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METAKAOLIN: FRESH PROPERTIES AND OPTIMUM CONTENT FOR MECHANICAL STRENGTH IN TRADITIONAL CEMENTITIOUS MATERIALS – A COMPREHENSIVE OVERVIEW

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Abstract. Kaolins can satisfy the world demand for filler, paper and ceramic industries. If kaolin thermally activated, it converts to a pozzolan material named metakaolin (MK). MK can be used in traditional paste, mortar and concrete to improve their properties. In addition, MK can be used as a source of cementing materials without Portland cement (PC) named geopolymer. This literature presents an overview of the pervious works carried out on the effect of MK on the fresh properties and mechanical strength of traditional cementitious materials based on PC in which MK was used as cement replacement. In addition, the optimum content of MK which exhibited the highest 28 days compressive strength was reviewed.

1. INTRODUCTION

Concrete is one of most extensively used construction materials in the world. Each year, the concrete industry produces approximately 12 billion tonnes of concrete and uses about 1.6 billion tonnes of PC worldwide [1]. Indeed, with the manufacture of one tonne of cement approximately 0.94 tonnes of CO_2 are launched into the atmosphere [2]. Not only CO_2 releases from cement manufacture but also SO_2 and NO_x which can cause the greenhouse effect and acid rain [3-5]. These cause serious environmental impact. In addition to consuming considerable amounts of virgin materials (limestone and sand) and energy (energy demand about 1700-1800 MJ/ tonne clinker) [2,3,5-7] , producing each tonne of PC of which about 1.5 tonnes of raw material is needed [2,3,5,6]. To reduce the environmental impact of cement industries, MK and other cementitious materials are used to replace part of cement [8-14] or as a source of new cementless materials [2,4,5].

The main sources of MK are either kaolin or paper sludge, after suitable thermal treatment. The optimum temperature for heating kaolin in order to obtain MK with a high pozzolanic index is still different from one researcher to another. The heating period also is still exactly undetermined. The optimum temperature for heating kaolin to obtain MK may be ranging from 600 °C to 850 °C for periods ranging from 1 h to 12 h. These differences may be related to the MK chemical composition [7]. How-

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ever, most of researches preferred to use 700 °C for 12 h to obtain MK from kaolin [7]. The best calcination of paper sludge in order to obtain MK may be ranging from 600 °C to 800 °C for heating period ranging from 2 h to 5 h. Most of researchers reported that the optimal calcination conditions were given by a temperature of 700 °C for a period of 2 h [7]. However, the calcination temperatures and calcination periods required to obtain MK from kaolin and paper sludge are completely covered in a comprehensive details in [7]. It is worth mentioning that MK can also be obtained by the calcination of indigenous lateritic soils [15]. However, MK reacts chemically with hydrating cement to form modified paste microstructure. In addition, to its positive impact, MK improves concrete mechanical properties and durability. The term of MK pozzolan refers to a silecious material which, in finely divided from and in the presence of water, will react chemically with calcium hydroxide to form cementitious compounds. In addition, employing MK as a part of traditional cement or as geopolymer, reduces the environmental Impact resulting from cement industry.

Although there are numerous numbers of review papers in the literature regarding to using MK as pozzolan for concrete [16], using MK to produce green cement for construction purposes [17], the influence of MK on the properties of mortar and concrete [18] and the optimum treatment conditions of kaolin and paper sludge to produce MK [7], the electronic library is still needs more review publications. However, there is no published review paper in the literature reviewed the previous works carried out on the effect of MK on the heat of hydration, workability, setting time and mechanical strength of traditional cementitious materials based on PC. On the same line with this, there is no published review paper reviewed and investigated the optimum replacement level of cement with MK versus w/b ratio of traditional paste, mortar and concrete based on PC. However, the main goal of this review to produce a short guide for Engineer about the effect of MK on heat of hydration, workability and mechanical strength as well as the optimum replacement level of cement with MK that exhibits the highest 28 days compressive strength.

2. FRESH PROPERTIES

2.1. Heat of hydration

Ambroise et al. [19] reported that temperature rises by 8 °C, 6 °C, and 1 °C over controls for 10%, 20%, and 30% replacement, respectively, in mortars. The smaller temperature increases at higher replacement levels are likely due to the dilution effect of removing such a large mass of cement from the system. Frías et al. [20] compared fly ash (FA), silica fume (SF) and MK in terms of heat evolution using a Langavant calorimeter. This semi-adiabatic method, described in the Spanish standard UNE 80 118, measures the heat generated during cement hydration using a thermally isolated Dewar flask. Heat is defined as the temperature difference between the hydrating mortar and an inert mortar (three months old at least). Blended cement pastes containing 10% or 30% SCM were used to produce mortars with a sand-to-cement ratio of 3:1 and a w/b of 0.5. The total heat evolved (up to 120 h) was found to decrease significantly with increasing FA substitution, increase slightly on substitution with 10% SF and essentially stay the same for increasing levels of MK substitution. They also measured the peak height relative to controls, for these hydrating mortars. FA mortars exhibited a continual reduction in temperature rise with increase in substitution level, SF incorporation resulted in a decrease of 1.5 – 3.0 °C and MK caused content of a mixture will reduce the heat output from cement hydration, but will not necessarily reduce the initial rate of heat evolution or the maximum temperature reached.

Bai and wild [21] looked especially at the effects of FA and MK on heat evolved using embedded thermocouples. Mortar mixtures were placed in 150 mm plywood cube moulds and thermally isolated by encasement in 100 mm thick expanded polystyrene and another layer of plywood. Increasing in replacement levels, decreasing the temperature rise in FA systems was noted. On the other hand, the temperature rise in MK systems was found to increase substantially. Numeric peak temperature values were 29 °C, 27 °C, and 31 °C for the control, 10% FA and 10% MK mixtures respectively. They also investigated the use of FA and MK in ternary blends at total cement replacement levels up to 40%. These appeared to have a compensatory effect on temperature rise as shown in Fig. 1.

Janotka et al. [22] studied heat of hydration of MK sands collected from Vyšný Petrovec deposit (Slovakia) with different MK contents of 31.5%, 36%, and 40%. The percentage of MK sands in the blended cement was 10%, 20% and 40%. They reported that the addition of 36% and 31.5% sands to cement induced a delay up to 2 h of precipitation of the main hydration products in the blended-cement pastes and decreased the maximum heat evolution rate. On the other hand, the incorporation of 40% MK sand shortened 6 h its apparition and increased

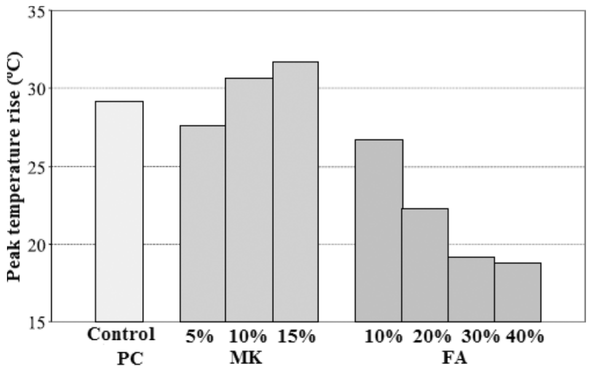

Fig. 1. Peak temperature rise for PC, MK and FA blended mortar. Reprinted with permission from J. Bai and S. Wild // *Cement & Concrete Composites* **24** (2002) 201, © 2002 Elsevier.

significantly the maximum heat evolution rate. The presence of MK sand reduced the heat released during the hydration process with respect to non-blended-cement pastes as a consequence of the precipitation of hydration products was less exothermic in the former and also the lower amount of hydration products formed in MK sands-blended-cement. Snelson et al. [23] studied the heat of hydration of blended cement pastes in binary and ternary partial replacement binders with MK and FA. For binary cement–MK blends, the results indicated that MK initially diminished cement hydration but the subsequent pozzolanic reaction of MK increasing contributed to the heat output causing some blends to exceed the heat output of the cement. For ternary cement-MK-FA blends the MK had a dominant influence on the heat output versus time profiles.

Rahhal and Talero [24] studied the effect of the rate of heat release due to the incorporation of MK or MK and quartz powder (QP) in cement matrix. The cement/MK/QP were 100/0/0, 60/40/0, and 60/20/20. The results showed that MK and MK/QP induced stimulation of the hydration reactions due to the generation of pozzolanic activity at very early stage, because of their reactive alumina contents. Lagier and Kurtis [25] examined plain cement paste and MK paste via isothermal calorimetry. Cement was partially replaced with 8% MK, by weight. Fixed w/b ratio of 0.5 was used. They reported that MK appeared to have catalysing effect on cement hydration, led to acceleration in the reaction rates, an increase in cumulative heat evolved during early hydration. Kadri et al. [26] studied the influence of MK on the heat of hydration of mortars. Cement was partially replaced with 10% MK, by weight. Fixed w/b ratio of 0.36 and various dosages of superplasticizer (SP) were employed. They reported that blended mortar with MK reached higher heating with respect to plain cement mortar. Heating between 63 and 72 °C was detected which means an increase in temperature between 10% and 15% with respect to plain cement mortar. Sonebi et al. [27] partially replaced cement with MK in cement grouts at various levels of 6% and 13%, by weight. Fixed w/b ratio of 0.4, various dosages of SP and viscosity-modifying agent were employed. They reported that the inclusion of MK increased the heat of hydration. The heat oh hydration increased with increasing MK content.

From the above review of the literature in this section, it can be noted that most of authors reported that the inclusion of MK in the mixture increased the heat evolved during the hydration. This had been attributed to the accelerating effect of MK on cement hydration and the high-reactivity of MK with CH.

2.2. Workability

Valipour et al. [28] partially replaced cement in concrete mixture with 5% MK, by weight. Fixed w/b ratio of 0.4 and various dosages of SP were employed. The results showed that MK mixture exhibited lower workability compared to the control. Wang et al. [29] partially replaced cement in concrete mixture with 8% MK, by weight. Fixed w/b ratio of 0.45 and fixed water reducing agent were employed. They found a reduction in the workability with the inclusion of MK. Li and Ding [30] partially replaced cement with 10% MK, by weight. Fixed w/b ratio of 0.28 and fixed dosage of SP were employed. They reported that the fluidity of MK blended cement became poorer than that of plain cement with the inclusion of MK into plain cement at the same dosage of SP and the same w/b ratio. Rashad [9] partially replaced cement in concrete mixture with 10% MK, by weight. Fixed w/b ratio of 0.45 and fixed dosage of SP were employed. The results showed a reduction in the workability with the inclusion of MK. Brooks et al. [31] and Brooks and Johari [32] partially replaced cement in concrete mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.28 and 14 kg/m^3 of SP were employed. The results showed a reduction in the workability with the inclusion of MK. The reduction in the workability increased with increasing MK content.

Siddique and Kaur [33] partially replaced cement in concrete mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. They used fixed w/b ratio and fixed dosage of SP of 0.45 and 4.95 l/m^3, respectively. The slump results showed a reduction in the workability with the inclusion of MK. Qian and Li [34] partially replaced cement in HPC mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.38 and fixed dosage of SP of 1% were employed. The results showed a reduction in the workability with the inclusion of MK. The reduction in the workability increased with increasing MK content. Dinakar et al. [35] partially replaced cement in HSC mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.3 and various dosages of SP were employed. The slump results showed a reduction in the workability with the inclusion of MK. Behfarnia and Farshadfar [36] partially replaced cement in SCC mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.38 and various dosages of HRWR were employed. They found a reduction in the workability with the inclusion of MK. Bai et al. [37] partially replaced cement in concrete mixtures with MK at levels of 0%, 2.5%, 5%, 7.5%, 10%, 12.5%, and 15%, by weight. Two w/b ratios of 0.4 and 0.5 were used. The results showed a reduction in the workability with the inclusion of MK at all w/b ratios. The reduction in the workability increased as the content of MK increased. Güneyisi and Gesoğlu [38] partially replaced cement in self-compaction mortar mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.4 was used. The results showed a reduction in the workability with the inclusion of MK.

Ramezanianpour and Jovein [39] partially replaced cement in concrete mixtures with MK at levels of 0%, 10%, 12.5%, and 15%, by weight. They used different w/b ratios of 0.35, 0.4, and 0.5. The polycarboxylic acid-based SP was employed to achieve the desired workability. The results showed a reduction in the workability with the inclusion of 10% and 15% MK at 0.5 w/b ration. At w/b ratio of 0.4, the inclusion of 10% MK reduced the workability. At w/b ratio of 0.35, the inclusion of 12.5% and 15% MK reduced the workability. Courad et al. [40] partially replaced cement in mortar mixtures with MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.5 was used. They reported that the inclusion of MK reduced the workability. Sonebi et al. [23] partially replaced cement in cement grout mixtures with MK at various levels ranging from 6% to 20%, by weight. Fixed w/b ratio of 0.4, various dosages of SP and viscosity-modifying agent were employed. They reported that the inclusion of MK reduced the mini-slump. Khatib [41] partially replaced cement in concrete mixtures with MK at levels of 0%, 5%, 7.5%, 12.5%, 15%, and 20%, by weight. Fixed w/b ratio of 0.3 and fixed dosage of SP of 1.36%, by binder weight, were employed. The results showed a reduction in the workability with the inclusion of MK. The reduction in the workability increased with increasing MK content. Paiva et al. [42] partially replaced cement in concrete mixtures with MK at levels of 0%, 10%, 20%, and 30%, by weight. Fixed w/b ratio of 0.6 was used. The HRWR dosages were 0%, 0.08%, 0.15%, and 0.2% for mixtures containing 0%, 10%, 20%, and 30% MK, respectively. The results showed a reduction in the workability with the inclusion of 10% and 20% MK, whilst 30% MK showed comparable workability to the control.

On the other hand, Caldarone et al. [43] incorporated 5% and 10% of high reactivity metakaolin (HRK) in concrete mixtures. The w/b ratios of the control mixture and mixtures containing 5% and 10% HRK were 0.41, 0.38, and 0.36, respectively. Various dosages of HRWR were employed. They found that the incorporation of 5% HRK improved the workability, whilst the incorporation of 10% HRK reduced it. Boddy et al. [44] partially replaced cement in mortar mixtures with HRK at levels of 0%, 8%, and 12%, by weight. Various w/b ratios of 0.3 and 0.4 and various dosages of SP were employed. They reported that HRK mixtures exhibited poorer workability at w/b ratio of 0.3, whilst 12% HRK achieved higher workability at w/b of 0.4 followed by the control mixture and mixture containing 8% HRK, respectively. Ding and Li [45] partially replaced cement in concrete mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.35, fixed dosage of HRWR and fixed dosage of retarder agent were employed. They found that at 5% and 10% replacement, MK mixtures exhibited a slightly higher slump than the control mixture. At 15% replacement, slump decreased approximately 10% related to the control. Badogiannis et al. [46] and Badogiannis and Tsivilis [47] partially replaced cement in concrete mixtures with either commercial metakaolin (CMK) of high purity or MK produced from poor Greek kaolin calcination at levels of 0%, 10%, and 20%, by weight. Fixed w/b ratio of 0.5 and various dosages of SP were employed. For commercial MK mixtures, the results showed an increase in the workability with the inclusion of 10% MK, whilst the inclusion of 20% MK reduced it. For the mixtures containing MK manufactured from poor Greek kaolin calcination, the workability decreased with the inclusion of 10% MK, whilst the inclusion of 20% MK did not affect the workability. Güneyisi et al. [48] partially replaced cement in concrete

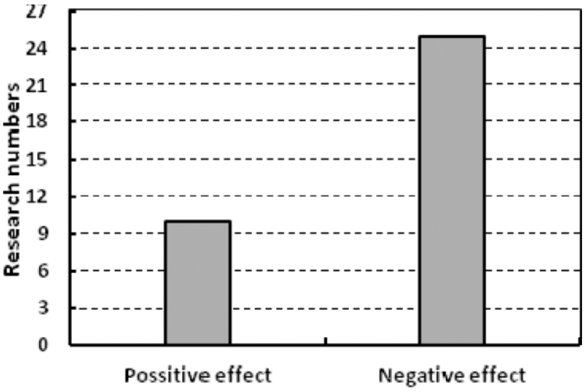

Fig. 2. Effect of MK on the workability.

mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.32 was used. 8.43 kg/m^3 of SP was used for control mixture, whilst 11 kg/m^3 was used for MK concrete mixtures. They reported that the workability increased with the inclusion of 5% and 10% MK, whilst the inclusion of 15% MK reduced it. Güneyisi et al. [49] partially replaced cement in SCC mixtures with MK at levels of 0%, 5%, 10% and 15%, by weight. Fixed w/b ratio of 0.32 and various dosages of HRWR were employed. The slump flow tests showed that the inclusion of MK increased the workability. The inclusion of 10% MK exhibited the highest workability followed by 5% and 15%, respectively. Rashad et al. [8] partially replaced cement in concrete mixtures with MK at levels of 0%, 10%, and 20%, by weight. Fixed w/b ratio of 0.541 and fixed dosage of HRWR of 7 l/m^3 were employed. They found that the inclusion of MK improved the workability especially at 20% replacement level followed by 10% replacement level.

Mansour et al. [50] partially replaced cement in paste mixtures with MK at levels of 0%, 5%, 10%, 15% and 20%, by weight. They found that the inclusion of MK improved the flowability especially at replacement levels of 10% and 15%. Hassan et al. [51] partially replaced cement in SCC mixtures with MK at levels of 0%, 3%, 5%, 8%, 15%, 20%, and 25%, by weight. Fixed w/b ratio of 0.4 and various dosages of HRWR were employed. The slump flow, T50, L-box and V-funnel tests showed that the inclusion of MK increased the workability. The inclusion of 25% MK exhibited the highest workability. Khatib [52] partially replaced cement in concrete mixtures with MK at levels of 0%, 5%, 10%, 15%, 20%, and 30% at constant w/b ratio of 0.5 with various dosages of SP. The results showed that the slump values were 5, 5, 10, 15, 15, and 10 mm at MK levels of 0%, 5%, 10%, 15%, 20%, and 30%, respectively. This means that the workability increased with increasing MK level up to 20%, then decreased at MK level higher than 20%. Wild et al. [53] partially replaced cement in concrete mixtures with MK at levels ranging from 5% to 30% with an increment of 5%. Water contents ranging from 156.2-157.6 kg/m^3 (w/b ratios from 0.446 to 0.45) with various dosages of SP were employed. The slump results showed an increase in the workability with the inclusion of MK. The workability increased as the content of MK increased (Table 1). Table 2 and Fig. 2 summarize the previous researches about the effect of MK on the workability of different mixtures.

From the above review of the literature in this section, it can be noted that most of authors reported that the inclusion of MK in the mixture reduced the workability (Fig. 2). This reduction in the workability due to the inclusion of MK was attributed to the high chemical activity of MK, which results in greater consumption of water (due to both the acceleration in cement hydration and the early pozzolanic reaction) than the case of plain PC mixture. The workability reduction produced by MK is a function of its high specific surface, which led to more water being absorbed. The combined effect of these actions results in an increase in water demand [37].

Table 1. Workability of concrete with the inclusion of MK, data from [53].

MK content (%)	Water kg/m^3	SP (%)	Slump (mm)	Compacting factor	Vebe time (sec)
0	157.6	0	5	0.81	26
5	157.3	0.6	10	0.84	15
10	157.1	1.2	15	0.88	10
15	156.8	1.8	25	0.89	9
20	156.7	2.4	75	0.89	7
25	156.4	3	75	0.89	4
30	156.2	3.6	90	0.9	5

Table 2. Effect of MK on the workability.

Author	MK content (%)	Mixture type	w/b ratio	Positive effect	Notes
Valipour et al. [28]	5	Concrete	0.4	×	With various SP dosages
Wang et al. [29]	8	Concrete	0.45	×	With reducing agent
Li and Ding [30]	10	Paste	0.28	×	With SP
Rashad [9]	10	Concrete	0.45	×	With SP
Brooks et al. [31] and Brooks and Johari [32]	5, 10, and 15	Concrete	0.28	×	With SP
Siddique and Kaur [33]	5, 10, and 15	Concrete	0.45	×	With SP
Qian and Li [34]	5, 10, and 15	Concrete	0.38	×	With 1% SP
Dinakar et al. [35]	5, 10 and 15	Concrete	0.3	×	With various SP dosages
Behfarnia and Farshadfar [36]	5, 10, and 15	Concrete	0.39	×	With various SP dosages
Bai et al. [37]	2.5-15	Concrete	0.4 0.5	×	
Güneyisi and Gesoğlu [38]	5, 10, and 15	Mortar	0.4	×	
Ramezanianpour and Jovein [39]	10, 12.5, and 15	Concrete	0.35	×	12.5% and 15.5% MK
			0.4	×	10% MK
			0.5	×	10%, 15% MK
Courad et al. [40]	5, 10, 15, and 20	Mortar	0.5	×	
Sonebi et al. [23]	6-20	Grout	0.4	×	With various SP dosages and viscosity-modifying dosages
Khatib [41]	5, 7.5, 12.5, 15, and 20	Concrete	0.3	×	With SP
Paiva et al. [42]	10, 20, and 30	Concrete	0.6	×	-With various HRWR dosages -10% and 20% MK
Caldarone et al. [43]	5 and 10	Concrete	0.41 0.38 0.36	×	-With various HRWR dosages -10% HRK
				✓	-With various HRWR dosages -5% HRK
Boddy et al. [44]	8 and 12	Mortar	0.3	×	With various SP dosages
			0.4	✓	-With various SP dosages -12%, 8% HRK
Ding and Li [45]	5, 10, and 15	Concrete	0.35	×	-With HRWR and retarder -15% MK
				✓	-With HRWR and retarder -5%, 10% MK

Badogiannis et al. [46] and Badogiannis and Tsivilis, [47]	10 and 20	Concrete	0.5	×	-With various SP dosages -20% CMK
				✓	-With various SP dosages -10% CMK
				×	-With various SP dosages -10% MK
				-	-With various SP dosages -20% MK
Güneyisi et al. [48]	5, 10 and 15	Concrete	0.32	×	-With various SP dosages -15% MK
				✓	-With various SP dosages -5, 10% MK
Güneyisi et al. [49]	5, 10, and 15	Concrete	0.32	✓	With various HRWR dosages
Rashad et al. [8]	10 and 20	Concrete	0.541	✓	With HRWR
Mansour et al. [50]	5, 10, 15, and 20	Paste EN	196-3	✓	With SP
Hassan et al. [51]	3, 5, 8, 15, 20 and 25	Concrete	0.4	✓	With various HRWR dosages
Khatib [52]	5, 10, 15, 20, and 30	Concrete	0.5	✓	With various SP dosages
Wild et al. [53]	5-30	Concrete	0.446-0.45	✓	With various SP dosages

2.3. Setting time

Brooks et al. [31] and Brooks and Johari [32] partially replaced cement in concrete mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.28 and 14 kg/m^3 of SP were employed. The results showed that the inclusion of MK retarded the initial and final setting time. Khaleel and Abdul Razak [54,55] partially replaced cement in mortar mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.32 and various dosages of SP were employed. The results showed that the initial and final setting time increased with increasing MK content (Fig. 3). Güneyisi and Gesoğlu [38] partially replaced cement in self-compaction mortar mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.4 was used. The results showed longer initial and final setting time with the inclusion of MK. Güneyisi et al. [56] partially replaced cement in SCC mixtures with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ration of 0.32 was used. They employed 8.43 and 11 kg/m^3 of SP for control mixture and MK mixtures, respectively. The results showed longer initial and final setting time with the inclusion of MK. The inclusion of 10% MK exhibited the longer setting time followed by 5% and 15% MK, respectively.

Batis et al. [57] partially replaced cement with calcined kaolin at levels of 0%, 10%, and 20%, by weight, as well as they partially replaced cement with 20% commercial MK. The results showed longer initial and final setting time with the inclusion of calcined kaolin and commercial MK. The setting time increased with increasing calcined kaolin content. Vu et al. [58] partially replaced cement in paste

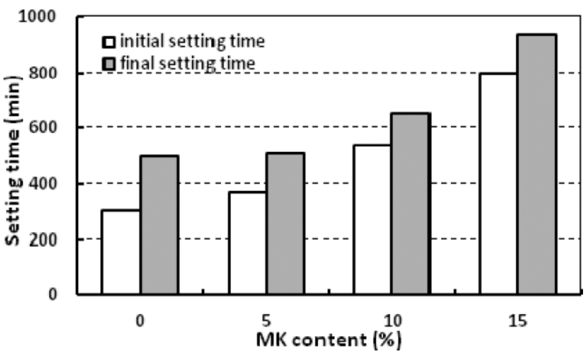

Fig. 3. Effect of MK content on the initial and final setting time of mortar mixtures [55].

mixtures with MK at levels of 0%, 10%, 15%, 20%, 25%, and 30%, by weight. W/b ratio of 0.25, 0.3, 0.33, 0.36, 0.38, and 0.41 was used for 0%, 10%, 15%, 20%, 25%, and 30% MK, respectively. They reported that the initial and final setting time of blended paste mixtures at lower replacement (10-20%) was not significantly affected. Beyond this range, the setting time significantly increased. Badogiannis et al. [59] studied the initial and final setting time of plain and blended cement paste mixtures with different types of MK at cement replacement levels of 0%, 10%, and 20%. Fixed w/b ratio of 0.4 was used. The results showed that the setting time increased with increasing MK content. At replacement level of 10%, the setting time of the blended cement paste mixtures was shorter or longer than the pure cement paste, depending on MK type. At replacement level of 20%, the setting time of the blended cement paste mixtures was longer than the pure cement paste. Justice et al. [60] studied the setting time of plain and blended cement with MK that had two different fineness of 11.1 and 25.4 m^2/g designated as MK235 and MK349, respectively. Cement was partially replaced with 8% MK. The w/b ratio that used to produce paste mixtures of normal consistency was 0.27, 0.31 and 0.34 for the control, MK235 and MK349, respectively, with various dosages of SP. The results showed that MK235 mixture exhibited longer initial and final setting time than the control, whilst paste mixture containing finer MK (MK349) exhibited slightly shorter setting time compared to the control. They also studied the initial and final setting time determined for the mixtures at a constant w/b ratio of 0.34. They found that all paste mixtures containing blended cement exhibited shorter initial and final setting time than the control. Finer MK mixture exhibited the shortest initial and final setting time followed by coarser MK.

Shekarchi et al. [61] partially replaced cement in concrete mixtures with MK at levels of 0%, 5%, 10%, and 15%. Fixed w/b ratio of 0.38 and various dosages of SP were employed. The results of the initial setting time showed a reduction of 13.15%, 14.93%, and 24.93% with the inclusion of 5%, 10%, and 15% MK, respectively. The final setting time increased by 0.63% and 5.37% with the inclusion of 5% and 15% MK, respectively, whilst 10% MK reduced it by 2.63%. Sonebi et al. [27] partially replaced cement in cement grout mixtures with MK at various levels ranging from 6% to 20%, by weight. Fixed w/b ratio of 0.4, various dosages of SP and viscosity-modifying agent were employed. They reported that the inclusion of MK reduced the setting time. Moulin et al. [62] blended 30% MK with cement. Fixed w/b ratio of 0.4 was used. They found that blended paste mixture made with MK exhibited shorter setting time compared to the control. These results were obtained using a Vicat needle apparatus according to ASTM C191. Kannan and Ganesan [63] partially replaced cement in mortar mixtures with MK at levels ranging from 5% to 30% with an increment of 5%, by weight. Fixed w/b ratio of 0.55 was used. The results showed a reduction in the initial and final setting time with the inclusion of MK. The reduction in the initial and final setting time increased as the MK content increased. Govindarajan and Gopalakrishnan [64] partially replaced cement with MK at levels of 10%, 20%, and 30%, by weight. Three types of water were used for mixing named distilled water, ground water and seawater. Fixed w/b ratio of 0.4 was used. The results showed a reduction in the initial and final setting time, for all mixing water types, with the inclusion of MK. The reduction in the setting time increased with increasing MK content. The paste mixtures mixed with seawater exhibited the highest reduction followed by the mixtures mixed with ground water and distilled water, respectively. Table 3 and Fig. 4 summarize the previous researches about the effect of MK on the setting time.

From the above review of the literature in this section, it can be noted that there are more than one factor affecting setting time namely cement content, chemical admixture type and its content, MK content and its fineness. However, many authors reported that the inclusion of MK in the mixture retarded the setting time (Fig. 4). This retardation in the setting time due to the inclusion of MK was mainly attributed to the lower cement content, science part of the cement was partially replaced with MK [31,54,55]. On the same line with this, the dispersion effects provided by MK on the cement particles could have contributed to the retardation

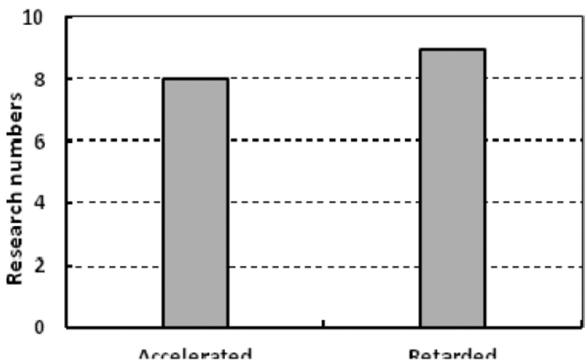

Fig. 4. Research numbers versus the effect of MK on the setting time.

Table 3. Effect of MK on the setting time.

Author	MK content (%)	w/b	Mixture type	Action	Notes
Brooks et al. [31] and Brooks and Johari [32]	5, 10, and 15	0.28	Concrete	Retarded	With SP
Khaleel and Abdul Razak [54,55]	5, 10, and 15	0.32	Mortar	Retarded	With various SP dosages
Güneyisi and Gesoğlu [38]	5, 10, and 15	0.4	Mortar	Retarded	With various SP dosages
Güneyisi et al. [56]	5, 10, and 15	0.32	Concrete	Retarded	
Batis et al. [57]	10 and 20	EN 196-3	Paste	Retarded	
Vu et al. [58]	10, 15, 20, 25, and 30	0.25-0.41	Paste	Retarded	Beyond 10-20% MK
Badogiannis et al. [59]	10 and 20	0.4	Paste	Retarded	20% MK
				Retarded or accelerated	10% MK, according to MK type
Justice et al. [60]	8	0.27-0.34	Paste	Retarded or accelerated	-With various SP dosages -According to MK fineness at the same consistency
Justice et al. [60]	8	0.34	Paste	Accelerated	With various SP dosages
Shekarchi et al. [61]	5, 10, and 15	0.38	Concrete	Accelerated	-With various SP dosages -Initial setting time
Sonebi et al. [27]	6-20	0.4	Grout	Accelerated	With various SP dosages
Moulin et al. [62]	30	0.4	Paste	Accelerated	
Kannan and Ganesan [63]	5-30	0.55	Mortar	Accelerated	
Govindarajan and Gopalakrishnan [64]	10, 20 and 30	0.4	Paste	Accelerated	

in the setting time. This is because the setting of cement paste has been postulated to result from two fundamental steps: coagulation establishing contacts between particles and the formation of hydrates in the contact zones making rigid the coagulation structure [65]. In addition, the inclusion of SP retarded setting time in which C_3S and C_3A are normally retarded by SP [66]. On the other hand, plain PC mixture, which has higher cement contend and lower dosage of SP, in most cases, the cement particles are expected to be more closely packed. This could result in greater interparticle contact, and thus speed up setting [31]. On the contrary, other authors believed that the inclusion of MK in the mixture accelerated the setting time. Moulin et al. [62] related this effect of MK on setting time to the accelerating effect of fine reactive MK on the hydration of the cement.

3. MECHANICAL STRENGTHS

3.1. Compressive strength

The pozzolanic properties of MK are documented. Kostuch et al. [67] indicated that calcium hydroxide (CH) released during cement hydration is consumed if the formation contains a sufficient quantity of HRK. The consumption of CH caused the formation of calcium silicate hydrate (CSH) and stratlingite (C_2ASH_8). De Silva and Glasser [68] reported that MK can react with sodium, potassium and CH, as well as gypsum and PC. The elimination of portlandite and extra of CSH are the keys of increasing compressive strength and durability. However in MK blended cement, MK reacts with CH to form CSH supplementary to that produced by cement hydration. This reaction becomes important within the interfacial transition zone (ITZ) located between aggregate and paste fractions. This region typically contains a high concentration of large, aligned CH crystals, which can lead to localized areas of increased porosity and lower strength [69]. MK can refine the ITZ resulting increasing strength [70]. However, there is a consensus in the literature that the pozzolanic reaction between MK and CH helps to refine the binder capillary porosity [71], with the direct consequence of improving the mechanical characteristics [40,72,73] mainly at early ages [74,75] and durability e.g. resistance to sulfate attack [73,76], chloride ingress alkali silica reaction [77,78].

Generally, the researchers are not yet to arrive at a unique conclusion regarding the optimum MK replacement percentage, and different researchers have reported different replacement levels as optimum for obtaining maximum strengths of concrete/mortar/paste. It has been reported that the optimum percentage is dependent on the cement type and content, type and dosage of admixtures, and also on the age of testing. Strength of cement paste, mortar or concrete is considered as an index of its overall quality because an increase in the strength generally leads to an improvement of almost all other properties where the compressive strength is the key parameter on determining the overall quality of any mixture. This is due to the compressive strength being directly related to the structure of hardened cement paste [79]. Thus, in many of the existing reports, the optimum MK content has been defined with regard to the compressive strength of cement paste, mortar or concrete. Some authors believed that the w/b ratio is the main factor that governs the optimum content of MK that exhibited the maximum 28 days compressive strength. Other authors believed that the calcination temperature and its period is the main factor that governs the optimum MK content. Others believed that the chemical composition may have major factor that affecting the optimum MK content. In general, there are numerous theories and experimental results in the literature related to the optimum MK content, many of that highlight the pozzolanic activity is the dominating; whereas many others report that the physical effect is the dominating one. These topics have been under study for many years, and a brief review of some of the existing works exhibited that, through some are in agreement, there are many others that are in opposition. However, in this part, the previous works carried out on the optimum MK replacement level that leads to the maximum 28 days compressive strength were reviewed.

3.1.1. Effect of w/b ratio

3.1.1.1. Optimum MK at levels of 5-8% in concrete

Bai et al. [80] partially replaced cement in concretes with MK at levels of 1%, 2%, 3%, 4%, and 5%. Four w/b ratios of 0.3, 0.4, 0.5, and 0.6 were used. The 28 days compressive strength indicated that 5% MK exhibited the highest compressive strength among all w/b ratios. At w/b ratio of 0.3, the enhancement in the 28 days compressive strength was 0.12%, 5.52%, 7.53%, and 10.66% with the inclusion of 1%, 3%, 4%, and 5% MK, respectively, whilst the inclusion of 2% reduced it by 0.88%. At w/b ratio of 0.6, the enhancement in the 28 days compressive strength was 14.13%, 19.33%, 25.28%, 39.78%, and 54.27% with the inclusion of 1%, 2%,

Table 4. 5-8% optimum MK replacement level versus w/b ratio for concrete.

Author	MK content (%)	W/b	Optimum content	Notes
Bai et al. [80]	1, 2, 3, 4, and 5	0.3, 0.4, 0.5, and 0.6	5	
Shelorkar and Jadhao [81]	4, 6, and 8	0.29	8	
Kim et al. [82]	5, 7.5, 15, and 20	0.25	5	With various SP dosages
Hooton et al. [83]	8 and 12	0.3, 0.4	8	

3%, 4%, and 5% MK, respectively. Shelorkar and Jadhao [81] partially replaced cement in concretes with MK at levels of 4%, 6%, and 8%, by weight. Fixed w/b ratio of 0.29 was used. The results indicated an enhancement in the 28 days compressive strength with the inclusion of MK. The inclusion of 8% MK exhibited the highest 28 days compressive strength followed by 6% and 4%, respectively. The enhancement in the 28 days compressive strength was 8.69%, 13.21%, and 21.74% with the inclusion of 4%, 6%, and 8% MK, respectively. Kim et al. [82] investigated the strength properties of HSCs using Korean MK. Cement was partially replaced with MK at levels of 0%, 5%, 10%, 15%, and 20%. Fixed w/b ratio of 0.25 and various dosages of SP were employed. Each mixture containing 141kg/m^3 FA. The results indicated that 5% cement replacement level with MK exhibited the highest compressive strength at age of 28 days. Hooton et al. [83] studied the effect of HRK on the compressive strength of concrete. Cement was partially replaced with HRK at levels of 0%, 8%, and 12%, by weight. Two different w/b ratios of 0.3 and 0.4 were used. The results indicated that 8% HRK exhibited 28 days compressive strength higher than that of 12% replacement in both w/b ratios. Table 4 and Fig. 5 summarize the previous researches that indicated 5-8% MK exhibited the highest 28 days compressive strength versus w/b ratio.

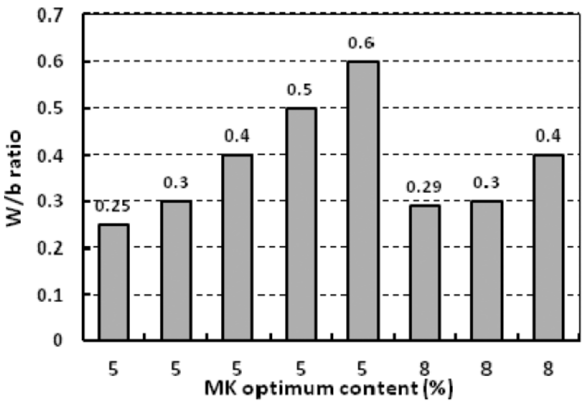

Fig. 5. 5-8% optimum MK replacement level versus w/b ratio for concrete.

3.1.1.2. Optimum MK at levels of 10-12.5% in concrete

Rashad [9] partially replaced cement in concrete with 10% MK, by weight. Fixed w/b ratio of 0.45 and fixed dosage of SP were employed. The results indicated 33.9% enhancement in the 28 days compressive strength with the inclusion of 10% MK. Brooks and Johari [32] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ration of 0.28 and fixed dosage of SP were employed. The results indicated that 10% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 5.17%, 19.54%, and 18.95% with the inclusion of 5%, 10%, and 15% MK, respectively. Dinakar et al. [35] partially replaced cement in HSCs with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.3 and various dosages of SP were employed. The results indicated that 10% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 4.1% and 7.55% with the inclusion of 5% and 10% MK, respectively, whilst the inclusion of 15% MK reduced it by 0.9%. Badogiannis et al. [46] and Badogiannis and Tsivilis [47] studied the MK, which is derived from poor Greek kaolin as cement replacement in concretes. Cement was partially replaced with MK at levels of 0%, 10%, and 20%, by weight. Fixed w/b ratio of 0.5 and various dosages of SP were employed. The results showed that 10% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 43.19% and 38.71% with the inclusion of 10% and 20% MK, respectively. Poon et al. [84] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, and 20%, by weight. Fixed w/b of

0.3 and various dosages of SP were employed. The results indicated that 10% MK exhibited the highest 28 days compressive strength. They also reported that 10% MK exhibited the highest 28 days compressive strength at 0.5 w/b ratio without any dosage of SP.

Ruo et al. [85] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.33 and fixed dosage of SP were employed. The results indicated higher compressive strength with the inclusion of MK. The inclusion of 10% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 8.89%, 14.53%, 9.92%, and 5.27% with the inclusion of 5%, 10%, 15%, and 20% MK, respectively. Huat [86] studied the compressive strength of different concrete mixtures modified with calcined kaolin at 750 °C for 3 h. Cement was partially replaced with MK at levels of 0%, 5%, 10%, 15%, 20%, and 30%, by weight. Fixed w/b ratio of 0.56 was used. The results indicated that 10% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 9.71%, whilst the inclusion of 5%, 15%, 20%, and 30% MK reduced it by 5.82%, 7.28%, 19.42%, and 27.91%, respectively. Khatib [52] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, 15%, 20%, and 30%, by weight. Fixed w/b ratio of 0.5 and various dosages of SP were employed. The specimens were cured in water at low temperature of 5 °C. The compressive strength results indicated that 10% MK exhibited the highest 28 days compressive strength followed by 20% and 15%, respectively. The enhancement in the 28 days compressive strength was 0.36%, 12.52%, 0.59%, 3.33%, and 3.33% with the inclusion of 5%, 10%, 15%, and 20% MK, respectively, whilst the inclusion of 30% MK reduced it by 27.36%.

Rashad et al. [8] and Seleem et al. [14] partially replaced cement in concretes with MK at levels of 0%, 10%, and 20%, by weight. Fixed w/b ratio of 0.541 and fixed dosage of HRWR of 7 l/m^3 were employed. The results indicated that 10% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 2.6% with the inclusion of 10% MK, whilst the inclusion of 20% MK reduced it by 3.9%. Siddique and Kaur [33] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, and 15%, by weight. W/b and SP were fixed for all mixtures at 0.45 and 4.95 l/m^3, respectively. The results indicated that 10% MK exhibited the highest 35 days compressive strength. The enhancement in the 35 days compressive strength was approximately 6.64% and 15.77% with the inclusion of 5% and 10% MK, respectively, whilst the inclusion of 15% MK exhibited comparable 35 days compressive strength to the control. Ghorpade and Rao [87] partially replaced cement in HPCs with MK at levels of 0%, 10%, 20%, and 30%, by weight. Various w/b ratios of 0.3, 0.35, 0.4, 0.45, and 0.5 and fixed dosage of 2.5%, by binder weight, of SP were employed. The results indicated that 10% MK exhibited the highest compressive strength among all w/b ratios. At w/b ratio of 0.3, the enhancement in the compressive strength was 12.76% with the inclusion of 10% MK, whilst the inclusion of 20% and 30% MK reduced it by 3.43% and 7.56%, respectively. At w/b ratio of 0.5, the enhancement in the compressive strength was 11.13% with the inclusion of 10% MK, whilst the inclusion of 20% and 30% MK reduced it by 3.35% and 6.03%, respectively.

Ramezanianpour and Jovein [39] partially replaced cement in concretes with MK at levels of 0%, 10%, 12.5%, and 15%, by weight. They used different w/b ratios of 0.4 and 0.5. The polycarboxylic acid-based SP was employed to achieve the desired workability. The results showed that 10% MK exhibited the highest 28 days compressive strength at w/b ratio of 0.5, whilst the inclusion of 15% MK exhibited the highest 180 days compressive strength. The enhancement in the 28 days compressive strength was 15.49% and 12.68% with the inclusion of 10% and 12.5% or 15% MK, respectively. At w/b ratio of 0.4, the inclusion of 12.5% MK exhibited the highest compressive strength at ages of 28 and 180 days. The enhancement in the 28 days compressive strength was 66.1%, 77.27%, and 71.21% with the inclusion of 10%, 12.5% and 15% MK, respectively. Roske [88] partially replaced cement in concretes with MK at levels of 0%, 8%, 10%, and 12%, by weight. Fixed w/b ratio of 0.35

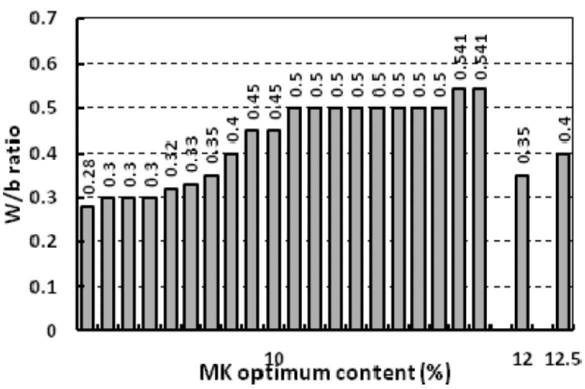

Fig. 6. 10-12.5% optimum MK replacement level versus w/b ratio for concrete.

Table 5. 10-12.5% optimum MK replacement level versus w/b ratio for concrete.

Author	MK content	W/b	Optimum content	Notes
Brooks and Johari [32]	0, 5, 10, and 15	0.28	10	with SP
Dinakar et al. [35]	0, 5, 10, and 15	0.3	10	with SP
Badogiannis et al. [46] and Badogiannis and Tsivilis [47]	0, 10, and 20	0.5	10	with various dosages of SP
Poon et al. [84]	0, 5, 10, and 20	0.3	10	with various dosages of SP
Poon et al. [84]	0, 5, 10, and 20	0.5	10	
Ruo et al. [85]	0, 5, 10, and 20	0.33	10	With SP
Huat [86]	0, 5, 10, 15, 20, and 30	0.56	10	
Khatib [52]	0, 5, 10, 15, 20, and 30	0.5	10	with various dosages of SP
Rashad et al. [8] and Seleem et al. [14]	0, 10 and 20	0.541	10	with HRWR
Siddique and Kaur [33]	0, 5, 10, and 15	0.45	10	-Strength at 35 days -with SP
Ghorpade and Rao [87]	0, 10, 20, and 30	0.3, 0.35, 0.4, 0.45, and 0.5	10	with 2.5% SP
Ramezanianpour and Jovein [39]	0, 10, 12.5, and 15	0.5 0.4	10 12.5	With SP
Roske [88]	0, 8, 10, and 12	0.35	12	With SP

was used with fixed dosage of SP. The results indicated that 12% MK exhibited the highest 28 days compressive strength. Table 5 and Fig. 6 summarize the previous researches that indicated 10-12.5% exhibited the highest 28 days compressive strength versus w/b ratio.

From the above review of the literature in this section, it can be noted that most of authors believed that 10% MK as cement replacement in concrete exhibited the highest 28 days compressive strength at w/b ratios of 0.5-0.54 (Fig. 7) with the inclusion of SP. W/b ratios of 0.28-0.35 came in the second place, whilst w/b ratios of 0.4-0.45 came in the last place.

3.1.1.3. Optimum MK at level of 15% in concrete

Bai et al. [89] partially replaced cement in concretes with MK at levels of 0%, 2.5%, 5%, 7.5%, 10%, 12.5%, and 15%, by weight. Various w/b ratios of 0.4, 0.5 and 0.6 were used. The results indicated that 15% MK exhibited the highest 28 days compressive strength at all w/b ratios. At w/b ratio of 0.6, the enhancement in the 28 days compressive strength was approximately 6.23%, 18.74%, 27.1%, 33.32%, 42.69%, and 45.83 with the inclusion of 2.5%, 5%, 7.5%, 10%, 12.5%, and 15% MK, respectively. At w/b ratio of 0.4, the enhancement in the 28 days compressive strength was approximately 4.22%, 8.12%, 18.74%, 20%, 20%, and 26.25% with the inclusion of 2.5%, 5%, 7.5%, 10%, 12.5%, and 15% MK, respectively. Qian and Li [34] partially replaced cement in HPCs with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.38, fixed dosage of SP and fixed dosage of retarder were employed. The results indicated that 15% MK exhibited the highest 28 days com-

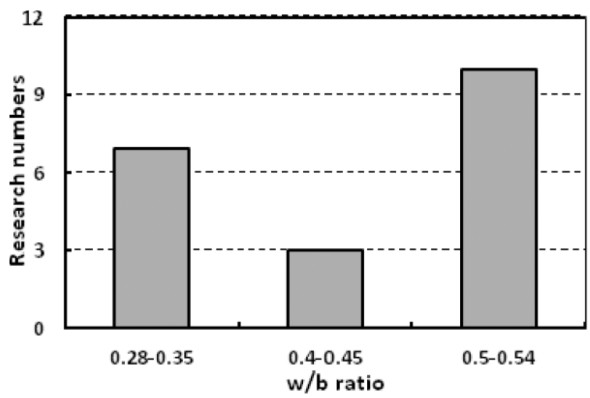

Fig. 7. 10-12.5% optimum MK replacement level versus w/b ratio for concrete.

pressive strength. The enhancement in the 28 days compressive strength was 2%, 32%, and 38% with the inclusion of 5%, 10%, and 15% MK, respectively. Ding and Li [45] studied the compressive strength of concrete at different ages when cement was partially replaced with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.35, fixed dosage of HRWR and fixed dosage of retarder agent were employed. They reported that by increasing the replacement level from 5% to 15%, the strengthening effect of MK increased. The compressive strength of MK5, MK10, and MK15 were approximately 28%, 38%, and 45% higher than that of the control at age of 3 days; 25%, 28%, and 53% higher at age of 28 days; and approximately 4%, 16%, and 21% higher at age of 65 days.

Phelps [90] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, and 15%, by weight. The optimum compressive strength was studied at w/b ratios of 0.25, 0.3, and 0.35 with various dosages of HRWR. The results indicated that 15% MK exhibited the highest compressive strength at all w/b ratios. Behfarnia and Farshadfar [36] partially replaced cement in SCCs with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.38 and various dosages of HRWR were employed. The results indicated that 15% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 5.02%, 13.57%, and 25.84% with the inclusion of 5%, 10%, and 15% MK, respectively. John [91] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.45 was used. The results indicated that 15% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 3.18%, 17.98%, 39.2%, and 22.81% with the inclusion of 5%, 10%, 15%, and 20% MK, respectively. Khatib [41] partially replaced cement in concretes with MK at levels of 0%, 5%, 7.5%, 12.5%, 15%, and 20%, by weight. Fixed w/b ratio of 0.3 and fixed dosage of SP of 1.36%, by binder weight, were employed. The results indicated that 15% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 9.68%, 23.15%, 29%, 35.7%, and 25.87% with the inclusion of 5%, 7.5%, 12.5%, 15%, and 20% MK, respectively. Parande et al. [92] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.45 was used. The results indicated that 15% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 9.44%, 17.41%, 29.63%, and 5.55% with the inclusion of 5%, 10%, 15%, and 20%, respectively.

Shekarchi et al. [61] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.38 and various dosages of SP were employed. The results indicated that 15% MK exhibited the highest 28 days compressive strength followed by 5% and 15%, respectively. The enhancement in the 28 days compressive strength was 7.2%, 10%, 19.6%, and 25.8% with the inclusion of 5%, 10%, and 15% MK, respectively. Güneyisi et al. [48,56] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.32 was used. 8.43 kg/m^3 of SP was used for the control mixture, whilst 11 kg/m^3 was used for MK concrete mixtures. The results indicated that 15% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 19%, 12.98%, and 21.88% with the inclusion of 5%, 10%, and 15% MK, respectively. In another similar investigation, Güneyisi et al. [49] partially replaced cement in SCCs with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ration of 0.32 was used. They employed 8.43 and 11 kg/m^3 of HRWR for control mixture and MK mixtures, respectively. The results indicated that 15% MK exhibited the highest 28 days compressive strength. Güneyisi et al. [93] partially replaced cement in concretes with MK at levels of 0%, 5%, and 15%, by weight. W/b rations of 0.25 and 0.35 with various dosages of SP were employed. The compressive strength results at age of 28 days indicated that 15% exhibited the highest compressive strength at both w/b ratios. Md et al. [94] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.33 and maximum 2% of SP were employed. The results showed an enhancement in the 28 days compressive strength with the inclusion of MK. The inclusion of 15% MK exhibited the highest compressive strength followed by 10% and 5%, respectively.

Valipour et al. [95] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.4 and various dosages of SP were employed. The results indicated that 15% MK exhibited the highest 28 days compressive strength. Ramezanianpour and Jovein [39] partially replaced cement in concretes with MK at levels of 0%, 10%, 12.5%, and 15%, by weight. Fixed w/b ratio of 0.35 was used. The polycarboxylic acid-based SP was employed to achieve the desired workability. The results indicated that 15% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 13.56%, 8.47%, and 9.49% with the inclusion of 10%, 12.5%, and 15% MK, respectively. The inclusion of 10% MK exhibited the highest compressive strength at age of 180 days followed by 12.5% and 15%, respectively. Zeljkovic [96] studied the compressive strength of concretes modified with MK at ages reached to 120 days. Cement was partially replaced with MK at levels of 0%, 10%, 15%, and 20%. Fixed w/b ratio of 0.4 was used. The compressive strength results indicated that MK15 and MK20 had the same identical performance in compressive strength and exhibited the highest compressive strength at age of 28 days. Table 6 and Fig. 8 summarize the previous researches that indicated 15% exhibited the highest 28 days compressive strength versus w/b ratio.

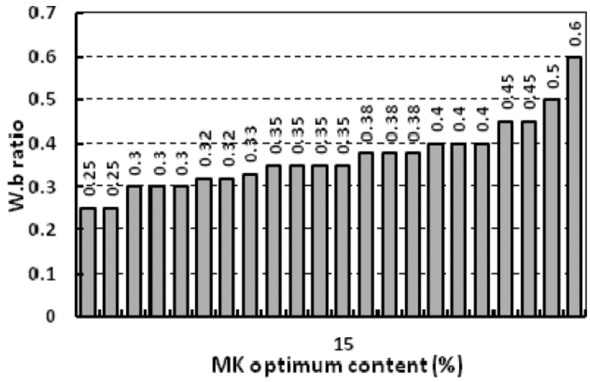

Fig. 8. 15% optimum MK replacement level versus w/b ratio for concrete.

From the above review of the literature in this section, it can be noted that most of authors believed that 15% MK as cement replacement in concrete exhibited the highest 28 days compressive

Table 6. 15% optimum MK replacement level versus w/b ratio for concrete.

Author	MK content (%)	W/b	Optimum content	Notes
Bai et al. [89]	0, 2.5, 5, 7.5, 10, 12.5, and 15	0.4, 0.5, 0.6	15	
Qian and Li [34]	0, 5, 10, and 15	0.38	15	With SP and retarder
Ding and Li [45]	0, 5, 10, and 15	0.35	15	With HRWR and redarted
Phelps [90]	0, 5, 10, and 15	0.25, 0.3 and 0.35	15	With various HRWR dosages
Behfarnia and Farshadfar [36]	0, 5, 10, and 15	0.38	15	With varying dosages of HRWR
John [91]	0, 5, 7.5, 15, and 20	0.45	15	
Khatib [41]	0, 5, 7.5, 15, and 20	0.3	15	With SP
Parande et al. [92]	0, 5, 10, 15, and 20	0.45	15	
Shekarchi et al. [61]	0, 5, 10, and 15	0.38	15	
Güneyisi et al. [48,56]	0, 5, 10, and 15	0.32	15	With various SP dosages
Güneyisi et al. [49]	0, 5, 10, and 15	0.32	15	With various HRWR dosages
Güneyisi et al. [93]	0, 5, and 15	0.25, 0.35	15	With various SP dosages
Md et al. [94]	0, 5, 10, and 15	0.33	15	With SP
Valipour et al. [95]	0, 5, and 15	0.4	15	With various SP dosages
Ramezanianpour and Jovein [39]	0, 10, 12.5, and 15	0.35	15	With SP
Zeljkovic [96]	10, 15, and 20	0.4	15 and 20 (same identical performance)	

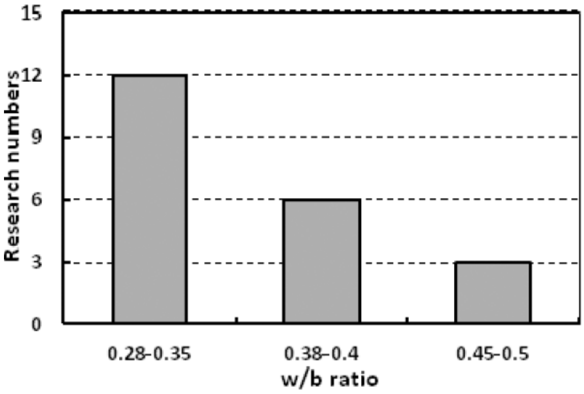

Fig. 9. Research numbers versus w/b ratio at 15% optimum MK replacement level for concrete.

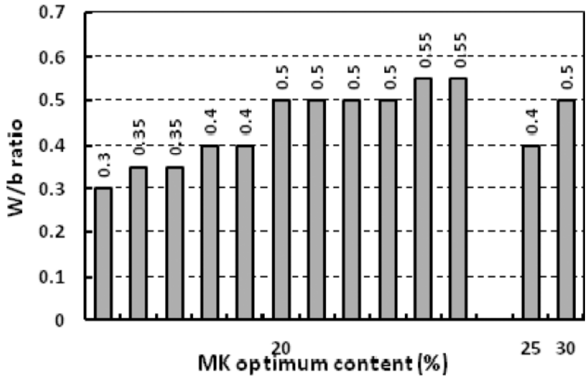

Fig. 10. 20-30% optimum MK replacement level versus w/b ratio for concrete.

strength at w/b ratios of 0.28-0.35 (Fig. 9) with the inclusion of SP. W/b ratios of 0.38-0.4 came in the second place, whilst w/b ratios of 0.45-0.5 came in the last place.

3.1.1.4. Optimum MK at levels of 20-30% in concrete

Kostuch et al. [67] have reported that: (i) CH was significantly reduced with age for replacement of cement with MK at levels of 10% and 20%; and (ii) 20% replacement level was required for fully remove all the CH in concrete at age of 28 days. Poon et al. [97] prepared HSCs and NSCs with blended cement. Cement was partially replaced with MK at levels of 0%, 5%, 10%, and 20%, by weight. Various dosages of SP were employed. For HSCs, the results indicated that 20% MK exhibited the highest 28 days compressive strength at w/b ratio of 0.3. The enhancement in the 28 days compressive strength was 24.91%, 43.31%, and 52.85% with the inclusion of 5%, 10%, and 20% MK, respectively. For NSCs, the inclusion of 20% MK exhibited the highest 28 days compressive strength at w/b ratio of 0.5. The enhancement in the 28 days compressive strength was 13.69%, 32.96%, and 63.13% with the inclusion of 5%, 10%, and 20% MK, respectively. Badogiannis et al. [46] and Badogiannis and Tsivilis [47] studied the compressive strength of MK concretes. Cement was partially replaced with commercial MK at levels of 0%, 10%, and 20%, by weight. Fixed w/b ratio of 0.5 was used with various dosages of SP. The results indicated that 20% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 32.62% and 35.48% with the inclusion of 10% and 20% MK, respectively. Khatib and Hibbert [98] partially replaced cement in concretes with MK at levels of 0%, 10%, and 20%, by weight. Fixed w/b ratio of 0.5 and various dosages of SP were employed. The results showed that 20% MK exhibited the highest 28 days compressive strength. Güneyisi and Mermerdas [99] and Güneyisi et al. [100] partially replaced cement in concretes with MK at levels of 0%, 10%, and 20%, by weight. Two different w/c ratios of 0.35 and 0.55 with various dosages of HRWR were employed. The results indicated that 20% MK exhibited the highest 28 days compressive strength. Hassan et al. [51] partially replaced cement in SCCs with MK at levels of 0%, 3%, 5%, 8%, 11%, 15%, 20%, and 25%. Fixed w/b ratio of 0.4 and various dosages of HRWR were employed. The results indicated that 20% and 25% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 3.15%, 10.41%, 6.29%, 11.14%, and 18.4% with the inclusion 5%, 8%, 11%, 15%, and 20% or 25% MK, respectively, whilst the inclusion of 3% MK decreased it by 4.6%. Paiva et al. [42] partially replaced cement in concretes with MK at levels of 0%, 10%, 20%, and 30%, by weight. Fixed w/b ratio of 0.6 was used. The HRWR dosages were 0, 0.08, 0.15, and 0.2 for 0%, 10%, 20%, and 30% MK, respectively. The results indicated that 30% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 4.46%, 17%, and 18.37% with the inclusion of 10%, 20%, and 30% MK, respectively. Table 7 and Fig. 10 summarize the previous researches that indicated 20-30% exhibited the highest 28 days compressive strength versus w/b ratio.

From the above review of the literature in this section, it can be noted that most of authors believed that 20% MK as cement replacement in concrete exhibited the highest 28 days compressive strength at w/b ratios of 0.5-0.55 (Fig. 11) with the inclusion of SP or HRWR. W/b ratios of 0.3-0.35

Table 7. 20-30% optimum MK replacement level versus w/b ratio for concrete.

Author	MK content (%)	W/b	Optimum content	Notes
Zeljkovic [96]	0, 10, 15, and 20	0.4	15 and 20	
Poon et al. [97]	0, 5, 10, and 20	0.3	20	-With various SP dosages -HSCs
Poon et al. [97]	0, 5, 10, and 20	0.5	20	-With various SP dosages -NSCs
Badogiannis et al. [46] and Badogiannis and Tsivilis [47]	0, 10, and 20	0.5	20	With various SP dosages
Khatib and Hibbert [98]	0, 10, and 20	0.5	20	With varying dosages of SP
Güneyisi and Mermerdas [99] and Güneyisi et al. [100]	0, 10, and 20	0.35 and 0.55	20	With various HRWR dosages
Hassan et al. [51]	0, 3, 5, 8, 11, 15, 20, and 25	0.4	20 and 25	With various HRWR dosages
Paiva et al. [42]	0, 10, 20, and 30	0.5	30	With various HRWR dosages

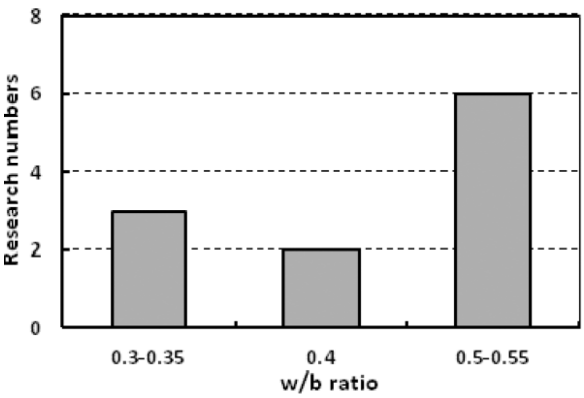

Fig. 11. Research numbers versus w/b ratio at 20% optimum MK replacement level for concrete.

came in the second place, whilst w/b ratio of 0.4 came in the last place. With a general scope of Section 3.1.1, Fig. 12 shows the optimum MK replacement level which exhibited the highest concrete compressive strength at age of 28 day versus w/b ratio at all replacement levels, whilst Fig. 13 shows the research numbers versus different MK replacement levels coupled with w/b ratios. It can be note that at w/b ratios ranging from 0.28 to 0.35 with the inclusion of SP, it is better to replace cement in concrete with 15% MK, by weight, to produce the highest 28 days compressive strength. On

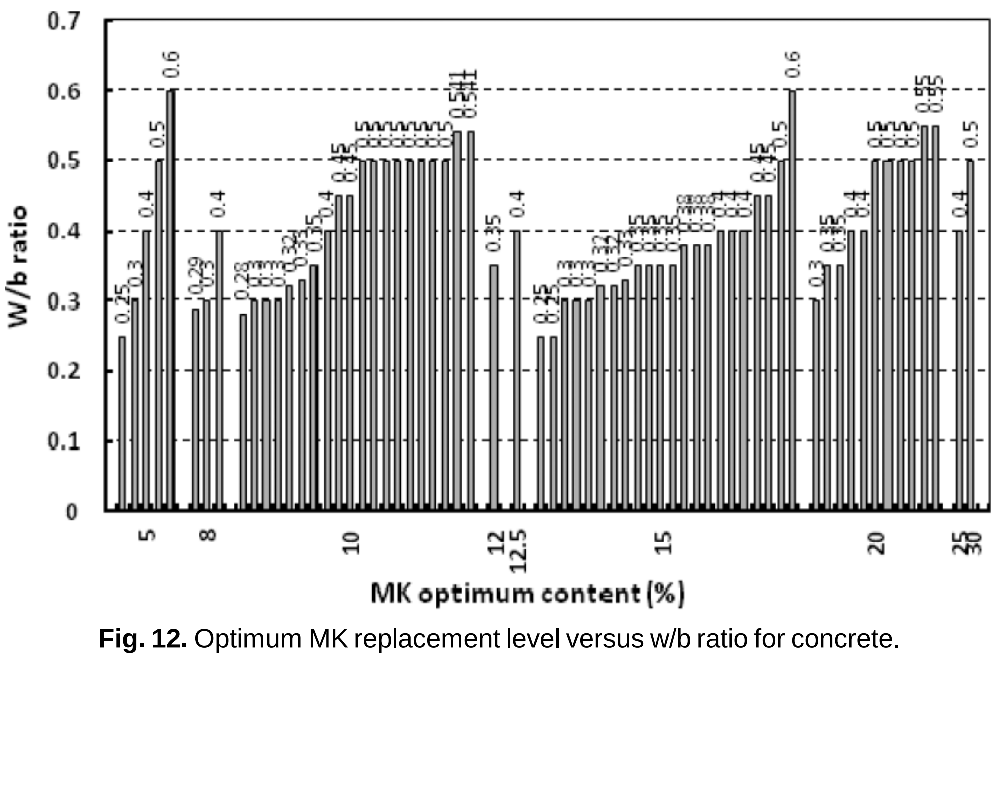

Fig. 12. Optimum MK replacement level versus w/b ratio for concrete.

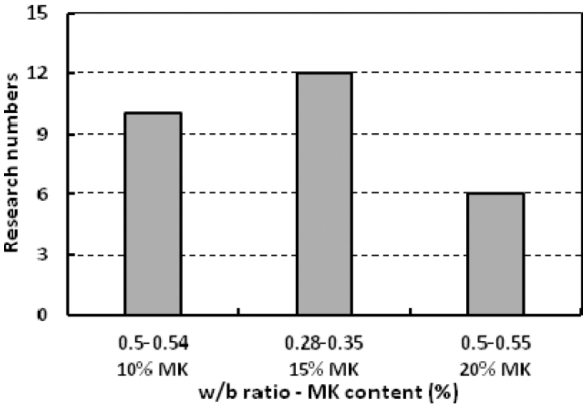

Fig. 13. Research numbers versus different optimum MK replacement levels coupled with w/b ratios for concrete.

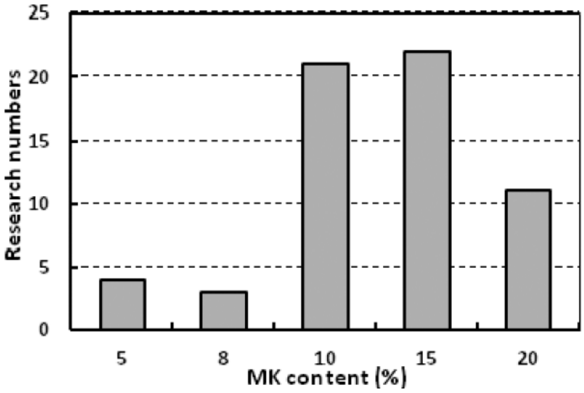

Fig. 14. Research numbers versus optimum MK content for concrete.

the other hand, at w/b ratios ranging from 0.5-0.55 with the inclusion of SP, it is better to replace cement with 10% MK, by weight, to get the highest 28 days compressive strength, whilst 20% MK came in the second place. However, in general, regardless the effect of w/b ratio, most of authors believed that 15% and 10% MK is the optimum replacement level of cement to get the highest 28 days compressive strength followed by 20%, 5% and 8%, respectively, (Fig. 14).

3.1.1.5. Optimum MK in mortar

Rabehi et al. [101] produced MK by thermally treatment of kaolin. They partially replaced cement in mortars with calcined kaolin at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.5 was used. The results indicated that 5% MK exhibited the highest compressive strength. Goel [102] partially replaced cement in mortars with MK at levels of 0%, 5%, and 10%, by weight. W/b ratios of 0.46 and 0.5 were used. The results indicated that 5% MK exhibited the highest compressive strength at w/b ratio of 0.46, whilst the inclusion of 10% MK exhibited the highest compressive strength at w/b ratio of 0.5. Said-Mansour et al. [103] partially replaced cement in mortars with MK at levels of 0%, 10%, 20%, and 30%, by weight. Fixed w/b ratio of 0.5 was used. 0.9% of SP was used for mixture containing 30% MK. The results indicated that 10% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 14.02% and 8.78% with the inclusion of 10% and 20% MK, respectively, whilst the inclusion of 30% MK reduced it by 5.42%. Potgieter-Vermaak and Potgieter [104] investigated the optimum compressive strength, at age of 28 days, of mortars containing 0%, 10%, 20%, and 30% South African MK as partially cement replacement. Fixed w/b ratio of 0.375 was used. The results indicated that 10% MK exhibited the highest 28 days compressive strength. Khaleel and Abdul Razak [55] partially replaced cement in mortars with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.32 and various dosages of SP were employed. The results showed higher compressive strength with the inclusion of MK. The inclusion of 10% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was approximately 28.57%, 32.86%, and 26.43% with the inclusion of 5%, 10%, and 15% MK, respectively.

Soriano et al. [105] partially replaced cement in mortars with 0% and 15% MK, by weight. Fixed w/b ratio of 0.5 was used. There were two curing temperatures of 5 °C and 20 °C. The results indicated an enhancement in the compressive strength at ages of 1, 2, and 7 days with the inclusion of MK at curing temperature of 5 °C, whilst it decreased at age of 28 days with the inclusion of MK. At curing temperature of 20 °C, the compressive strength increased with the inclusion of MK at ages of 1, 7, and 28 days, whilst it decreased at age of 2 days. The enhancement in the 28 days compressive strength was 20.48%. Courard et al. [40] partially replaced cement in mortars with MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.5 was used. The results indicated that 15% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 14.21%, 23.16%, 24.91%, and 20% with the inclusion of 5%, 10%, 15%, and 20% MK, respectively. Parande et al. [92] partially replaced cement in mortars with MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.4 was used. The results indicated that 15% MK exhibited the highest compressive strength.

The enhancement in the 28 days compressive strength was 30%, 40%, 50%, and 45% with the inclusion of 5%, 10%, 15%, and 20% MK, respectively. Vu et al. [58] partially replaced cement in mortars with MK at levels of 0%, 5%, 10%, 15%, 20%, 25%, and 30%, by weight. W/b ratios ranging from 0.4 to 0.53 were used. 1.3% and 0.5% of SP were employed for mixtures containing w/b ratios of 0.4 and 0.44, respectively. The results indicated that 15% MK exhibited the highest 28 days compressive strength at w/b ratios of 0.44 and 0.47, whilst the inclusion of 20% MK exhibited the highest 28 days compressive strength at w/b ratios of 0.4, 0.5, and 0.53. The enhancement in the 28 days compressive strength at w/b ratio of 0.4 was 7.27%, 9.32%, 11.36%, and 8.41% with the inclusion of 5%, 10%, 15%, 20%, and 25%, respectively, whilst the inclusion of 30% MK reduced it by 4.32%. The enhancement in the 28 days compressive strength at w/b ratio of 0.53 was 6.35%, 10.49%, 11.05%, and 5.25% with the inclusion of 5%, 10%, 15%, 20%, and 25%, whilst the inclusion of 30% MK reduced it by 1.38%.

Morsy et al. [106,107] partially replaced cement in mortars with MK at levels of 0%, 5%, 10%, 20%, and 30%, by weight. Fixed flow of 94±5% was used. This flow satisfied w/b ratio of 0.9957. The results indicated that 20% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 22.51%, 27.58%, 91.56%, and 21.37% with the inclusion of 5%, 10%, 20%, and 30% MK, respectively. Gonçalves el al. [108] partially replaced cement in mortars with MK at levels of 0%, 10% and 20%, by weight. Fixed w/b ratio of 0.5 was used. 0.2% of SP was added to the mixture containing 20% MK. The results indicated that 20% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 13.21% and 15.62% with the inclusion of 10% and 20% MK, respectively. Khatib et al. [109] partially replaced cement in mortars with MK at levels ranging from 10% to 50% with an increment of 10%. Fixed w/b ratio of 0.5 was used. The results showed an increase in the compressive strength with the inclusion of 10%, 20%, and 30% MK, whilst the inclusion of 40% MK showed slightly lower compressive strength than the control. The inclusion of 50% MK showed approximately 20% reduction in the compressive strength compared to the control. The inclusion of 20% MK indicated the optimum content where it exhibited the highest compressive strength. Gonçalves et al. [110] partially replaced cement in mortars with commercial MK at levels of 0%, 10%, 20%, 30%, and 40%, by weight. Fixed w/b ratio of 0.5 was used. The results showed an increase in the compressive strength with the inclusion of commercial MK. The inclusion of 20% commercial MK showed the highest compressive strength.

Roy et al. [73] partially replaced cement with MK at levels of 0%, 7.5%, 15%, and 22.5%, by weight. Fixed w/b ratio of 0.36 was used. The results indicated that 7.5% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 4.31% with the inclusion of 7.5% MK, whilst the inclusion of 15% and 22.5% MK reduced it by 3.39% and 0.82%, respectively. They also measured the 28 days compressive strength at w/b ratio of 0.4 for 15% and 22.5% MK mixtures. The results indicated that 22.5% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 7.49% with the inclusion of 22.5% MK, whilst the inclusion of 15% MK reduced it by 8.37%. Kannan and Ganesan [63] partially replaced cement in mortars with MK at levels ranging from 5% to 30% with an increment of 5%, by weight. Fixed w/b ratio of 0.55 was used. The results showed an enhancement in the compressive strength with the inclusion of MK. The inclusion of 25% MK indicated the optimum replacement level in which it exhibited the highest 28 days compressive strength. Tironi et al. [111] partially replaced cement in mortars with 30% MK, by weight. Fixed w/b ratio of 0.5 was used. The results showed 3.22% and 28.95% enhancement in the compressive strength at ages of 7 and 28 days, respectively, with the inclusion of MK. Antoni et al. [112] partially replaced cement in mortars with 30% MK, by weight. Fixed w/b ratio of 0.5 was used. The results showed 33% reduction in the 1 day compressive strength with the inclusion of MK, whilst the inclusion of MK enhanced the compressive strength at ages of 7, 28, and 90 days by 7%, 19% and 4%, respectively. Table 8 and Fig. 15 summarize the previous researches about the optimum MK replacement level versus w/b ratio in mortar.

From the above review of the literature in this section, it can be noted that most of authors believed that 20% MK as cement replacement in mortar exhibited the highest 28 days compressive strength at w/b ratios of 0.5-0.53 without SP. Other authors believed that 15% MK is the optimum replacement level of cement in mortar at w/b ratios of 0.4-0.53, whilst 10% MK is the optimum content at w/b ratios of 0.375-0.5. However, in general, regardless the effect of w/b ratio, most of authors believed that 20% MK is the optimum replacement level of

Table 8. Optimum MK replacement level versus w/b ratio for mortar.

Author	MK content (%)	W/b	Optimum content	Notes
Rabehi et al. [101]	0, 5, 10, 15, and 20	0.5	5	
Goel [102]	0, 5 ,and 10	0.46	5	
		0.5	10	
Said-Mansour et al. [103]	0, 10, 20, and 30	0.5	10	SP for 30% MK
Potgieter-Vermaak and Potgieter [104]	0, 10, 20, and 30	0.375	10	
Khaleel and Abdul Razak [55]	0, 5, 10, and 15	0.32	10	With various SP dosages
Soriano et al. [105]	0 and 15	0.5	15	Curing at 20 °C
Courard et al. [40]	0, 5, 10, 15, and 20	0.5	15	
Parande et al. [92]	0, 5, 10, 15, and 20	0.4	15	
Vu et al. [58]	0, 5, 10, 15, 20, 25, and 30	0.44 and 0.47	15	
		0.4, 0.5 and 0.53	20	
Morsy et al [106] and Morsy et al. [107]	0, 5, 10, 20, and 30	~1	20	
Gonçalves el al. [108]	0, 10, and 20	0.5	20	SP for 20% MK
Khatib et al. [109] 0, 10-50	0.5 20			
Gonçalves et al. [110]	0, 10, 20, 30, and 30	0.5	20	
Roy et al. [73]	0, 7.5, 15, and 22.5	0.36	7.5	
		0.4	22.5	
Kannan and Ganesan [63]	0, 5-30	0.55	25	

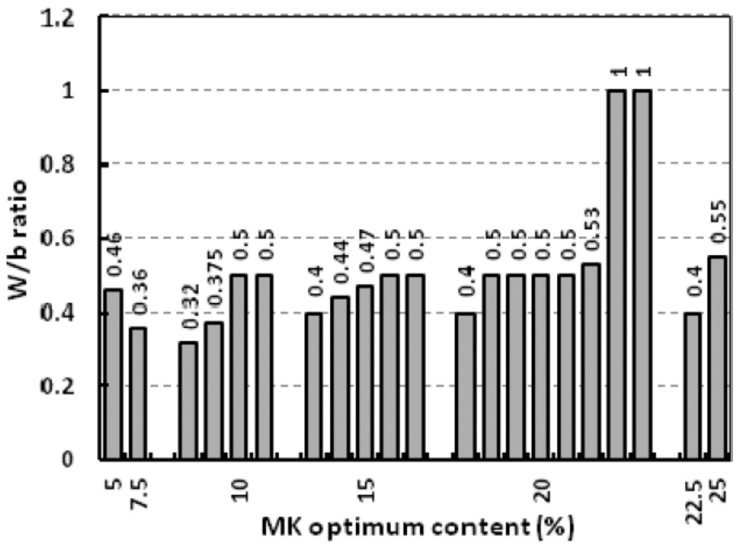

Fig. 15. Optimum MK replacement level versus w/b ratio for mortar.

cement to get the highest 28 days compressive strength followed by 15% and 10%, respectively, (Fig. 16).

3.1.1.6. Optimum MK in paste

Poon et al. [113] partially replaced cement in pastes with MK at levels of 0%, 5%, 10%, and 20%, by

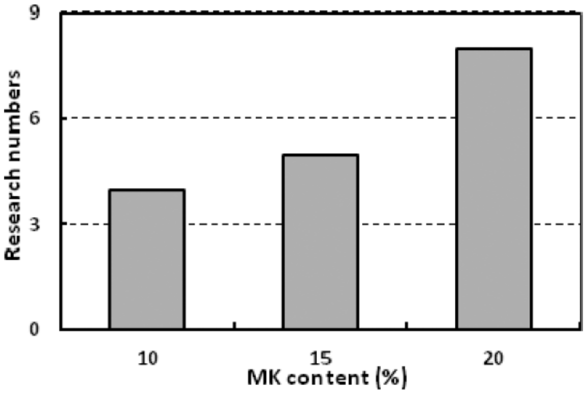

Fig. 16. Research numbers versus optimum MK content for mortar.

weight. Fixed w/b ratio of 0.3 and small amount of SP (<0.3% by binder weight) were employed. The results indicated that 10% MK exhibited the highest 28 days compressive strength. The enhancement in the 28 days compressive strength was 0.43%, 20.27%, and 12.56% with the inclusion of 5%, 10%, and 20% MK respectively. Badogiannis et al. [72] studied the compressive strength of four types of MK derived from poor Greek kaolin as well as a commercial MK of high purity in cement pastes at a fixed w/b ratio of 0.4. Cement was partially replaced with MK at levels of 0%, 10%, and 20%, by weight. The results indicated that the compressive strength at age of 28 days of 10% replacement level was higher than that of 20% replacement level. They concluded that 10% MK content more favorable than 20%. The produced MK derived from poor Greek kaolin as well as the commercial one imparted similar properties with respect to the cement strength development. Amin et al. [114] partially replaced cement in pastes with burnt clay at levels of 0%, 10%, 20%, and 30%, by weight. Fixed w/b ratio of 0.3 was used. The results indicated that 10% MK exhibited the highest 28 days compressive strength. Oriol and Pera [115] partially replaced cement with MK at levels of 0%, 5%, 10%, 15%, 20%, 25%, and 30%, by weight. Fixed w/b ratio of 0.4 was used. Specimens were treated for 3 h at 5% power level. They reported that for complete lime consumption at age of 28 days, 15% MK was required. They also partially replaced cement with MK at levels of 0%, 10%, 20%, 30%, and 40%, by weight. Fixed w/b ratio of 0.5 was used. Specimens were cured at 20 °C with 100% RH for 24 h, then in lime-saturated water for 28 days. They reported that 30% to 40% MK is required to remove all the CH in MK pastes. Govindaraja and Gopalakrishnan [116] partially replaced cement with MK at levels of 0%, 10%, 20%, and 30%, by weight. Fixed w/b ratio of 0.4 was used.

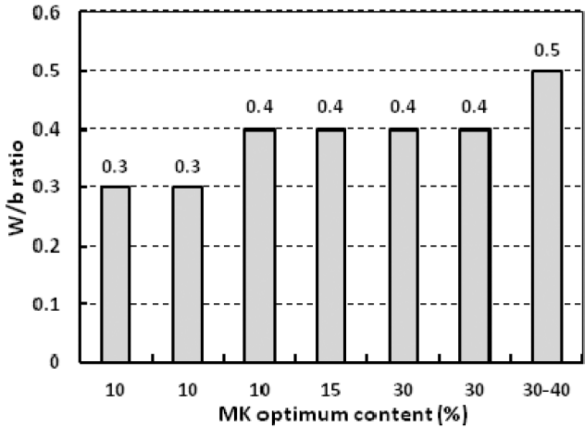

Fig. 17. Optimum MK replacement level versus w/b ratio for paste.

The compressive strength results indicated that 30% MK exhibited the highest compressive strength. The enhancement in the 28 days compressive strength was 15.93%, 45.28%, and 55.56% with the inclusion of 10%, 20%, and 30% MK, respectively. Table 9 and Fig 17 summarize the previous researches regarding to the optimum MK replacement level versus w/b ratio in paste.

3.1.2. Effect of calcination temperature and heating period

Potgieter-Vermaak and Potgieter [104] investigated the optimum compressive strength at age of 28 days of mortars containing 0%, 10%, 20%, and 30% South African MK as partially cement replacement. Fixed w/b ratio of 0.375 was used. MK was obtained by calcination of kaolin at 550 °C for 30 and 60 min, 650 °C for 30 and 60 min, 750 and 850 °C for 60 min. They reported that the optimum replacement level was 30% when calcination temperature was 550 °C for 30 min, 10% when calcination temperature was 550 °C for 60 min, 10% when calcination temperature was 650 °C for 30 min, 30% when calcination temperature was 650 °C for 60 min, 10% when calcination temperature was 750 °C for 60 min and 10% when calcination temperature was 850 °C for 60 min. The specimens containing treated kaolin at 850 °C for 60 min exhibited the highest compressive strength followed by that treated at 750 °C for 60 min. Taylor-Lange et al. [117] partially replaced cement in mortars with 15% MK, by weight. Fixed w/b ratio of 0.4 was used. MK was prepared by calcination of kaolinite at 500, 550, 600, and 650 °C for 1 h. The compressive strength results at age of 28 days indicated that 15% MK obtained from kaolinite calcination at 650 °C exhibited the highest compressive strength.

Table 9. Optimum MK replacement level versus w/b ratio for paste.

Author	MK content (%)	W/b	Optimum content	Notes
Poon et al. [113]	0, 5, 10, 15, and 20	0.3	10	With SP < 0.3% by weight of binder
Badogiannis et al. [72]	0, 10, and 20	0.4	10	
Amin et al. [114]	10, 20, and 30	0.3	10	MK from burnt clay
Oriol and Pera [115]	0, 5, 10, 15, 20, 25, and 30	0.4	15	treated 3 hours at power level 5%
Govindaraja and Gopalakrishnan [116]	0, 10, 20, and 30	0.4	30	
Oriol and Pera [115]	0, 10, 20, 30, and 40	0.5	30 to 40	cured for 24 hours at 20 °C and RH 100%, then in lime saturated water

De Gutiérrez et al. [118] activated Colombian kaolin at various temperatures of 500, 600, 700, 800, and 900 °C for 1 h. Fixed w/b ratio of 0.4 was used. They calculated the pozzolanic activity of each type of thermally treated Colombian kaolin by measuring the ratio of the compressive strength of mortar with 20% added MK to that of the reference mortar with no additional MK. The compressive strength results indicated that kaolin samples heated at temperatures of 700 to 800 °C showed higher relative compressive strength. The largest proportion of lime fixed by the MK, 47.7%, corresponded to the sample heated at 700 °C, followed by the sample heated at 800 °C. Rabehi et al. [101] thermally activated clay at different temperatures of 650, 700, 750, and 800 °C. Cement in mortars was partially replaced with activated clay at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.5 was used. The results indicated that 5% calcined clay exhibited the highest compressive strength. The highest pozzolanic reactivity was obtained at 750 °C followed by 700 °C, 650 °C, and 800 °C, respectively. He et al. [119] activated kaolin for 100 min at different temperatures of 550, 650, 800, and 950 °C. Cement in mortars was partially replaced with 20% calcined kaolin, by weight. Fixed w/b ratio of 0.5 was used. The results indicated that the optimum calcination temperature was 800 °C followed by 950 °C, 550 °C, and 650 °C, respectively. The enhancement in the 28 days compressive strength was 20%, 17%, 31%, and 25% with the inclusion of calcined kaolin treated at temperatures of 550, 650, 800, and 950 °C, respectively. Badogiamis et al. [120] partially replaced cement with different types of calcined poor Greek kaolins at levels of 0% and 20%, by weight. They calcined each kaolin type at temperatures of 550, 650, 750, 850, and 950 °C for 3 h. Most of the used kaolins containing low alunite content (7%), whilst other one containing high alunite content (22%). The results indicated that specimens manufactured from kaolin containing low alunite content treated at 650 °C exhibited the highest 28 days compressive strength, whilst specimens manufactured from kaolin containing high alunite content treated at 850 °C exhibited the highest 28 days compressive strength. Said-Mansour et al. [103] calcined Algerian kaolin at 650, 750, 850, and 950 °C for 2, 3 and 4 h. Cement in mortars was partially replaced with treated kaolin at levels of 10%, 20% and 30%, by weight. Fixed w/b ratio of 0.5 was used. 0.9% SP was used for the mixture containing 30% treated kaolin. They concluded that thermal treatment of kaolin at 850 °C for 3 h was efficient for the conversion of kaolin to MK. At these conditions the produced MK exhibited the highest pozzolanic reactivity. The inclusion of 20% treated kaolin exhibited the highest compressive strength at age of 28 days.

Huat [86] studied the compressive strength of different concrete mixtures modified with calcined kaolin. The different calcination temperatures of kaolin were 600, 650, 700, 750, and 800 °C for 3 h. Cement was partially replaced with calcined kaolin at levels of 0%, 5%, 10%, 15%, 20%, and 30%, by weight. Fixed w/b ratio of 0.56 was used. The results indicated that 10% calcined kaolin treated at 750 °C exhibited the highest 28 days compressive strength followed by 800 °C. The enhancement in the 28 days compressive strength was 9.71% and 5.1% at calcination of kaolin at 750 and 800 °C, respectively. Cara et al. [121] thermally activated kaolin at 530, 630, and 800 °C for 100 min. They reported that thermally activation at 630 °C seemed to be a good compromise between activation and economics. The reactivity at 630 and 800 °C showed similar results at long curing times.Table 10 and Fig. 18 summarize the pervious researches regarding to the optimum MK replacement level versus kaolin calcination temperature and heating period. However, this item is completely covered by Rashad [7].

From the above review of the literature in this section, it can be noted that the optimum MK level in the mixture did not only depend on w/b ratio, but also affected by the chemical composition of the source of MK, calcination temperature and its period of the kaolin. If the source kaolin containing high alumite content (around 22%), it is better to use 850 °C for 3 h to convert it to MK aiming to get the highest 28 days compressive strength. On the other hand, if the source kaolin containing lower alumite content (around 7%), 650 °C for 3 h are enough to convert it to reactive MK. On the same line with this, calcination temperature and its period of kaolin are very important factor govern the optimum replacement level of MK. Some authors believed that kaolin calcination at 850 °C for 3 h are the best treatment conditions that can produce high reactive MK. Fig. 19 shows the most common calcination temperatures and their periods versus number of researches. However, this item is completely covered by Rashad, 2013 [7].

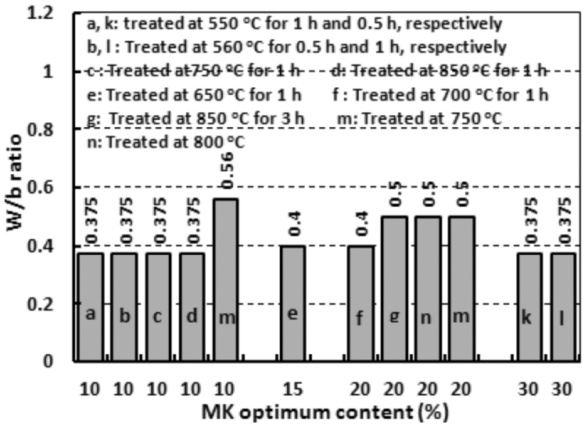

Fig. 18. Optimum MK replacement level versus kaolin calcination temperature and heating period.

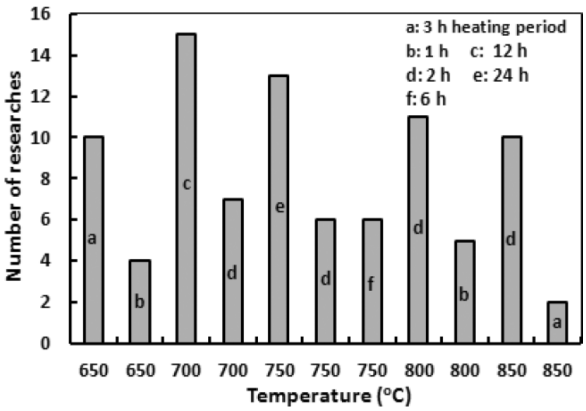

Fig. 19. Common calcinations temperatures versus research numbers at different heating periods, see [7].

3.2. Splitting tensile strength

Splitting tensile strength results also generally showed increases with MK compared to ordinary concrete. Splitting tensile strength for the MK mixtures generally ranging between 3 and 4 MPa across the w/b ratios of 0.4, 0.5, and 0.6 at age of 28 days [60], which was about 15% greater than the tensile strength of ordinary concrete at this age. This is similar to what was reported by Qian and Li [34]: the average tensile strength increased over plain cement concrete were 7% and 16% for MK at replacement levels of 5% and 10%, respectively. On the same line with this, Rashad [9] partially replaced cement in concrete with 10% MK, by weight. Fixed w/b ratio of 0.45 and fixed dosage of SP were employed. The results indicated 17.59% enhancement in the 28 days splitting tensile strength with the inclusion of 10% MK. Dinakar et al. [35] partially replaced cement in HSCs with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.3 and various dosages of SP were employed. The results showed 0.42% and 9% enhancement in the 28 days splitting tensile strength with the inclusion of 5% and 10% MK, respectively, whilst 15% MK reduced it by 1.47%.

Güneyisi et al. [100] partially replaced cement in concretes with MK at levels of 0%, 10% and 20%, by weight. Two different w/b ratios of 0.35 and 0.55 with various dosages of HRWR were employed. The results indicated that 20% MK exhibited the highest tensile strength for both w/b ratios. Kim et al. [82] partially replaced cement in HSCs with Korean MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.25 and various dosages of SP were employed. Each mixture containing 141 kg/m^3 FA. The results indicated that there is no significant effect of 5%, 10%, and 15% MK on the splitting tensile strength, whilst the inclusion of 20% MK exhibited a slight reduction in the splitting tensile strength. John [91] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.45 was used. The results indicated higher splitting tensile strength with the inclusion of MK. The enhancement in the 28 days splitting tensile strength was 0.72%, 3.94%, 8.96%, and 5.73% with the inclusion of 5%, 10%, 15%, and 20% MK, respectively.

Table 10. Optimum MK replacement level versus kaolin calcination temperature and heating period.

Author	Treatment conditions	MK content (%)	W/b	Optimum content	Optimum treatment conditions
Potgieter-Vermaak and Potgieter [104]	550 °C for 30 and 60 min	0, 10, 20, and 30	0.375	10	550 °C for 60 min
				30	550 °C for 30 min
	650 °C for 30 and 60 min	0, 10, 20, and 30	0.375	10	650 °C for 30 min
				30	650 °C
	750 °C for 60 min	0, 10, 20, and 30	0.375	10	750 °C for 60 min
	850 °C for 60 min	0, 10, 20, and 30	0.375	30	850 °C
Taylor-Lange et al. [117]	500, 550, 600, and 650 °C for 1 h	0 and 15	0.4	15	650 °C
De Gutiérrez et al. [118]	500, 600, 700, 800, and 900 °C for 1 h	0 and 20	0.4	20	700 °C
Rabehi et al. [101]	650, 700, 750, and 800 °C	0, 5, 10, 15, and 20	0.5	20	750 °C
He et al. [119]	550, 650, 800, and 950 °C	0 and 20	0.5	20	800 °C
Badogiamis et al. [120]	550, 650, 750, 850, and 950 °C for 3 h	0 and 20	EN 196-1	20	650 °C for low alunite content 850 °C for high alunite content
Said-Mansour et al. [103]	650, 750, 850, and 950 °C for 2, 3 and 4 h	0, 10, 20, and 30	0.5	20	850 °C for 3 h
Huat [86]	600, 650, 700, 750, and 800 °C for 3 h	0, 5, 10, 15, 20, and 30	0.56	10	750 °C
Cara et al. [121]	530, 630, and 800 °C for 100 min				650 °C

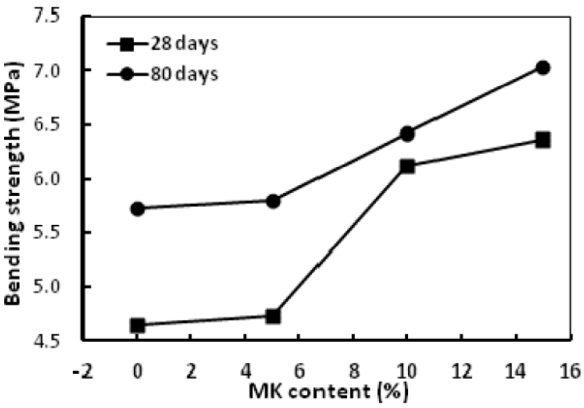

Fig. 20. Effect of MK content on the bending strength. Reprinted with permission from XiaoqianQian and Zongjin Li // *Cement Concrete Res*. **31** (2001) 1607, © 2001 Elsevier.

3.3. Flexural strength (modulus of rupture, MOR)

Dubey and Banthia [122] examined both MK and SF and their influence on flexural strength of high performance steel fiber reinforced concrete. As controls, specimens were cast with 10% supplementary cementitious materials without fibers and vice versa. Both MK and SF increased the MOR by 15% over the plain cement specimen in the prisms without fibers. From the complete load displacement curves, the post-peak performance of fiber-reinforced concrete with MK was superior to other composites. That is, MK incorporation served to increase toughness. On the other hand, SF concrete exhibited a relatively brittle behaviour and showed poor energy absorption performance. Yerramala et al. [123] partially replaced cement in ferrocements with MK at levels ranging from 5% to 25%, by weight, with an increment of 5%. Fixed w/b ratio of 0.5 was used. The flexural strength was measured at ages of 7, 28, 90, and 180 days. The results showed an enhancement in the flexural strength with the inclusion of 5%, 10% and 15% MK, whilst 20% and 25% showed lower strength than the control. The inclusion of 10% MK exhibited the optimum content in which highest flexural strength was obtained. Filho et al. [124] partially replaced cement in mortars with 50% MK, by weight. Fixed w/b ratio of 0.4 and 2% of SP were employed. The results showed 43.41% enhancement in the flexural strength with the inclusion of MK. Qian and Li [34] measured the flexural strength, at ages of 28 and 80 days, of concrete beams in which cement was partially replaced with MK at levels of 0%, 5%, 10%, and 15%, by weight. The results indicated that the MOR increased with increasing MK content (Fig 20). The enhancement in the 28 days bending strength was approximately 1.74%, 31.64%, and 36.91% with the inclusion of 5%, 10%, and 15% MK, respectively, whilst the enhancement in the 80 days bending strength was approximately 1.39%, 12.24%, and 22.9%, respectively.

Vu et al. [58] monitored the flexural strength of blended cement mortars with MK. They found that the flexural strength increased as a result of MK. Courard et al. [40] studied the effect of MK content on the bending strength of mortars. Cement was replaced with MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. The results indicated that the inclusion of MK decreased the bending strength at age of 3 days and almost attained equal strength at age of 7 days. At ages of 14 and 28 days, mortars containing MK attained higher strength. The enhancement in the 28 days flexural strength was 4.28%, 3.85%, 3.62%, and 0.22% with the inclusion of 5%, 10%, 15%, and 20%, respectively. Kim et al. [82] studied strength properties of HSC using Korean MK. The results indicated that the flexural strength increased with the inclusion of MK up to 15%. On the contrary, the flexural strength decreased at 20% replacement level. Tafraoui et al. [125] used MK instead of SF to produce UHPC with or without crushed quartz and fibers. They reported that the flexural strength was slightly positive when crushed quartz and metal fibers are associated with MK (+3.3%) and negative for crushed quartz with heat treatment (-5% for the 150 °C treatment). Steel fibers improved the flexural strength (+98.7%). The flexural strength depend on the heat treatment conditions. It decreased at 90 °C thermal treatment and increased at 150 °C thermal treatment. John [91] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.45 was used. The results indicated 4,79%, 8.22%, 15.24 and 10.44% enhancement in the 28 days flexural strength with the inclusion of 5%, 10%, 15%, and 20% MK, respectively. Rao et al. [85] partially replaced cement in concretes with MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed w/b ratio of 0.33 and SP were employed. The results showed higher flexural strength with the inclusion of MK. The inclusion of 10% MK exhibited the highest flexural strength. The enhancement in the 28 days flexural strength was 5.96%, 13.16%, 8.95% and 2.98% with the inclusion of 5%, 10%, 15%, and 20% MK, respectively.

3.4. Modulus of elasticity (MOE)

There is little existing literature regarding to the effect of MK on the MOE of concrete. As it has been shown to increase compressive strength and densify the microstructure, this lead to increase elastic modulus, or stiffer concrete. From the literature, the MOE generally seems to increase with increasing MK content, although the rate of increase is lower than that for compressive strength. Caldarone et al. [43] performed ASTM C-469 to determine the static MOE of concretes containing 0%, 5%, and 10% HRK. Based on average of two moist-cured 6 × 12 inches cylinders, MOE were measured at ages of 28 and 91 days. The enhancement in the 28 days MOE was 14.78% and 17.38% with the inclusion of 5% and 10% HRK, respectively, whilst the enhancement in the 91 days was 14.16% and 18.07%, respectively. Dinakar et al. [35] partially replaced cement in HSCs with MK at levels of 0%, 5%, 10%, and 15%, by weight. Fixed w/b ratio of 0.3 and various dosages of SP were employed. The results showed 2.51% and 3.81% enhancement in the 28 days elastic modulus with the inclusion of 5% and 10% MK, respectively, whilst 15% MK showed a comparable result to the control.

Qian and Li [34] reported that at three days curing, concrete containing 15% MK exhibited MOE of 26.2 GPa, as compared to 24.1 GPa for the control specimen at this age. At age of 60 days, the measured values of MOE of 15% MK and control concretes were 34.7 and 30.4 GPa, respectively. Khatib and Hibbert [98] evaluated dynamic MOE of concretes containing 0%, 10%, and 20% MK, by weight, as cement replacement. Fixed w/b ratio of 0.5 and various dosages of SP were employed. The results showed higher MOE with the inclusion of MK. There was a sharp increase towards the end of the examination period: between 28 and 90 days, MOE increased from 38 MPa to 50 MPa. Khatib [41] partially replaced cement in concretes with MK at levels of 0%, 5%, 7.5%, 12.5%, 15%, and 20%, by weight. Fixed w/b ratio of 0.3 and fixed dosage of SP of 1.36%, by binder weight, were employed. The results indicated that MK between 12.5% and 15% exhibited the maximum dynamic modulus of elasticity.

3.5. Pullout

The influence of mortar fineness and several adhesive additives (FA, MK, latex, and polyvinyl alcohol) on the pullout load-versus-slip response of steel fibers (smooth, round, hooked round or triangular twisted) were studied by Guerrero and Naaman [126]. They reported that the addition of 10% MK, by cement weight, was generally more effective in improving the bond stress-versus-slip response than FA, polyvinyl alcohol solution or latex. For hooked and twisted triangular steel fibers, for which the mechanical component of bond is significant, the inclusion of all the additives was beneficial, specially MK, which improved the peak load by up to 60% and the pullout energy by more than 100% in comparison with the control.

4. CONCLUSIONS

The use of MK as partial substitute of cement in concrete, mortar and paste has been widely investigated in the previous years. The fresh properties and mechanical strength were reviewed in this investigation. The optimum 28 days compressive strength versus w/b ratio and versus kaolin calcination temperature and its period were also reviewed. The conclusions of this literature review can be summarized as following:

1. MK increased the heat evolved during hydration.
2. Most of authors believed that MK reduced the workability.
3. As reported by many authors, the inclusion of MK in cement system retarded the setting time. The setting time slightly increased with increasing MK content, but this mainly depended on cement content, chemical admixture dosage and its content, MK content and its fineness
4. In general, MK enhanced and increased the mechanical strength of cement system.
5. The optimum MK replacement percentage that exhibited the highest compressive strength is not a constant one but functions of the w/b ratio, MK chemical composition, calcination temperature and its heating period of kaolin.
6. Few number of authors reported that 5% MK exhibits the optimum content in concrete at w/b ratios 0.3-0.6 with or without SP.
7. Most authors reported that 10% MK exhibits the optimum MK content in concrete at w/b ratios around 0.5-0.54 with the inclusion of SP. W/b ratios 0.28-0.35 and 0.4-0.45 came in the second and third place, respectively.
8. Most of authors reported that 15% MK exhibited the optimum content in concrete at w/b ratios of 0.28-0.35 with the inclusion of SP or HRWR. W/b ratios of 0.38-0.4 and 0.45-0.5 came in the second and third place, respectively.
9. Most of authors reported that 20% MK exhibited the optimum content in concrete at w/b ratios of 0.5-0.55 with the inclusion of SP or HRWR. W/b

ratios of 0.3-0.34 and 0.4 came in the second and third place, respectively.

10. In general, based on Figs. 12 and 13 it is recommended to replace cement in concrete with 15% MK at w/b ratios 0.28-0.35 with the inclusion of SP or HRWR. The inclusion of 10% MK is more effective at w/b ratios of 0.5-0.54 with the inclusion of SP, whilst 20% MK is recommended at w/b ratios 0.5-0.55 with the inclusion of SP or HRWR.

11. In general, based on Figs. 12 and 14, regardless w/b ratio, most of authors reported that the optimal cement replacement with MK in concrete is 15%, followed by 10%, 20%, 5% and 8%, respectively.

12. Based on Fig. 15, most of authors reported that the optimal cement replacement with MK in mortar is 20% at w/b ratios of 0.5-0.53 without SP, whilst 15% MK is recommended at w/b ratios of 0.4-0.53. At lower w/b ratio, 10% MK is recommended.

13. Based on Figs. 15 and 16, regardless w/b ratio, most of authors reported that the optimal cement replacement with MK in mortar is 20%, followed by 15% and 20%, respectively.

14. The optimum treatment conditions of kaolin to produce MK with high reactivity depend on many factors as calcination temperature, heating period and kaolin chemical decomposition.

15. The modulus of elasticity generally seems to increase with increasing MK content, but the rate of increasing is lower than that for compressive strength.

16. The inclusion of MK in cement system improves other mechanical strength such as splitting tensile strength, flexural strength and pullout strength.

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