Journal of Engineering
journal homepage: www.joe.uobaghdad.edu.iq
Number 8 Volume 27 August 2021

Civil and Architectural Engineering

Utilization of Iraqi Metakaolin in Special Types of Concrete: A Review Based on National Researches

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ABSTRACT

Portland cement concrete is the most commonly used construction material in the world for decades. However, the searches in concrete technology are remaining growing to meet particular properties related to its strength, durability, and sustainability issue. Thus, several types of concrete have been developed to enhance concrete performance. Most of the modern concrete types have to contain supplementary cementitious materials (SCMs) as a partial replacement of cement. These materials are either by-products of waste such as fly ash, slag, rice husk ash, and silica fume or from a geological resource like natural pozzolans and metakaolin (MK). Ideally, the utilization of SCMs will enhance the concrete performance, minimize environmental pollution and mitigate the drawbacks of cement production attributed to the highly CO_2 emission. In general, MK's ultra-fineness and high pozzolanic activity are exhibited a remarkable performance of concrete in terms of strength and durability. However, the filler effect, acceleration of cement hydration, and the pozzolanic reaction with calcium hydroxide (CH) are the main factors influencing the performance of metakaolin as a cementitious material. Therefore, numerous researches have been undertaken on inclusion MK in concrete and mortar and production of (free-cement concrete) geopolymer concrete. This paper reviews some of previous native researches on effect of using Iraqi metakaolin as a pozzolanic material in different types of concrete. The standpoint of this review will guide the researchers on the importance of utilization of local MK and highlight the missing researches toward completing a comprehensive understanding of incorporation Iraqi-metakaolin in concrete technology.

Keywords: ordinary Portland cement, concrete, supplementary cementitious materials, Iraqi-metakaolin.

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Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2021.08.06

Article received:20/3/2021
Article accepted:5/6/2021
Article published:1/8/2021

استخدام الميتاكؤلين العراقي في أنواع خاصة من الخرسانة: مراجعة مبنية على أبحاث محلية

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الخلاصة

تعتبر خرسانة السمنت البورتلاندي من مواد البناء والانشاء الأكثر استخدامًا في العالم منذ عقود. ومع ذلك، فإن البحوث في مجال تكنولوجيا الخرسانة لا تزال في تزايد مستمر لتلبية وتطوير بعض الخواص المعينة فيما يتعلق بالمقاومة والديمومة والاستدامة. لذلك تم تطوير عدة أنواع خاصة من الخرسانة لتحسين أداءها. تحتوي معظم أنواع الخرسانة الحديثة على مواد إسمنتية تكميلية (SCMs) كبديل جزئي للأسمنت. ان معظم هذه المواد هي نواتج عرضية (مخلفات) لبعض الصناعات مثل الرماد المتطاير، وخبث الافران، ورماد قشور الرز, وابخرة السيليكا. كما يمكن ان تنتج هذه المواد من مصادر الارض الطبيعية مثل البوزولان الطبيعي والميتاكؤلين. ان اضافة المواد السمنتية التكميلية كبديل جزئي من السمنت تعمل على تحسين خصائص الخرسانة وديمومتها, وتقليل التلوث البيئي بالمخلفات الصلبة, كما تعمل على تقليل انبعاثات غاز ثنائي اوكسيد الكربون (CO_2) الناتج من صناعة السمنت. أن النعومة الفائقة والفعالية البوزولانية العالية للميتاكاؤولين يظهران اداءً رائعاً في مقاومة وديمومة الخرسانة. وبشكل عام فان تأثير الميتاكاؤولين كمادة مالئة ومساهمتها في تسريع عملية الاماهة للسمنت والتفاعل البوزولاني مع هيدروكسيد الكالسيوم تعتبر من العوامل الاساسية المؤثرة على اداء الميتاكاؤولين كمادة اسمنتية في الخرسانة.

تم إجراء العديد من الأبحاث والدراسات حول استخدام الميتاكاؤولين (MK) في الخرسانة ومونة السمنت، بالإضافة إلى إنتاج الخرسانة الجيوبوليمرية (الخرسانة الخالية من السمنت) المعتمدة على الميتاكاؤولين. في مقالة المراجعة هذه سيتم استعراض بعض الأبحاث المحلية السابقة والمتضمنة تأثير استخدام الميتاكؤلين العراقي كمادة بوزولانية في أنواع خاصة من الخرسانة. مما يسلط الضوء حول أهمية استخدام الميتاكاؤولين المحلي في الخرسانة، ويبين مسارات البحث المفقودة نحو استكمال فهم شامل لتأثير الميتاكؤلين العراقي في تكنولوجيا الخرسانة.

الكلمات الرئيسية: السمنت البورتلاندي الاعتيادي, الخرسانة, المواد السمنتية التكميلية, الميتاكؤلين العراقي.

1. INTRODUCTION

Concrete is the most widely used construction material worldwide, and it has taken place as a second consumed substance after water **(Duchesne, 2020)**. Therefore, the global demand for cement (the main constituent in the concrete matrix) has increased dramatically to reach up to 4.2 billion tons in 2019 **(Lišovský, et al., 2021)**. Consequently, cement manufacturing is responsible for 5%-8% of the world's carbon dioxide (CO_2) emissions, causing a serious environmental greenhouse emissions and sustainability impact. One of the primary efforts for reducing the CO_2 emission associated with concrete production is that the using of supplementary cementitious materials (SCMs) as partial replacement of ordinary Portland cement (OPC). However, utilization of SCMs not only minimize the OPC consumption and its related environmental pollution but also improves the fresh and hardened properties of concrete and enhancement its durability toward sustainable concrete industry **(Juenger, et al., 2019)**, **(Siddique and Khan, 2011)**, **(Ramezanianpour, 2014)**.

One type of (SCMs) is metakaolin (MK) which obtained by controlled heat treatment (calcination) of pure kaolin clay. The main reason for the inclusion of MK in cement based system is its pozzolanic activity, which is referred to the ability of silicates and aluminates in SCMs like (MK) to react with calcium hydroxide (CH) from cement hydration to form secondary calcium-silicate-hydrate (C-S-H) gel **(Ramezanianpour, 2014)**, **(Khatib, et al., 2018)**. This reaction will directly improve the interfacial transition zone (ITZ), and the microstructure becomes denser with less pores. As a result, the strength (mechanical properties) and durability of cementing composite will have been an enhancement. Kaolinite is the minerals clay that consists of an alternate crystalline layer structure of hydrated aluminum disilicate ($Al_2O_3.2SiO_2.2H_2O$), and this electrically- lamellar structure gives fine particle size, plate-like morphology, and softness soapy feel **(Rashad, 2013)**. The geological formations of kaolin clay can be found in different regions worldwide like China, South America, North America, and Europe **(Khatib, et al., 2018)**. There is an abundance of sedimentary (transported) kaolinite clay in Iraq, which have various names as; kaolin clay, ball clay, and kaolinitic claystone. Generally, most Iraqi kaolin clay deposits are recorded in the Western Desert of Anbar province, as shown in **Fig. 1**. The main exposed formations sectors containing kaolin clay are Ga'ara, Hussainiyat, and Amij Formations. The mineral composition of ball clay brought from (Duekhla deposit - Ga'ara Formation) is consist of (88% kaolinite, 8% quartz, 0.4% organic matter and 3.6% others) depending on X-ray diffractometry **(Tamar-Agha, et al., 2019)**, **(Tamar-Agha, et al., 2020)**.

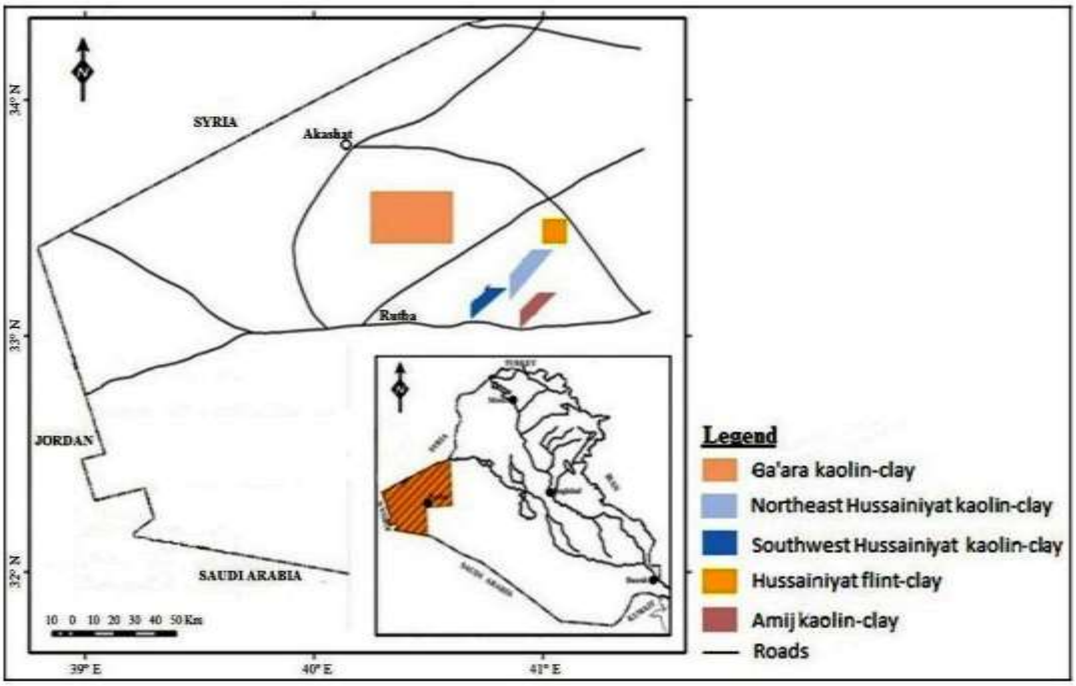

Figure 1. Location map of kaolin-clay deposits in the western desert of Iraq. **(Tamar-Agha, et al., 2019)**.

The plenty of kaolinite clay in Iraq's geological formation and the promising results of using MK in concrete have encouraged the native researchers to adopt the utilization of local MK as a pozzolanic addition for concrete and mortar. However, extensive research papers and academic thesis have been demonstrated using local metakaolin to produce different types of concrete.

Therefore, this paper gives a review of the native researches that carried out on the effect of using Iraqi metakaolin as SCMs replacement of cement in concrete, or as a resource binder in the synthesis of geopolymer concrete.

2. MANUFACTURING PROCESS AND CHEMICAL COMPOSITIONS OF IRAQI-MK

Most of SCMs are by-products from industrial waste like fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF), while some of them are pure as a natural pozzolan. However, metakaolin is produced by calcinating kaolin clay under carefully controlled heat treatment to temperatures of 600-900°C **(Khatib, et al., 2018)**. The calcination temperature (thermal treatment) plays a crucial role in reactivating kaolinite toward production metakaolin as supplementary cementitious material by completing dehydroxylation as possible. However, during the burning or calcination process, kaolin would lose structural OH groups with more rearrangement of alumina and silica layers, leading to collapse and losing their long chains. Finally, the kaolinite flakes become more deformed and condensed into disordered, amorphous material known metakaolin. This product has a highly reactive transition phase, pozzolanic activity, and suitable for use as supplementary cementing materials in concrete applications **(Khatib, et al., 2018)**, **(Rashad, 2013)**, **(Wang, et al., 2018)**.

The lower temperature is less effective in developing a reactive metakaolin. In contrast, the overheating causes the sintering of the kaolinite clay to form the dead burnt phase of non-reactive refractory named mullite **(Ilić, et al., 2010)**. Most native researchers have taken the temperature of 700-750°C as an optimum calcination temperature of Iraqi metakaolin, depending on experimental work or previous studies. The study of **(Ibrahem and Abdul Wahab, 2008)** was carried out to optimization the calcination temperature and time of converting Iraqi kaolin to active metakaolin. The kaolinite clay has burned at five different temperatures (550, 600, 650, 700, and 750) °C for one-half hour. The results indicated that the 700°C was the optimum calcination temperature with respect to the highest strength activity index (102%). Moreover, the authors determined the best soaking time at 700°C by burning kaolinite for 0.5, 1, 1.5, and 2 hours, then tested compressive strength of mortar with replacement of cement by 20%MK for each tested time. The results show that the optimum calcination temperature of Iraqi kaolin clay is at 700°C for one hour. Not much different from these findings, **(Sldozian, 2012)** has found that among (500, 700 and 900) °C, the highest compressive strength of concrete mixtures containing (5, 10, 15 and 20) % of MK would be gained by calcination Iraq kaolinite clay at 700°C for 1hr. The optimum replacement dosage was 5% which gain 30 MPa of compressive strength at 28-day. In spite of the mineralogical of MK is like silica fume, which composed essentially of amorphous aluminosilicate (Si-Al-O) phase. Still, the chemical composition of SF contains more than 85% SiO_2 by mass vs. 50% for MK.

Consequently, MK is taking a second level after SF in pozzolan hierarchy as active pozzolan material **(Nawy, 2008)**. Generally, the main chemical components of Iraqi MK are the silica and alumina oxides (over 80% by mass) with less quantity of ferric oxide. **Table 1** summarizes the calcination temperature and chemical composition of researchers that used Iraqi metakaolin.

Table 1. Calcination temperature and chemical composition of Iraqi-MK used in previous studies.

Ref.	Calcination temp. (°C)	Time (hr)	Chemical composition (%)								
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	L.O.I
(Ibrahem and Abdul Wahab, 2008)	700	1	53.0	32.0	0.9	1.10	1.08	/	/	/	13
(Al-mishhadani, et al., 2009)	700	/	51.32	32.90	1.10	1.70	0.10	0.18	0.23	0.43	6.47
(Hussein , 2011)	700	1	51.34	33.40	2.30	3.0	0.17	0.15	/	/	7.8
(Hadi and Habeeb, 2011)	700	1	55.24	37.1	1.47	1.12	0.13	0.07	0.15	/	3.59
(Fawzi, et al., 2013)	700	1	52.38	37.31	1.21	1.68	0.30	/	/	0.44	/

Continue ….

(Frieh et al., 2014)	700	1	55.22	32.38	1.54	2.24	0.41	2.85	/	/	3.35
(Shihab, 2016)	700	1	57.45	36.83	1.41	1.12	0.03	0.08	0.50	/	1.54
(Aday, 2018)	750	/	51.70	32.90	1.10	1.70	0.10	0.18	0.51	/	8.64
(Owaid, et al., 2018)	800	2	53.60	36.80	1.97	0.78	0.32	0.17	0.43	0.84	4.83
(Razaq , 2019)	700	1	54.88	36.29	1.40	0.38	0.21	0.21	0.66	/	2.47
(Hasan, 2016)	700	1	51.59	38.11	1.82	0.45	0.23	0.14	0.11	0.43	6.12
(Shamsa, 2018)	700	2	56.77	30.85	2.48	0.58	0.59	/	/	/	/
(Ahmed, 2020)	700	2	54.20	39.0	0.92	1.37	0.15	0.45	0.22	0.27	0.71

According to **(ASTM C618-17)**, the calcination natural clay can be categorized as pozzolanic material if the summation of the three main oxides (SiO_2, Al_2O_3, and Fe_2O_3) is equal to or higher than 70%. From **Table 1**, it can be concluded that all the Iraqi metakaolin can be classified as pozzolanic for use in concrete. Moreover, the electronic scanning microscopy (SEM) revealed that the Iraqi metakaolin particles are platy-form, angular, and have a lamellar structure, as shown in **Fig. 2.**

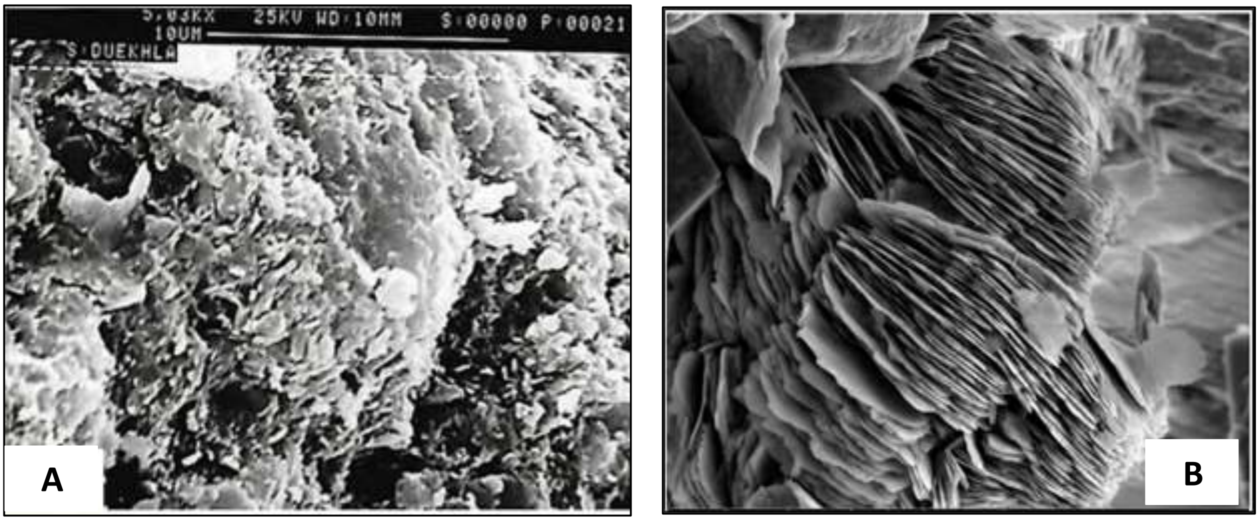

Figure 2. SEM image of Iraqi MK. (view-A) **(Tamar-Agha,et al., 2020)** (view-B) **(Shamsa, 2018)**.

3. SPECIAL TYPES OF CONCRETE INVOLVING IRAQI-METAKAOLIN

In the last decades, several types of concrete have been developed for meeting the desirable properties under specific circumstances such as workability, strength, and durability. On the other hand, a new generation of concrete has been modified in some ways for sustainable development in concrete technology and considered its strong performance. This section briefly reviews and discusses the influence of using local metakaolin on some properties of self-compacting concrete (SCC), high-performance concrete (HPC), and other miscellaneous types and the production of geopolymer concrete based on Iraqi metakaolin as the main precursor.

3.1 Self-compacting concrete

Self-compacting concrete is considered as one of the modern and developing concrete, that have ability of flowing and passing under its weight without segregation **(Sirivivatnanon et al., 2003)**. Many local researchers have investigated the effect of utilization Iraqi metakaolin on the characteristics of SCC, as discussed in the following sections:

3.1.1 Fresh properties

Generally, the inclusion of MK seems to have an adverse effect on the workability of concrete **(Siddique and Khan, 2011)**, **(Ramezanianpour, 2014)**, and that related to the high fineness of MK and its plate-like particles. The relationship between fresh properties of SCC and Iraqi-MK content has been widely investigated by local studies **(Hadi and Habeeb, 2011)**, **(Owaid, et al., 2018)**, **(Razaq, et al., 2019)**, **(Alwash, 2013)**, and **(Hameed, 2019)**. Generally, all authors found that the inclusion of MK as cement replacement would minimize the workability of SCC in relation to the slump flow diameter, the ratio of L-box, and the time of the V-funnel test. **Fig. 3** shows the variation of workability tests results of SCC with different MK contents from previous studies.
It can be observed that without adequate dosage of superplasticizer, replacement of 15%MK can be reduced the slump flow diameter and L-Box ratio up to 6% and 10%, respectively. In

comparison, the time of V-funnel increased by 50% compared to the control SCC mix. as in the research of **(Razaq et al., 2019**).

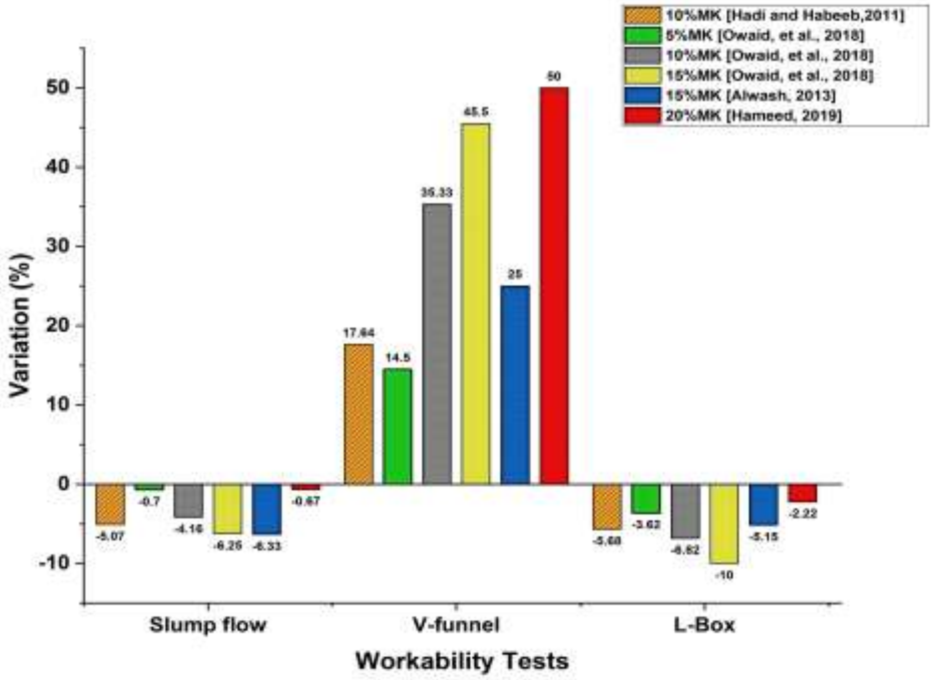

Figure 3. The relative percentage for the effect of MK content on the workability of SCC.

3.1.2 Mechanical properties

The mechanical properties of concrete provide an essential quantification of concrete strength. The compressive, flexural, tensile strength and static modulus of elasticity are the main variables for the structural design process and determining the concrete quality and durability properties **(Pillay et al., 2020)**. The adding of Iraqi metakaolin as a partial content of the binder in SCC significantly affects its mechanical properties. **Table 2** summarizes some of the previous local researches on mechanical properties of SCC containing different amounts of Iraqi-MK. It can be observed that the substitution of ordinary Portland cement with Iraqi metakaolin has improved the mechanical properties of SCC. However, both studies **(Hadi and Habeeb, 2011) (Razaq, et al., 2019)** showed that the replacement level of 10%MK attaining the optimum strength performance. This enhancement in mechanical properties attributed to the pozzolanic activity of MK to forming additional gel (C-S-H), as mentioned in the introduction section. Also, MK displays filler materials that can fill the voids and pores present in the microstructure and, therefore, reduce the porosity within the concrete matrix. **(Siddique and Khan, 2011)** .

Table 2. Mechanical properties of SCC with different contents of Iraqi-MK.

Reference	MK content	Strength properties studied	Findings (in comparison with reference mix)
(Hadi and Habeeb, 2011)	10%	Compressive	(+) by 14.2%, 11.4% and 14.5% at 28, 90 and 180 days, respectively.
		Splitting	(+) by 5.2%, 10.3% and 31.3% at 28, 90 and 180 days, respectively.
		Static modulus of elasticity	(+) by 11.2%, 13% and 9.6% at 28, 90 and 180 days, respectively.
(Owaid, et al., 2018)	5%	Compressive	(+) by 3.9% and 2.1% at 28 and 90 days, respectively.
	10%		(+) by 11.1%, and 8.8% at 28 and 90 days, respectively.
	15%		(+) by 8.7%, and 4.9% at 28 and 90 days, respectively.
(Razaq et al., 2019)	5%	Compressive	(+) by 11.8%, and 11.1% at 28 and 90 days, respectively.
		Splitting	(+) by 15.1%, and 13.5% at 28 and 90 days, respectively.
	10%	Compressive	(+) by 17.6%, and 15.7% at 28 and 90 days, respectively.
		Splitting	(+) by 24.2%, and 21.6% at 28 and 90 days, respectively.
	15%	Compressive	(+) by 2.17%, and 7.5% at 28 and 90 days, respectively.
		Splitting	(+) by 9%, and 13.5% at 28 and 90 days, respectively.
(Alwash, 2013)	15%	Compressive	(+) by 8.4%, 9.5% and 13.4% at 7, 28 and 90 days, respectively.
		Flexural	(+) by 8.6%, and 16.5% at 28 and 90 days, respectively.
		Static modulus of elasticity	(+) by 2.1%, 9.5% and 4.1% at 28 and 60 days, respectively.

3.1.3 Durability properties

The durability of concrete is defined as the capability of concrete components to withstand the severe exposure conditions for which it has been designed throughout the structure's service life **(Mehta and Monteiro, 2006)**. The durability properties of SCC contain Some native researchers have conducted Iraqi metakaolin.

(Hadi and Habeeb, 2011) have investigated the durability performance of SCC that exposed to (sulfates-chlorides) solution at a concentration similar to that of soil and groundwater in the south part of Iraq. Four mixes of SCC have been prepared with mineral admixture: control SCC mix (0% admixture), 10% MH, 30% LSP (limestone powder), and blended of 10%MK+30%LSP. The mechanical properties and the changes in weight and length have been determined after sub-immersion in (Cl-1 + SO4-2) saline till 180 days for each mix. The authors found that compressive and tensile strengths of exposed SCC-10%MK would increase continuously without any deterioration. Also, it has provided the minimum reduction in mechanical properties, weight loss, and length changes compared to the control mix and other mixes.

(Ammash, et al., 2013) evaluated the effect of internal sulfates in fine aggregate on some mechanical properties of SCC containing blended 10%MK plus limestone powder. Natural gypsum was added as a partial replacement for the sand weight at four dosages as; (0.37, 0.5, 1, 1.5) %. All SCC specimens were tested for compressive and splitting strength at 28, 56, and 90 days of curing. The results indicated that the optimum gypsum content was 0.5% relative to the higher strength, and then the mechanical properties decreased with an increase of sulfate content. The inclusion of 10% MK as cement replacement has a positive effect in reducing the loss of strength (compressive and tensile) at all ages.

3.2 High Performance Concrete

High performance concrete (HPC) is concrete that has been designed to attain mechanical properties, durability, or constructability that exceeds those of normal concrete. ACI concrete terminology has been defined (HPC) as concrete meeting special combinations of performance and uniformity requirements. Thus, the production of (HPC) is required more attention in mixing, placing, and curing practices **(Sirivivatnanon et al., 2003)**. Typically, utilization of SCMs (mainly silica fume) as a part of cement and noticeable superplasticizer dosage are essential requirements in HPC production **(Aïtcin, 1998)**. Despite utilizing silica fume as a main and fabulous cementitious material in making HPC, but some national researchers have focused on producing HPC based on using Iraqi activated kaolinite clay as SCMs. Generally, the inclusion of local MK as a partial replacement of cement has produced HPC with a mean of compressive strength ranged (60-70) MPa at the age of 28-day, and this depending on a high content of cement (more than 500 kg) and sufficient amount of high range water reducer. **Fig. 4** shows some values of compressive strength of HPC for previous studies. **(Shihab, 2016)**, **(Aday, 2018) (Mohammed, 2012)**, **(Al-galawi and Hassooni, 2016)**.

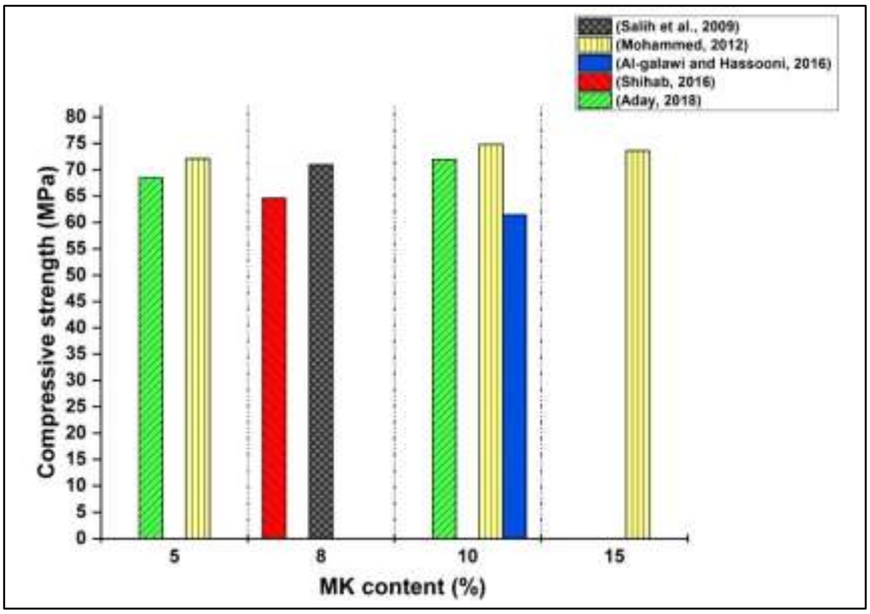

Figure 4. Compressive strength of HPC with different contents of Iraqi – MK.

(Al-janabi, 2007) has used two types of local pozzolanic materials in the synthesis of HPC, where the cement was replaced either by 8% of high reactive metakaolin (HRM) or 10% fly ash. Another study about the effect of using HRM on the properties of high performance steel fiber reinforced concrete was prepared by **(Mohammed, 2012)**. The dosages 5%, 10%, and 15% of HRM have been used as a cement replacement with steel fiber at 2% of volume concrete. Also, **(Shihab, 2016)** has evaluated the chloride ion penetration of HPC containing 8% HRM and reinforced with 2% of steel fiber.

Moreover, **(Al-galawi and Hassooni, 2016)** have investigated the durability properties of two mixes of HPC, ones containing 10% of local HRM, and the other with silica fume at 8% and 10% for cement weight. The main findings and results based on previous studies regarding the mechanical and durability properties of HPC containing local MK are summarized in **Table 3**.

Table 3. Summary of HPC behavior containing local Metakaolin.

Reference	MK content	Investigated properties	Type of Exposure	Main findings
(Shihab, 2016)	8%	Durability	External chloride ion solution up to 300 days	The inclusion of 8% MK enhanced the chloride resistance, as reducing chloride penetration, electrical conductivity, and the ratio of (Cl free/Cl total).
(Mohammed, 2012)	5%	Mechanical	/	Improved compressive, flexural, and splitting strength observed in the sample of HPC containing MK; and optimum MK content is 10% respect to the highest compressive strength.
	10%			
	15%			
(Al-galawi and Hassooni, 2016)	10%	Durability	Internal sulfate attack by adding natural gypsum as a replacement of sand weight (1, 2, and 3) % up to 120 days.	HPC with 10%HRM showed better resistance to internal sulfate attack than those of 8% and 10% SF at all ages of the test.
(Al-janabi, 2003)	8%	Durability	Internal sulfate attack by adding natural gypsum as a replacement of sand weight up to 270 days.	8%MK minimized the negative impact of internal sulfate attack on losing compressive and flexural strength of HPC.

3.3 Miscellaneous Types

Recently, Iraqi research has been expanded in concrete technology that involves the utilization of local metakaolin. **(Fawzi, et al., 2013)** have developed lightweight concrete based on porcelinate aggregate with four percentages of MK (5, 10, 15, and 20) % as cement replacement. Compared with the reference mix (0% MK), all lightweight concrete mixtures containing MK have a higher fresh and dry density and a significant improvement in mechanical properties. The authors indicated that the 10% of MK is the optimum replacement level as the compressive strength of the control mix increased from 20 MPa to 47.1 MPa, whereas the dry unit weight (1806 kg/m^3) stay in the range of lightweight concrete, which can be used as lightweight structural concrete in many civil engineering applications.

On the other hand, **(Frieh et al., 2014)** investigated using a high fraction of Iraqi metakaolin (10% up to 70%) instead of ordinary Portland cement to produce a high volume-metakaolin concrete a solution in mass concrete products. The results indicated that the workability decrease with an increase of MK content, and it should increase the dosage of superplasticizer to get the same workability. Moreover, the optimum replacement dosage was 20% of MK, which provided the highest compressive, flexural, splitting strengths and static modulus of elasticity, and after this dosage, a noticeable reduction of mechanical properties has been recognized, especially for mixes with 60% and 70% MK content.

Another study was carried out by **(Awad et al., 2018)** to evaluate the effect of the inclusion of three percentages (5%, 7%, and 10%) of MK on the performance of reactive powder concrete exposed to internal sulphate attack. For each MK replacement dosage, fine natural aggregate with high sulphate content (SO_3= 0.75%) was used to prepared reactive powder concrete specimens. All specimens have been tested for compressive, flexural, and splitting tensile strengths at 7 up to 120 days. The results revealed that the mechanical properties increased with an increase of MK content, whereas 10% MK content was the optimum replacement dosage with the highest strengths at all ages. On the other hand, regardless of the MK replacement level, the mixtures' contented high dosage of sulfate in fine aggregate has shown lower mechanical properties compared to control mixes at all test ages. Also, the mix of 10% MK and sulphate sand content has shown the lowest reduction in strengths among other mixes, whereas the reduction of compressive strength for 10% MK-samples reached 1.95% at 120 days vs. 3.1% and 2.35% for mixes with 5% and 7% MK content, respectively.

3.4 Geopolymer Concrete

Geopolymer concrete is represented as the next generation of conventional concrete to be accepted for using in construction and building sector due to its durable properties and high strength associated with more environmentally benefits which eliminate the production of ordinary Portland cement and subsequently, minimizing the CO_2 emissions universally **(Amran et al., 2021),(Imtiaz et al., 2020)**. Geopolymer is synthesized by interacting aluminosilicate precursors such as fly ash, metakaolin, slag, or silica fume with an alkaline solution of either NaOH or KOH and Na_2SiO_3 or K_2SiO_3 **(Mahmoodi et al., 2021)**. The environmental advantages, besides to proven excellent strength and durability performance of geopolymer concrete, have encouraged the national researchers to deal with Iraqi metakaolin as the main source of silica and alumina toward the production of sustainable geopolymer concrete.

Basil et al. **(Al-Shathr et al., 2015)**, and **(Al-Shether, et al.,)** have presented an extensive investigation of optimization mix design and curing system of geopolymer concrete based on local Iraqi metakaolin. The main parameters were silicate to hydroxide ratio of alkaline solution, fineness of metakaolin, and curing regime. At the same time, the mix proportions have been fixed at (400, 720, and 1100) kg/m^3 for metakaolin, fine aggregate, and coarse aggregate, respectively. It has been reported that the compressive strength of geopolymer concrete increased with a high fineness of metakaolin, and the optimum curing system was under sunlight in the summer season at a temperature (32-48) °C.

In the same manner, **(Shamsa et al., 2018)** have studied the effect of concentration and ratio of (NaOH: Na_2SiO_3) of alkaline solution and amount of binder on the strength of MK-based geopolymer concrete. The curing regime was carried by placing the molds after casting inside an electric oven for 16 hours, and then de-molded the specimens and continuously the heat treatment at 45±5°C for 48 hours. In the other part of their investigation, Mohammed et al. **(Shamsa et al., 2019)** have evaluated the durability performance against 300 cycles of freezing and thawing for MK-based geopolymer concrete. Compared with fly ash geopolymer concrete and ground granulate blast furnace slag geopolymer concrete, the specimens of MK-based geopolymer concrete would provide less resistance to freezing and thawing at 68% durability factor, reaching 77% and 81% for FA and GGBFS samples, respectively.

(Alserai et al., 2019) studied the effect of iron filling on the mechanical properties of sustainable MK-based geopolymer concrete. Two series of geopolymer concrete have been produced, once with natural coarse aggregate and the other with recycled concrete coarse aggregate. For each group, the iron filling was added at 0.5%, 0.75%, and 1%. Generally, the mixtures with natural aggregate have exhibited higher mechanical properties in comparison with those of recycled aggregate, while the increase of iron filling would increase all the mechanical properties.

On the other hand, **(Ahmed et al., 2019)** conducted a series of trials to optimize the mix proportions of MK-based geopolymer concrete related to the highest strength and more sustainable-sufficient curing regime. However, the maximum obtained compressive strength reached up to 40 MPa at 7 days with 14 molarity of the alkaline solution and curing for 5 hours at 60°C followed with exposure to sunlight in summer season at degree (35-49)°C.

Another advantage of using metakaolin-based geopolymer concrete is that it allows reusing and recycling solid waste materials as constituents within concrete matrix. **(Ahmed et al., 2019)** and **(Khalil et al., 2019)** have been evaluated the possibility of utilization waste clay brick as a binder and as a coarse aggregate in the synthesis of MK-geopolymer concrete, respectively. The MK has substituted with waste clay brick powder at 10%, 15%, and 20% by weight, while the natural coarse aggregate has replaced with crushed clay brick aggregate at volume levels 10%, 20%, and 30%. In spite, the inclusion of waste brick in each feature has impacted negatively upon compressive strength. Still, the obtained strengths ranged between 20.5 to 41.7 MPa at the age of 28 days, thus providing a more sustainable concrete that can be used in structural applications. The main mix proportions and influence parameters of production Iraqi-MK geopolymer concrete by various researchers are summarized in **Table 4**.

Table 4. The observed parameters of production geopolymer concrete based on Iraqi MK

Items	References			
	(Al-Shathr et al., 2015)	**(Shamsa et al., 2018)**	**(Alserai et al., 2019)**	**(Ahmed et al., 2019)**
MK content (kg)	400	300	400	415
Mix proportions (MK:Sand:Gravel)	(1 : 1.8 : 2.75)	(1 : 2.16 : 4)	(1 : 1.8 : 2.75)	(1 : 1.14 : 2.98)
Fineness of MK (m^2/gm)	23.0	17.25	/	14.3
Molarity of solution	10	12	14	14
$NaOH:Na_2SiO_3$	1:3.5	/	1:3.5	1:2
Curing method of specimens	Exposed to sunlight in summer	Inside oven at 45±5°C as follow: With mold for 16 hr, After de-molded for 20 hr.	Under sunlight at (27-30) °C	Inside oven at 60 °C for 4-5 hr, then under sunlight at (35-49) °C in summer
Compressive strength (MPa)	27.53@ 7 days	24.95@ 7 days 34.44@28 days	30.8 @28 days	41.4 @ 7 days 44.03 @ 28 days

4. CONCLUSIONS

This review paper summarizes some of the national researches regarding the effect of using Iraqi activated kaolinite clay (metakaolin) as a partial cement replacement in different types of concrete. This study included the geographical information of kaolinite deposits in Iraq, chemical compositions, and thermal optimization treatment of metakaolin. Additionally, the fresh, hardened properties and some durability aspects have been investigated for particular types of concrete-like self-compacting concrete, high-performance concrete, and geopolymer concrete. The main findings notes across various studies of Iraqi researchers can be described in the following:

1- It is possible to produce (metakaolin) throw thermal activation of Iraqi kaolin clay at an optimum temperature of 700 °C for 1-2 hr.

2- The chemical composition analysis and strength activity index has indicated that Iraqi metakaolin can be classified as natural pozzolan type N according to ASTM C-618 for using as cementitious or pozzolanic materials in concrete.

3- The workability of self-compacting concrete has been adversely affected by the inclusion of MK as a partial replacement of cement. Therefore, more attention should be considered to using an optimum dosage of MK content in the SCC mixture.

4- Incorporation of 10%-15% of Iraqi metakaolin as SCMs would provide the ability to produce HPC with compressive strength up to 60 - 70 MPa, with superior durability performance.

5- There is a significant withstanding against aggressive environments like sulfate, chloride attacks, and external crude oil exposure of special concrete types containing MK.
6- The high volume fraction of Iraqi-MK within cement composite is an appropriate technique for a mass concrete application. In contrast, the highest strength gained by 20% MK content and mixes of 30-50% MK content have a moderate strength for structural purposes, while the dosage of 70% MK is unacceptable for replacement cement in concrete.
7- A scientifically proven Iraqi metakaolin can be used as a main precursor in synthesizing geopolymer concrete with great strength properties depending on accurate mix proportions, concentration of alkali solution, and sufficient curing regime.

Summarily, there was a common agreement across all previous national studies that the utilization of Iraqi metakaolin has shown a beneficial impact on developing special types of concrete. This also proves the feasibility of MK as an alternate binder of cement for enhancing sustainability in concrete technology. Therefore, further investigations are required to determine the characteristics and serviceability of structural applications based on special concrete types containing MK.

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