et al.* [77] also tested de-icing salt scaling, according to ASTM C 672. Their results showed that the metakaolin concrete is marginally inferior to that of the control concrete, but the reason is not known.

The use of brightly coloured concrete to make sculptures, monuments and decorative public walled and paved areas is becoming popular. Metakaolin can be used to enhance the appearance of such concrete and prevent efflorescence over long time periods [78]. Dow and Glasser [79] have developed a semi-quantitative model to explain the most common form of efflorescence, caused by calcium carbonate deposition. A thin static film of water on the surface of the concrete is required. This film dissolves alkali from the concrete and the resulting alkaline solution rapidly absorbs carbon dioxide from the atmosphere to give carbonate and bicarbonate ions. These ions diffuse through the liquid layer to the surface of the concrete where they interact with calcium ions, which mostly derive from sparingly soluble portlandite. Metakaolin concrete is less susceptible to efflorescence, probably because it reduces the pH of the pore water, removes some of the portlandite and the finer pore structure leads to reduced diffusion of water and ions

within the concrete. Glass fibre reinforced concrete (GRC) is an example of a specialist application where metakaolin is used to improve durability in outdoor environments, Marikunte *et al*. [80]. Even alkali-resistant glass (AR-glass) fibres are rapidly weakened by the alkaline pore water and this leads to reduced tensile strength and increased brittleness (i.e. loss of elasticity). Accelerated tests predicted that metakaolin should maintain the strength and elasticity of GRC for at least 25 years if AR-glass fibres are used. Steel fibres are sometimes used to make very high strength concrete.

Banthia and Yan [81] have carried out pull-out tests on steel fibres6 embedded in cement matrices. The effect of replacing 10 mass per cent PC with metakaolin was to increase the maximum pull-out load from 170 to 200 N and increase the energy absorbed at 9.75 mm slip from 680 to 1180 N-mm. The pullout load should not exceed the tensile strength of the fibre. Otherwise, the concrete would be undesirably brittle. Metakaolin can be used with PC in conjunction with other pozzolans such as silica fume, fly ash and ground granulated blast-furnace slag, ggbs. By varying the relative amounts of two pozzolanas, it may be possible to optimize the cement formulation on cost and performance. Several papers have been published on this large topic [82,83,59,37], but further discussion is outside the scope of this review.

Metakaolin in engineering concrete Metakaolin in its 'pure' form (i.e. manufactured from kaolin greater than about 90 per cent purity) conforms to the ASTM C 618, Class N definition of a natural pozzolan suitable for use in concrete. The proposed European Standards for cement and concrete will also provide for pure metakaolin. The British Board of Agrément (1998) has approved certain grades of metakaolin for applications in engineering concrete. The production of commercial metakaolin, suitable for use in high-quality concrete, is typically controlled according to mineral purity, particle size distribution, pozzolanic reactivity and if necessary colour.

As discussed earlier, metakaolin is widely used in concrete for decorative applications such as paving slabs, floor screeds, renders and sculptures. Other trials, where metakaolin concrete has been used for its engineering durability properties, have been reported. Martin [76] described the development of a Portland/ggbs/ metakaolin concrete for acid-resistant silage clamps. After two years of use, the surface of the pozzolanic concrete was significantly less corroded than the control concrete. Metakaolin concrete has been used to repair bridges [84] and to construct foundations, a marine slipway and a river diversion scheme [85]. Large pre-stressed bridge beams are manufactured from metakaolin concrete and certain advantages of using metakaolin concrete in this application have been described [86]. The beams are made from 75 MPa concrete and can span longer distances and can be used at a wider spacing than conventional concrete beams. When used for motorway or rail bridges, they can be used to increase headroom clearances and overall durability is improved.

Trade journals that serve the construction industry also report that metakaolin concrete has been used to make roads and bridge decks [87,88]. Further examples of the use of metakaolin/PC concrete and metakaolin/alkali silicate polymers (geo-polymers) are described on various Internet websites and the patent literature is extensive.

CONCLUSION

Many researchers have studied the properties of ordinary Portland cement concrete and steel fibre reinforced concrete using fly ash, silica fume, as cement replacement materials. Due to the associated environmental pollution caused in the production of cement to reserve the virgin raw materials used in cement making for future generations and at the same time due to the availability of supplementary cementing materials like Metakaolin which is an engineered material, an attempt has been made to study strength and durability properties of Metakaolin concrete with and without crimped steel fibres. The use of supplementary cementing materials like fly ash, rice husk ash, silica fume, ground granulated blast furnace slag (GGBS) and Metakaolin are permitted to use in the concrete making as per clause 5.2 of IS: 456-2000 for long-term sustainability and durability.

The existing literature indicates that many researchers have studied the properties of ordinary Portland cement concrete and steel fibre reinforced concrete using fly ash, silica fume, GGBS, rice husk ash, as cement replacement materials. Not much literature is available on durability properties of Metakaolin concrete. Also, no comprehensive study was done on strength and durability properties of Metakaolin concrete. Hence, considering the gap in the existing literature, an attempt has been made to study the strength, durability properties of Metakaolin concrete.

Compared with other pozzolanic additions, such as silica fume, slag and fly ash, metakaolin does not yet have a long or extensive track record. Published reports indicate that metakaolin shows all the well-known advantages ascribed to other pozzolanic additions. No serious disadvantages have been highlighted by the

authors. The future of metakaolin concrete would seem to depend on the balance between desirable properties (improved durability, strength, etc.) and other economic factors such as the cost of raw material, plus logistical problems associated with changing the formulation and handling properties of mass concrete. The attitudes of industrial economies towards the whole-life costs of infrastructure projects is constantly evolving. The future of metakaolin concrete promises to be an interesting subject of study over the next few decades; it will be determined by the investment decisions of the producers of metakaolin and concrete, by concrete customers and, of course, government and regulatory agencies.

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