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The Synergic Effects of Mineral Admixtures in Ternary Blended Cement: A Review

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ABSTRACT

In the last decades, using mineral admixture in concrete became very necessary to improve concrete properties and reduce CO_2 emissions associated with the cement production process. Subsequently, more sustainable concrete can be obtained. Ternary blended cement containing two different types of mineral admixture can achieve ambitious steps in this trend. In this research, the synergic effects of mineral admixtures in ternary blended cement and its effects on concrete fresh properties, strength, durability, and efficiency factors of mineral admixture in ternary blended cement, were reviewed. The main conclusion reached after reviewing many literature pieces is that the concrete with ternary blended cement, depending on types of mineral admixtures used, replacement percentages by weight of cement, and age of concrete, exhibited superior properties than with no mineral admixtures and corresponding binary blended cement concrete.
Keywords: Synergic effect, Ternary blended cement, binary blended cement, Efficiency factor

التأثيرات المشتركة للمضافات المعدنية في مزيج السمنت الثلاثي: مراجعة

شبر جواد كاظم العبيدي
مدرس مساعد قسم الهندسة المدنية
الجامعة التكنلوجية
بغداد - العراق

الخلاصة

اصبح استخدام المضافات المعدنية في العقود الاخيرة مهما جدا لتحسين خواص الخرسانة ولتقليل كمية انبعاثات CO_2 المرتبطة بعملية انتاج السمنت، وبالنتيجة يمكن الحصول على الكثيرمن الخرسانة المستدامة. مزيج السمنت الثلاثي الحاوي على نوعين مختلفين من المضافات المعدنية يمكن ان يحقق خطوات طموحة بهذا الاتجاه. في هذا البحث تم مراجعة التأثيرات المشتركة

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للمضافات المعدنية في مزيج السمنت الثلاثي وتأثيراته على الخواص الطرية، المقاومة والديمومة للخرسانة، بالاضافة الى معامل الكفاءة. اهم الاستنتاجات التي تم الوصول اليها بعد مراجعة الكثير من الادبيات هي ان الخرسانة الحاوية على مزيج السمنت الثلاثي واعتمادا على انواع المضافات المعدنية المستخدمة، نسبة الاستبدال من وزن السمنت و عمر الخرسانة، اظهرت خواص متفوقة على الخرسانة الخالية من المضافات المعدنية و خرسانة السمنت ثنائي المزيج المطابقة لها.

الكلمات الرئيسية: التأثيرات المشتركة، مزيج السمنت الثلاثي، مزيج السمنت الثنائي، معامل الكفاءة

1. INTRODUCTION

The ordinary Portland cement (OPC) production has increased at a faster rate in the last decades. The global cement production in 2015 reached 3 billion tons, with an annual growth rate of 6.3% (**Tamanna and Raman, 2020**). This percentage represents 5%–8% of the total global CO_2 resulting from human-made activities **(Teixeira, et al., 2019)**. Many industrial, municipal, agricultural activities can generate huge by-products and waste a quantity; a big concern is how to dispose of these materials properly. Some of these wastes and by-product materials have either pozzolanic or cementitious properties, so using them as a partial replacement by the weight of cement in concrete can lower the high cost of production and environmental pollution related to cement manufacturing. Pozzolanic or supplementary cementitious materials (SCMs) can significantly reduce cement amounts and give required properties to concrete products that help obtain modern construction Requirements **(Sakir, et al., 2020)**. Recently using pozzolanic materials is becoming very necessary. The replacement of a considerable mass of clinker by a comparable mass of (SCMs) or pozzolana is meaningful from a sustainability perspective because they reduce the CO_2 emissions and permit the recycling of industrial by-products materials. In addition to improving mechanical and durability properties of concrete, due to the pozzolanic reaction which transform hydrated lime $Ca(OH)_2$ which has no binding properties to calcium silicate hydrate(C-S-H) **(Massazza, 1998)**. Various kinds of artificial by a product like (fly ash, silica fume, slags, etc.) and natural such as (volcanic tuffs, diatomaceous earth, etc.) SCMs are available to use in concrete, these SCMs different in their activity and reaction speed. Generally, the activity of SCMs depends on their fineness, amorphous silica contents, and the amount of $Ca(OH)_2$ liberated during the hydration of cement **(Malhotra and Metha, 2012)**. Several SCMs due to cement production increases are now blended with (OPC) clinker to produce binders with high sustainability. These blended types of cement can be defined as binary, ternary, and quaternary. Many researchers are trying to incorporate two or even more SCMs materials with clinker to form ternary blended cement. Ternary cement may comprise silica fume with slag or silica fume with fly ash **(Nkinamubanzi and Aïtcin, 1999)**. **(ASTM C595/C595M, 2014)** has defined ternary blended cement as "blended hydraulic cement incorporating Portland cement with a pozzolan, slag, or a limestone powder". **(EN 197/1-2011)** standardized ternary composite cements as CEM IIB-M (21–35% incorporation of SCMs and limestone powder), CEM II/A-M (6–20% incorporation of SCMs and limestone powder), CEM V/A (18–30% fly ash in addition to 18–30% slag or raw or calcined natural pozzolan) and CEM V/B (31–50% fly ash in addition to 31–50% slag or raw or calcined natural pozzolan). In Canada, a mixture of Portland cement clinker, silica fume (3–5%), slag (20–25%), and gypsum was ground together in a factory from 1999, and when this mixture was tested, has exhibited a comparatively early age and superior long term strengths relative to (OPC) captured from the similar clinker type **(Thomas, et al. 2007)**.

Ternary blended cement allows replacing a high volume of (OPC) with two different mineral admixtures types. One of these has slow reactivity, such as furnace slag, type F fly ash, etc., while the other has high reactivity, such as metakaolin, silica fume, etc. Incorporating high and slow reactivity mineral admixture mechanical and durability properties can be improved due to synergic effects **(Mala, et al., 2013)**. **(Radlinski and Olek 2012)** defined synergy as the interaction of two or even more than two mineral admixtures to get a mutual effect is greater than the summation of their singular effects. An example of a synergic effect is replacing cement with fly ash. The strength gain is lazy at an early age. This will be undesirable when high early-age strength is required. Still, by incorporating silica fume with high pozzolanic reactivity, this problem can be overcome due to the effect of these admixtures' synergy in ternary blended cement **(Mullick, 2007a)**. This research reviewed the synergic effects of mineral admixtures and its effects on concrete fresh properties, strength and durability, and efficiency factors of mineral admixture in ternary blended cement.

1.1 The Advantages of Ternary Blended Cement

In a ternary binder, the weakness when low activity mineral admixture is used can be compensated by incorporating another one with higher activity due to the synergic effect. In such a case, a greater level of (OPC) can replace in the concrete mixture. The reduction in cement content when a ternary blend is used means lower clinker and total binder contents. As a result, the carbon footprint and embodied energy of the concrete will be lower. Due to the synergic effect, ternary blended cement can exhibit substantial advantages and enhancements in mechanical and durability properties compared with binary blended cement and even pure Portland cement concrete **(Hooton, 2018)**. An example of the synergic effect in ternary blended cement is using silica fume jointly with fly ash or slag. While the silica fume gives higher early strengths, long term strength can be obtained by the fly ash or slag. The second example of the synergic effect is incorporating high-calcium fly ash (class F) with slag. The slag's early strength has been accelerated by the fly ash, while the slag helps to reduce the harmful effects of sulfates and alkalis **(Thomas, et al., 2010)**.

1.2 Physical and Chemical Requirements for Ternary Blended Cement

The **(ASTM C595, 14)** released in 2014 a standard specification for blended cement related to hydraulic cement taken by limestone (L), slag (S), pozzolana (P) or incorporations of these with Portland cement or combination of (S) with (L). **(ASTM C595, 14)** divided blended cement into two main groups (1) binary blended cement, which contains Portland cement with an (L), a (P) or an (S), and (2) ternary blended types of cement (Type IT), which contain Portland cement with either incorporation of two different types of pozzolans, a (P) and an (S), (L) and a (P) or an (S) and a (L). The physical and chemical requirements for Type IT cement according to **(ASTM C595, 14)** are included in **Tables 1** and **2,** respectively.

Table 1. Physical requirements for Type IT cement according to **(ASTM C595, 14).**

Autoclave Expansion (%)	Autoclave Cont. (%)	Le Chatelier Expansion (mm)	Initial setting time (minute)	Final setting time (hour)	Air content of mortar (%)
≤ 0.8	≤ 0.20	-	≥ 45	≤ 7	12

Table 2. Chemical requirements for Type IT cement according to **(ASTM C595, 14).**

Chemical requirement	IT(P < S < 70) IT(L < S < 70)	IT(S ≥70)	IT(P ≥S) IT(P ≥L)	IT(L ≥S) IT(L ≥P)
MgO, %	-	-	≤ 6.0	-
SO3, %	≤3.0	≤ 4.0	≤ 4.0	≤3.0
S2−, %	≤ 2.0	≤ 2.0	-	-
Ins. Res., %	≤ 1.0	≤ 1.0	-	-
LOI, %	≤3.0	≤ 4.0	≤ 5.0	≤ 10.0
Cl−, %	-	-	-	-

2. PROPERTIES OF TERNARY BLENDED CEMENT CONCRETE

2.1 Fresh Properties of Ternary Blended Cement

(Hooton, 2000) stated that the addition of low-calcium fly ash or slag for mixtures containing mineral admixtures with the high-surface-area, such as metakaolin or silica fume, which require a high dosage of superplasticizer to get specified workability in a fresh state, can improve workability and reduce superplasticizer dosage, which can cause stickiness when used with high dosage, so finishing process will be easier in addition to improve pump-ability **(PCA, 2009)**. **(Menéndez et al., 2002)** reported that by adding 20% slag to binary blended cement consisting of Portland cement and 18% limestone powder better slump retention can be obtained.

(MALA, 2014) investigated the effect of using fly ash (FA) and silica fume (SF) in binary and ternary blended cement mixes on superplasticizer (SP) dosage used to get given workability. The author concluded that (SP) dosage was reduced with increasing replacement percentages of (FA) in binary blended mixes, and it always lower than (SP) dosage of reference mix. While for these with (SF), (SP) dosage increased under the similar condition with respect to reference mix and binary blended cement of (FA). For ternary blended mixtures of (OPC+FA+SF), the (SP) dosages were more than their corresponding binary mixtures of (OPC+FA), but they were lesser than the reference mix at total replacement percentages larger than 20%. The reduction in (SP) dosages in ternary blended cement mixtures can be attributed to increased fluidity because of the spherical shape of (FA) particles.

(Georgescu and Saca, 2009) investigated the effect of using a powder of limestone (LMP) and fly ash (FA) on the mortar mixes consistency. The researchers concluded that the addition of (FA) or (LMP) apart or in incorporation led to improved consistency and reduced water demand of the mixes.

(Wang et al., 2011) examined the effect of using ternary blended cement of (LMP) and (FA) with various (LMP)/ (FA) ratio while total replacement percentages were kept constant at 50%. The researcher concluded that increasing the percentage of limestone powder led to the mix's consistency and reduced slump loss by increasing slump retention larger than one hour after mixing.

(Al Obaidey, 2019) reported that replacing a part of fly ash (FA) with high reactivity attapulgite (HRA) to produce ternary blended cement led to increasing superplasticizer dosages required to get the equivalent slump of control mixes, and the (SP) dosages increased with increasing of percentages of replacement of (FA) with (HRA). In contrast, binary blended cement mixes of

(FA) exhibited lower (SP) dosages than control mixes. The reduction in (SP) dosages increased with increasing percentages of replacement of (FA) by weight of cement due to the spherical shape of (FA) particle.

(Bentz, 2010) reported that using high mineral admixtures content such as 40% fly ash can reduce early-age strength and retard time of setting. Using ternary blended cement mixes with Nano limestone powder can help avoid the retardation of setting time for these mixes **(Sato and Beaudoin, 2011)**. Incorporating ultrafine mineral admixtures jointly with slag or fly ash can enhance cohesiveness and decrease segregation. The heat of hydration in massive concrete can reduce by using ternary blended cement due to the lowering of cement content in concrete mixtures **(Kashima, et al. 1992a)**. A ternary blend of cement with fly ash and cementitious slag with 30% and 50% contents was used to place mass concrete for walls and foundations of Akashi Kaikyo bridge **(Kashima, et al. 1992b)**.

(Mounanga et al., 2011) examined the effect of ternary blended cement involving fly ash (FA) and powder of limestone (LMP) on hydration heat. Firstly, binary blended cement was produced by replacing a part of the ordinary cement with fly ash. Then, mixes of ternary blended cement were produced by substituting a part of the (FA) with (LMP). For all binary and ternary mixes, the total replacement was kept constant. The researcher reported that replacement of (FA) partially with (LMP) led to an increment in the peak of heat flow but remained under the peak of heat for control mix (cement only mix). The researchers imputed that increasing the cement hydration rate because of the nucleation effect of (LMP). The authors also reported that the setting time of the mix generally accelerated by using limestone powder. Furthermore, mixes that contained more (FA) content than (LMP) tended to obtain an extended time of setting compared to the corresponding binary blended cement mixes vice versa.

(Snelson et al., 2007) investigated the effect of using binary and ternary blended cement containing metakaolin (MK) and fly ash (FA) on hydration heat. The researcher concluded that incorporating (FA) in ternary blended cement decreased hydration heat. At the same time (MK) increased it, especially at high replacement levels, but it still lower than this reference mix. Only 5% (FA) with 15 % (MK) exhibited an increase in heat evolution than the reference mix.

2.2 Efficiency Factor of Ternary Blended Cement

(Sridhar and Vanakudre, 2014) defined efficiency factor (k) as the efficiency of mineral admixtures to act as cement. For cement, only mixes (k) always equal to 1. If k>1, that means the mineral admixtures used are more efficient than cement, and the hydration is fast compared with that of cement. In other words, reducing cement content is possible and leads to the use of economic mix design. When k<1, mineral admixtures are less efficient, and hydration is slow compared with the hydration of cement. More quantity of mineral admixtures is required to obtain the equivalent strength of cement only concrete mixes. **(Shrihari, et al., 2016)** defined efficiency factor as a factor that characterizes mineral admixtures' capability to work as a cementing material. The contribution of mineral admixtures in concrete strength is due to its ability to react with $Ca(OH)_2$ consequent on the hydration of cement process, which is known as pozzolanic reaction (PR). The k value determines when the pozzolanic reaction (PR) is contrasted with the rate of cement hydration (CHR). When k=1, that means both (CHR) and (PR) would be the same, and the water to binder ratios of concretes with and without mineral admixtures could be nearly equal. When k<1, (PR) would be slower than (CHR). In such case, the mineral admixture at the same water to binder ratio exhibits less contribution than (OPC) in the strength of concrete, so the water to binder ratio of concrete containing mineral admixtures must be lower for equivalent strengths than that of concrete with no mineral admixtures when k>1, (PR) would be quicker than (CHR). In such a case, the mineral admixtures at the same water to binder ratio exhibits more contribution than (OPC) in concrete strength. The efficiency factor (*k*) was expounded firstly by **(Smith, 1967)**. A k value of (0.25) was found for mixtures including replacement up to (25%) by using Eq. (1) below, which is based on the law of Abram **(Abram, 1919),** which combines (w/c) ratio and compressive strength (fc).

$$\frac{W}{C} = \frac{W}{C'}\left[\frac{1}{1+\left(\frac{kF}{C'}\right)}\right] \qquad (1)$$

W and C are water content (kg/m^3) and the control mixture's cement content (kg/ m^3). (C') and (F) are cement and fly ash contents (kg/m^3) in the blended concrete of even strength; k is the efficiency factor.

Efficiency factor (k) values can also be determined depending on Bolomey's (**Bolomoy, 1927)** or Feret's **(Feret, 1897)** equations as given in Eq. (2) and (3) below, respectively

$$fc = K_B\left(\frac{C}{W+v} - k'\right) \qquad (2)$$

$$fc = K_f\left(\frac{c}{c+w+v}\right)^2 \qquad (3)$$

where, K_B and K_f are the Bolomey and Feret's coefficients respectively; *k*' is a factor; *fc* is the compressive strength (N/mm^2); *c* and *w* are the (OPC) and water contents in (dm^3/m^3) respectively, while *v* is voids volume (dm^3/m^3). W and C are water and cement contents in (kg/m^3), respectively.

Mainly, laws of Bolomey and Feret depend on the truth of concrete strength is correlated strongly with solids amount, voids, and liquids presence in the concrete mixture.

Many researchers in the last two decades have employed modifications and improvement of Eq. (1-3) mentioned above to estimate the efficiency factors of other pozzolans, in addition to fly ashes.

(Babu and Rao, 1996) estimated the efficiency factor of fly ashes (FA) by finding a connection between the (w/c) ratio and strength, in addition to age and amount of (FA) replacing the (OPC). The authors appoint three types of efficiency factors: (1) a general efficiency factor (k_e), which is age-dependent, (2) a percentage efficiency factor, (k_p), which is depending on fly ash amount which is replacing the cement and (3) an overall efficiency factor (*k*) which can be founded by the summation of (k_p) and (k_e). The author firstly tried to find the values of (FA) mixes strength close to that of their control concrete (concrete with Portland cement only) by using the Eq. (4) below:-

$$fc' = [W/(C + k_e FA)] \qquad (4)$$

W and C are water and cement contents of control mixture (kg/m3). FA is fly ash content in (kg/m^3) in the blended concrete; (k_e) is the general efficiency factor. The Authors found that the general efficiency factor, (k_e), was not sufficient for all levels of replacement by itself, so, by evaluating the difference in concrete strength by using the (k_p), the authors were capable of finding the strengths of mixtures contained fly ash adjacent to those of control concrete mixes by utilizing Eq.(5) below:-

$$fc' = [W/\,(C + keFA + KpFA)] \tag{5}$$

Finally, they suggested (k_p) and (k) for different ages as Eq.s (6) and (7-9), respectively.

$$kp = 2.54p2 - 3.62p + 1.13 \tag{6}$$

where p is the percentage of fly ash (%) relative to total cementitious materials.

$$k7 = 2.67p^2 - 3.75p + 1.45 \tag{7}$$

$$k28 = 2.78p^2 - 3.8p + 1.64 \tag{8}$$

$$k90 = 2.5p^2 - 3.59p + 1.73 \tag{9}$$

Where (7, 28 and 90) represent concrete ages (days).

(Babu and Kumar, 2000) applied similar **(Babu and Rao 1996)** conclusions for concrete containing ground granulated blast furnace (GGBFS). The researchers found that the efficiency factors, (k_e), (k_p) and (k), were 0.90, 0.39 to 0.20 and 1.29 to 0.70 for (OPC) replacement percentages ranged between (10% to 80%) by (GGBFS) at 28 days.

(Antiohos, et al., 2005) intermixed two types of fly ash, one with high calcium content (T_f) and another with lower calcium content (T_m). Before using them in ternary blended cement (T_f) and (T_m) were grounded in a mill to get an identical fineness to reduce the effect of fineness in their pozzolanic reactivity. Then the fly ashes were intermixed together with specified proportion by rotating blender until obtaining required homogeneity. The specified proportion were (T_1 =75% T_f + 25% T_m), (T_2= 50% T_f + 50% T_m), and (T_3= 25% T_f + 75% T_m). To evaluate efficiency factors (k), compressive strength for binary and ternary blended mortar was calculated. For binary cement mortar, T_f and T_m fly ashes were used as replacement percentages of 20% and 30% by cement weight. While for ternary blended mortar, T_1, T_2, and T_3 blends were used as a replacement percentage of (20 and 30) % by cement's weight. While w/c ratio was preserved constantly for a better comparison. To evaluate the efficiency factors (k) the authors suggested Eq. (10):

$$fc = K\left(\frac{1}{W/(C + kP)} - a\right) \tag{10}$$

where fc is the compressive strength, K is a constant reliance on the cement type (for cement used in the research is 38.8MPa), C, P, and W are the contents of cement, fly ash, and water respectively (kg/m^3), while (a) is a parameter depending on curing and time mainly. To find (a) value, Eq. (10) above used for control mixes (P=0) for each age. The efficiency factors of the all mixes were shown in **Table 3.**

Table 3. (*k*) value for all mixes **(Antiohos, et al., 2005).**

Age (days)	*k* value									
	SCM replacement of 20 %by cement weight					SCM replacement of 30 %by cement weight				
	Tf	Tm	T1	T2	T3	Tf	Tm	T1	T2	T3
2	0.67	0.81	0.72	0.82	0.8	0.63	0.71	0.65	0.71	0.70
7	0.92	0.72	0.89	0.94	0.84	0.73	0.65	0.72	0.76	0.78
28	0.92	0.88	0.75	1.09	0.85	0.76	0.78	0.76	0.85	0.92
90	0.99	0.97	1.12	1.15	1.06	0.99	0.82	0.91	0.95	1.03

The authors concluded that (*k*) factor for binary blended is always less than 1, and its values increase with increasing mortars ages. The results also showed that the efficiency factor for ternary blended cement is still more than that for binary blended cement at the same age and replacement percentages by cement weight. The authors attributed that to synergistic effects between the ashes, which caused improvements in the efficiency of the pozzolanic systems compared with control mixes and the corresponding binary blended cement mixes.

(Mala, et al., 2013) evaluated efficiency factor (*k*) for binary and ternary blended cement. For binary blended cement, two mixes of OPC + silica fume (SF) and four mixes of OPC + fly ash (FA). SF and FA contents of (7 and 10 %) and (20, 30, 40 and 50 %) as a replacement percentage by weight of cement were used, respectively. While for ternary blends, eight mixtures of (OPC + 7% SF+ FA) and (OPC + 10% SF+ FA) and total replacement percentages of 20, 30, 40 and 50 % by weight of cement were used. The total content of binder (OPC+ mineral admixtures) was kept at 450 kg/m^3 for all mixes used in this research. The authors suggested an equation to calculate the (*k*) value of (SF) and (FA) independently in ternary blended cement based on the modified equation of Bolomoy used for binary blended cement. Compressive strength for control mix can be predicted by using Bolomey's equation, as shown in Eq. (11) below:

$$fc = A_1(C/W) + A_2 \quad (11)$$

Where (*fc*) is compressive strength (MPa), while (C) and (W) are cement and water contents (kg/m^3) respectively, and A_1, A_2 are constants depended on concrete age and ingredients. For binary blend cement concrete containing FA and SF. Eq. (11) above was modified by **(Malathy and Subramanian, 2007)**:

$$fc = A_1\{C + k_{SF}P_{SF}/W\} + A_2 \quad (12)$$

$$fc = A_1\{C + k_{FA}P_{FA}/W\} + A_2 \quad (13)$$

Where P_{SF} and, P_{FA} are (SF) and (FA) contents (kg/m^3) respectively, k_{SF} and k_{FA} are the factors of efficiency for (SF) and (FA) respectively in the mixes of binary blended cement. To calculate (*k*) value of (SF) and (FA) when used in the mixes of ternary blended cement, the authors modified the equations above, as shown below:

$$fc = A_1\{C/W + k_{TB}\ (k_{SF}\ P_{SF} + k_{FA}P_{FA})/W\} + A_2 \quad (14)$$

Where k_{TB} is a synergistic effect factor of (FA+ SF) in ternary blended cement mixes.

$$k'_{SF} = k_{TB} * k_{SF} \quad (15)$$

$$k'_{FA} = k_{TB} * k_{FA} \quad (16)$$

Where (k'_{FA}) and (k'_{SF}) represent the factors of efficiency of (FA) and (SF) in ternary blended cement, respectively. A_1 and A_2 can be obtained at any age of concrete by using regression analysis and using the compressive strength of control mixes for specified concrete age. Then k_{SF} and k_{FA} were calculated using Eq.s (12) and (13) by applying the results of respective mixtures of binary blended cement. While (k_{TB}) was evaluated by utilizing Eq. (14) by applying the ternary blended cement mixtures results. Finally, (FA) and (SF) efficiency factors in ternary blended cement were computed by using Eq.s. (15) and (16). The results of the efficiency factor are shown in **Table 4**. The results clearly showed that factors of efficiency of ternary blend cement for (FA) and (SF) were always greater than their respective binary blended cement. The authors attributed that to the synergic effect, whereas the combined effect in ternary blended cement of (SF+FA) is greater than the summation of their singular effects. **(Isaia, et al., 2003)** attributed the synergic effect of mineral admixtures to the changes in the microstructure of hardened concrete. The reduction in pores size resulted from mineral admixtures pozzolanic activity and filling effect due to high fineness of (FA) particles **(Mala, et al., 2013)**.

Table 4. Factors of efficiency for (FA) and (SF) in ternary blended cement mixes **(Mala, et al., 2013).**

Days	A_1	A_2	k_{FA}	k_{SF}	k_{TB}	$k' = k_{TB} * k_{SF}$	$k' = k_{TB} * k_{FA}$
7	31.13	38.23	0.378	1.485	1.056	1.568	0.399
28	26.9	-8.64	0.469	2.524	1.09	2.75	0.511
56	24.45	8.35	0.563	2.692	1.065	2.866	0.599

(Al-Obaidey, 2019) calculated the efficiency factor for ternary blended cement containing high reactivity attapulgite (HRA) and fly ash (FA). Firstly the author evaluated the efficiency factor for binary blended cement of (OPC+ HRA) and (OPC+FA). For mixes containing HRA, two percentages of replacement were used (5% and 10%), while for binary blended cement mixes containing FA, three percentages of replacement were used (20%, 30%, and 40%). For ternary blended cement tow series of mixes were used (OPC+ 5% HRA+FA) and (OPC+ 10% HRA+FA) with total binder content of 500 Kg/m^3 kept constant for all mixes in the research. w/c ratio of 0.45 used for all mixes. Compressive strengths were tested at ages (7, 28, 56, and 90) days for all mixes. Bolomoy's Eq. (17) suggested by **(Bolomey, 1927)** and modified Bolomoy's Eq. (18) adopted by **(Khokhar, et al., 2010)** was used to calculate the efficiency factor:

$$fc = K\left(\frac{C}{W} - 0.5\right) \quad (17)$$

$$fc = K\left(\frac{C + kP}{W} - 0.5\right) \quad (18)$$

Where fc is compressive strength (MPa), K is Bolomoy´s constant, which can be calculated by Eq. (17) for control mixes containing cement only, and K is assumed to be constant for a given type of cement and aggregate but varies with age. C, W, and P are cement, water, and pozzolanic material contents (kg/m^3). While (k) is an efficiency factor depending on the type of mineral admixture used, age, and percentages of replacement with cement. **Table 5**. below includes the results of (k) values. For binary blended cement results, (k) values were lower at an early age and increased with increasing concrete age. For binary blended cement of (OPC+HRA), the results show that (*k)* values are more than 1 because of HRA's high pozzolanic reactivity. For the same replacement percentages, ternary blended cement exhibited higher (*k*) values than the corresponding binary blended cement due to FA and HRA's synergic effect, which produces additional CSH gel and reduces intermediate transition zone porosity by filling and strengthening effects **(Thanongsak, et al., 2010)**.

Table 5. (*k*) values for binary and ternary blended cement **(Al-Obaidey, 2019).**

Mixes designation	7 days	28 days	56 days	90 days
20% FA	0.15	0.64	0.84	0.86
30% FA	0.11	0.63	0.733	0.77
40% FA	0.1	0.6	0.64	0.72
5% HRA	1.0	1.36	1.64	1.56
10% HRA	1.48	1.55	1.96	1.7
15%FA + 5% HRA	0.63	0.81	0.92	0.9
10%FA+10%HRA	0.88	1.0	1.24	1.1
25%FA+5%HRA	0.51	0.75	0.78	0.8
20%FA+10%HRA	0.67	0.87	0.9	0.9
35%FA+5%HRA	0.4	0.68	0.72	0.75
30%FA+10%HRA	0.51	0.7	0.76	0.8

2.3 Strength of Ternary Blended Cement

(Shannag, 2000) examined the mortar's strength of ternary blended cement by incorporating natural pozzolan and silica fume (SF). Compressive strengths obtained at 28-days ranged between 69 and110 MPa. The highest increasing percentage in strength reached 26% and 60% higher than the corresponding binary blended cement of 15% SF, and 15% natural pozzolan concretes, respectively, was obtained by using a ternary blend containing 15% natural pozzolan and 15% SF, by weight of cement.

(Thomas, et al., 1999) examined the compressive strength of ternary blended cement concrete consists of type F fly ash and silica fume. The authors concluded that incorporating silica fume and fly ash together in ternary blended cement is synergistic and complementary. The results showed also that ternary blended cement of silica fume and type F fly ash increased concrete strength at all ages, and most of the increases can be obtained at an early age. While at later ages, the strength gain rate is comparable to silica fume mixes and 100% OPC concrete.

(De Weerdt, et al., 2011) investigated compressive and flexural strengths of ternary blended cement mortar comprised (30%) fly ash (class F) and 5% limestone powder. An increment of (15%) in compressive strength at the age of 90 days relative to reference (cement only) mix was noticed. While increments of 9% and 7% for binary blends of 30% fly ash and 5% limestone powder were obtained, respectively. For flexural strength, an increment of 23% at the age of 90 days relative to the reference mix was obtained. The authors attributed the useful effect of limestone powder in ternary blended cement to carbo-aluminates resulting from the chemical reaction between ettringite and carbonates from limestone powder.

(Seshasayi, et al., 2001) investigated the compressive strength of binary and ternary blends of silica fume (SF) and type F Fly ash (FA). The replacement percentages of (SF) and (FA) were (4%, 8%, 12% and 16%) and (10%, 20%, 30% and 40%) by weight of cement respectively. The maximum total replacement in ternary blended cement reached to 56%. **Fig. 1** included the results of compressive strength at (28) and (56) days. The results show that ternary blended cement mixtures of above 4% (SF) and up to 30% (FA) exhibits higher compressive strength than control mixes and corresponding binary blended containing (FA) at age of (28) and (56) days. The authors reported that the increase in ternary blends compressive strength was superior to the summation of increases obtained in the binary mixes at the same replacement percentages due to the effect of synergy between (SF) and (FA) ternary blended cement concrete.

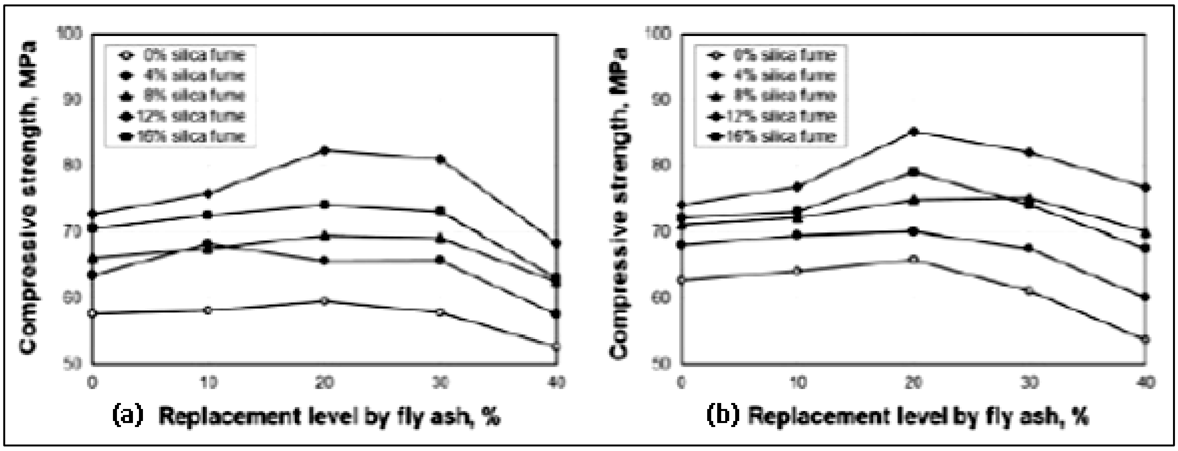

Figure 1. Compressive strength at (a) 28 days and (b) 56 days for ternary blended cement mixes of (OPC+SF+FA) **(Seshasayi, et al, 2001).**

(Antiohos, et al.,2007) used three types of fly ash to examine the compressive strength of binary and ternary blended cement mortars at ages of (2, 7, 28, and 90) days. Two high-calcium fly ashes (T_f) with moderate CaO and high reactive silica contents and (T_k) with low active silica were used. The third ash is (Tm) with a low calcium content. Various dosages of (T_f), (T_k), and (T_m) were intermixed to produce new fly ashes (T_1, T_2, T_3, and T_4) according to details shown in **Table 6.** below. Two replacement percentages for both binary and ternary blended, 20% and 30% by weight of cement were used.

Table 6. Mix proportions used for preparing the fly ash intermixtures **(Antiohos, et al., 2007).**

Intermixture	T_f (%)	T_k (%)	T_m (%)
T1	50	0	50
T2	0	50	50
T3	25	0	75
T4	0	25	75

The compressive strength results for replacement percentages of 20% and 30% are included in **Fig. 2,** respectively. For 20% replacement percentage, **Fig. 2(a)** shows that mixes containing fly ash have been started to improve strength faster than the control mix after the first two days. At ages beyond 28 days, both binary and ternary blended mixes exhibit either equal or approach the control mix's strength. (T_1) a mix containing (50% T_F + 50% T_m) shows maximum strength, and its strength value exceeded the strength value of the corresponding binary blended mixes containing either (T_f) or (T_m). The authors attributed that to the (Tf) synergic effect and (T_m) fly ashes. The synergic effect has also been noticed with other mixes, which exhibit a slight strength improvement than their corresponding binary blended cement mixes at the age of 90 days. This can indicate that synergic effects between the ashes increase with increasing in mixes age. The same conclusion was obtained for mixes containing 30%, except that mixes (T_3 and T_4), which contained a high content of low calcium fly ash (Tm) exhibited a slightly higher strength improvement than other mixes. The authors attributed that to the higher content of the active glassy phase of silica.

(Kannan and Ganesan, 2014) tested compressive and splitting tensile strengths for ternary blended metakaolin (MK) and rice husk ash (RHA) in SCC. The blending ratio was 1:1, while total replacement percentages ranged between (10% - 40%) by weight of cement. The results showed that both compressive and splitting tensile strength for ternary blends had to be improved relative to the control mix (100% OPC) at 28 days, and optimum replacement percentages were 30 % (15% RHA + 15% MK). The author attributed that to the synergic effect between (RHA) and (MK). However, a little synergistic effect between the RHA and MK was noticed, because both RHA and MK have a high reactivity and all binary blended cement mixes of (RHA) and (MK) in the range of replacement percentages of (5–25%) and (5–30%) by weight of cement respectively, exhibited improvements in compressive and splitting tensile strengths of concrete at the same age.

(Allahverdi and Salem, 2007) investigated the compressive strength of ternary and binary blended cement mortars. Binary blended cement mixes of limestone powder (LSP) and micro-silica (MS) with replacement percentages of (10%, 15%, 20%, 25%, and 30%) and (4%, 6%, 8%, 10%, 12%, 14%, and 16%) by cement weight were used, respectively, and for ternary blended cement mixtures with different replacement percentages of limestone powder and micro-silica were examined. Compressive strength for each mix was tested at (7) and (28) days. The compressive strength results at 7 and 28 days are included in **Fig. 3** and **Fig. 4,** respectively. For binary blended cement, the results showed that incorporating limestone powder led to reducing compressive strength, and the reduction increased with increasing replacement percentages by weight of cement. The results showed that incorporating micro silica caused increments in compressive strength relative to control mix for replacement percentages up to 12% for binary blended cement of micro silica. The authors attributed that to the high reactivity of micro silica containing 96% of glassy silica. The results show that incorporating limestone powder with micro silica led to increased compressive strength relative to corresponding binary blended cement of limestone powder for ternary blended cement. And mixes containing 12% micro silica and limestone powder up to 25 % either exceeded or equalized compressive strength of control mixes at both ages.

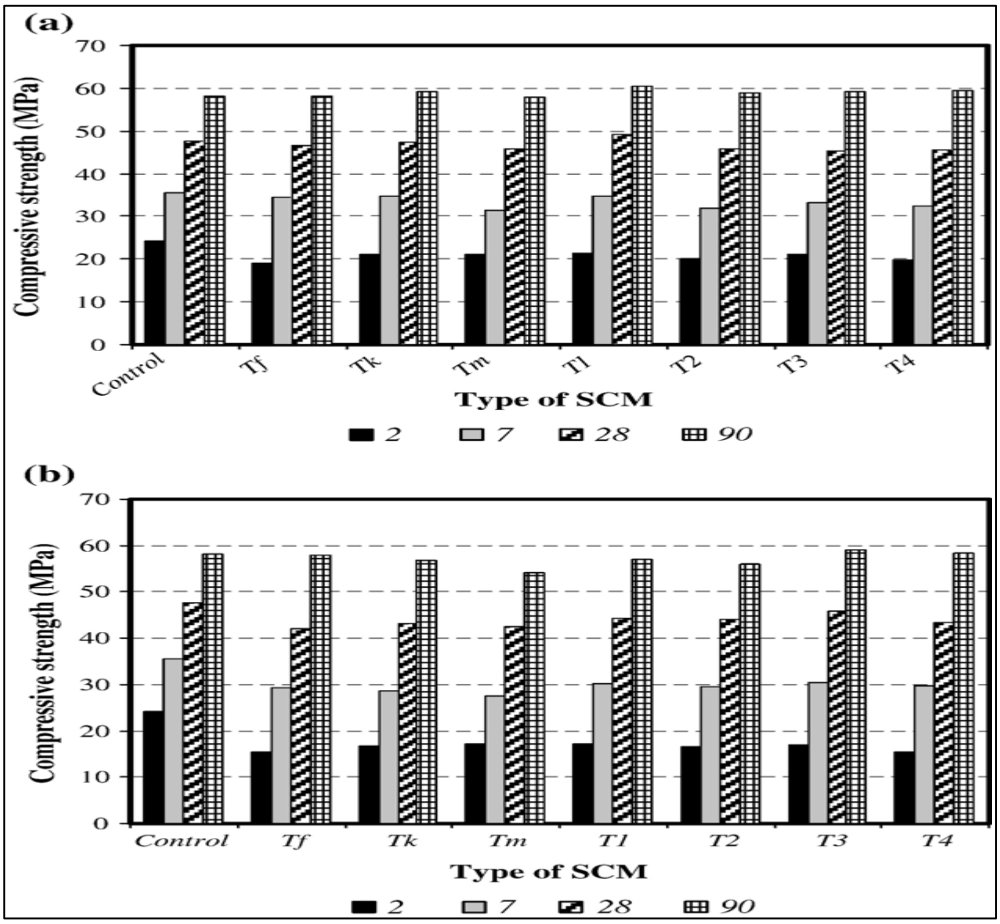

Figure 2. Compressive strength for (a) 20% and (b) 30% (SCMs) by weight cement replacement **(Antiohos, et al., 2007).**

2.4 Durability of Ternary Blended Cement

The use of mineral admixtures like silica fume, meta-kaolin, slag and fly ash is one of the best methods used to inhibit a destructive expansion resulting from alkali silica reaction (ASR), because of their ability to decrease the content of alkali in concrete when used as a replacement percentage by weight of cement. In addition to their ability to increase strength due to increasing the formation of C-S-H gels and decreasing the rate of silica dissolution from aggregate **(Shafaatian and Akhavan, 2013)**. Besides, their high ability to reduce ASR, mineral admixtures

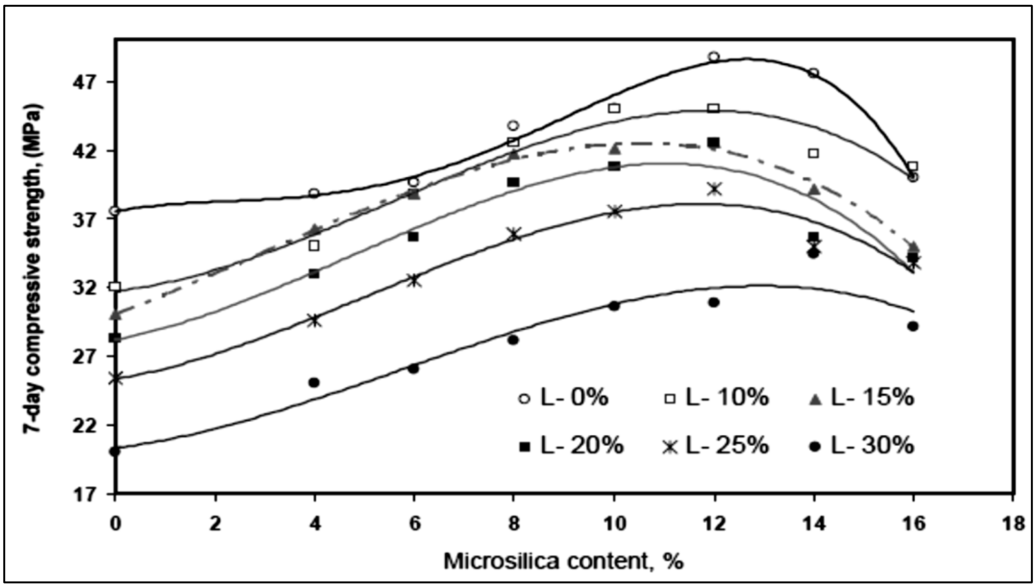

Figure 3. 7-day compressive strengths of ternary blends with (LSP) and (MS) **(Allahverdi and Salem, 2007).**

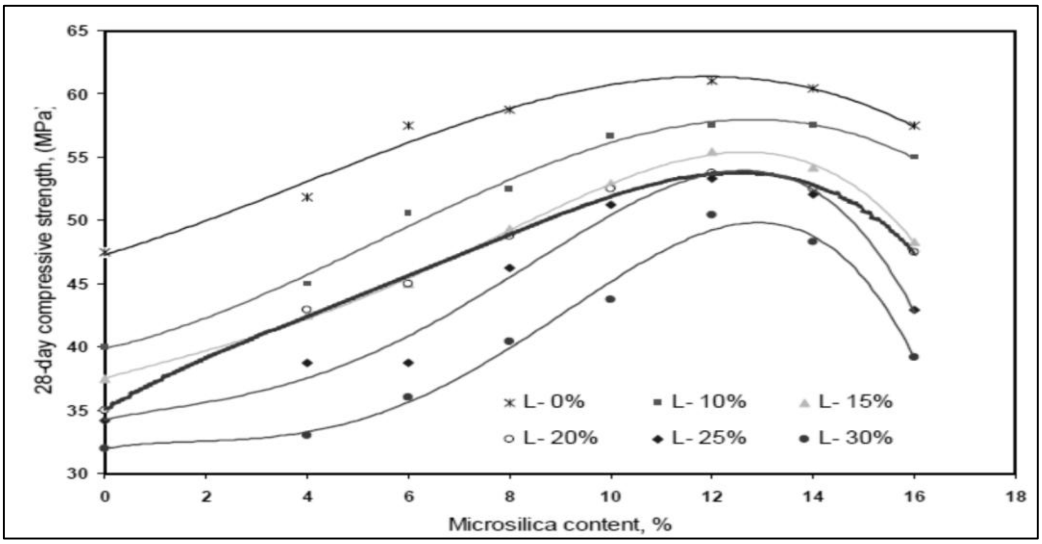

Figure 4. 28-day compressive strengths of ternary blendes with (LSP) and (MS) **(Allahverdi and Salem, 2007).**

have been utilized to mitigate sulfate attack due to minimizing both gypsum formation and ettringite **(Barcelo, et al., 2014)**. As a result of the pozzolanic reaction, mineral admixtures consume Ca(OH)2 liberated during the cement hydration process (**Al-Obaidy, 2017).** Thus secondary C-S-H gel can form denser than the primary C-S-H gel and leads to pore refinement **(Atahan and Dikme, 2011)**. According to **(Bye, 2011)**, blended cement can reduce sulfate attack by reducing C3A and C3S contents due to reduced cement content. This leads to a reduced amount of $Ca(OH)_2$ and aluminate hydrates, which can react with sulfates (**Al-galawi and Hassooni, 2016)**. Permeability of concrete increases external sulfate's ability to go deeply into concrete, so blended cement with a high finer pore structure can reduce permeability, thus improving resistance to sulfate attack **(Bijen, 1996)**. Because of a strong correlation between the $Ca(OH)_2$ content in cement paste and sulfate attack, so ternary blended cement with a lower $Ca(OH)_2$ content which consumed significantly during the synergic pozzolanic reaction, the obtained relationship emphasizes that $Ca(OH)_2$ consumption is a contributing factor for the improved ternary blends performance **(Kandasamy and Shehata, 2014)**. **(Mullick, 2007b)** stated that by incorporating fly ash, silica fume, and slag in ternary and binary blended cement, higher durable concrete can be obtained in an aggressive environment. This durability improvement can be attributed to strengthened aggregate-matrix interface, denser microstructure, increasing water tightness, and decreasing of micro cracks.

(Jones et al., 1997) scrutinized the durability by testing chlorides penetration and carbonation of ternary blended cement concrete included silica fume (SF) and fly ash (FA) compared to (OPC) and a binary blend of (OPC+FA) mixtures. The researchers reached that the chloride penetration and carbonation of all the ternary blended cement concrete mixtures were appreciably lower than the corresponding (OPC) and binary blended cement mixtures.

(Hart, et al., 1997) stated that the use of ternary blended cement of silica fume with fly ash or slag exhibited high resistance to chloride penetration for high performance concrete used for the lining of tunnels and cast-in-place concrete utilized in decks for bridges and parking.

(Saraswathy and Song, 2007) examined the corrosion resistance of blended cement consisting of fly ash and pozzolana cement (PPC). The researchers used multi electrochemical tests on pre-cracked reinforced concrete slabs and concluded that blended cement of fly ash and (PPC) concrete showed higher corrosion resistance than mixes contained ordinary Portland cement only.

(Hooton, 2014) investigated the ability to reduce the deleterious effects due to alkali-silica reaction (ASR) and chloride penetration by using a ternary blended cement of slag and silica fume. Hooton found that a binary blend of slag with low slag content of 25% had a limit effect to resist the deleterious expansion of ASR, but using a ternary blended cement of slag and silica fume with silica fume content ranged between 5-6% exhibited excellent resistance to ASR and penetration of chlorides

(Turk, et al., 2017) investigated the effect of using binary and ternary blended cement on alkali-silica reaction (ASR) of mortar was prepared according to **(ASTM C 1260, 2014)** and **(ASTM C 227, 2003)**. Total binder content of 440 gm. The water to binder ratio of 0.47 was used for all mortars. For binary blended cement, limestone powder (LSP) and fly ash (FA) with replacement percentages of (10, 20, and 30) % by weight of cement were used. While for ternary blended cement replacement percentages of 10%, 15%, and 20% were used for LSP and FA. The results of the expansion of the binary and ternary blends of (FA) and (LSP) are shown in **Fig. 5** and **Fig. 6,** respectively. The results show that the expansion ratio resulting from (ASR) at 3 days for control mortar was lower than that for all ternary blended mortar, but the expansion ratios at longer ages begin to decrease with increasing of (FA) and (LSP) contents relative to control mixes. The results show also that the ratio of expansion for the ternary blends of 20% (FA) + 20% (LSP) at 14 days was lesser than that of corresponding binary blends of 20% (LSP) and 20% (FA). The authors concluded that ternary blends exhibited greater activity than the binary blended cement mixes to reduce (ASR) and attributed that to the synergetic effect between FA and LSP. Whereas FA reduces pore solution alkalinity, permeability, and diffusivity due to pozzolanic activity. While

LSP with no alkali, therefore, it lowers the contents of alkali in the mixes of concrete when used to replace cement content in concrete

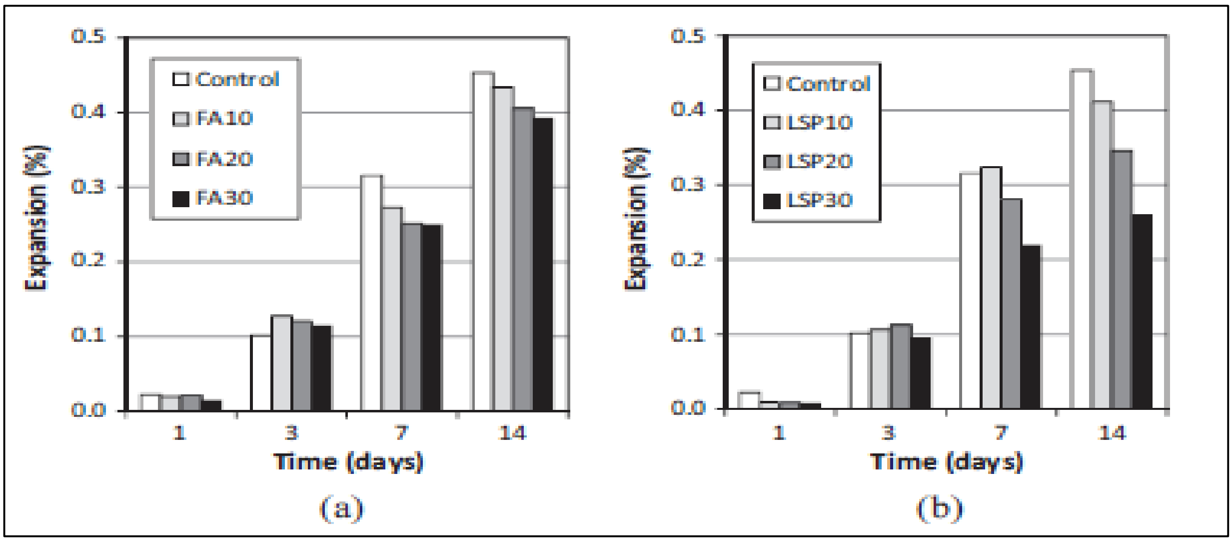

Figure 5. Expansion of mortar with binary blended cement of (a) FA, (b) LSP **(Turk, et al., 2017)**.

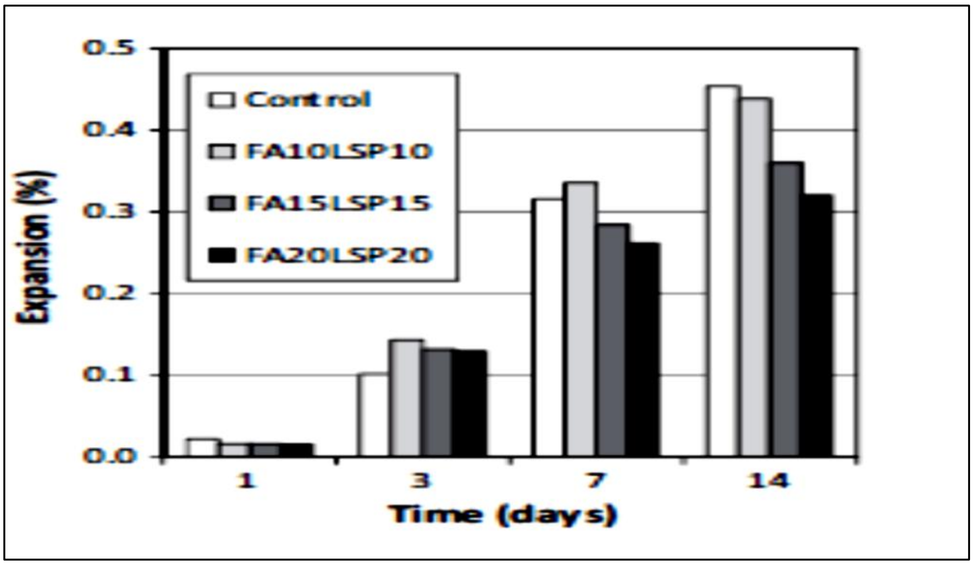

Figure 6. Expansion of mortar with ternary blended cement of LSP and FA **(Turk, et al., 2017)**.

(Sullivan, et al., 2020) investigated the effect of using binary blended cement containing 15% metakaolin (MK) and ternary blends cement consists of 30% blast furnace slag and 15% (MK) as a cement replacement on rapid chloride-ion penetrability (RCPT) according to (**ASTM C1202, 2017)** and sulfate resistance according to **(ASTM C1012, 2018)**. One mix with (45%) fly ash content was used for comparison purposes. Two blast furnace slag of grade 120 are used, denoted as (Sla) and (SLb). Binder content of 422 (kg/m^3) and w/c ratio of 0.43 and 0.485 were used for (RCPT) for concrete and sulfate resistance for cement mortar, respectively. The results of (RCPT) are included in **Fig. 7,** and it shows that for a binary blended cement, only mix contained 15%

(SLb) reduced (RCPT) by lowering the total passing charge to1440 Coulombs (C), i.e., less penetrability was obtained according to **(ASTM C1202, 2017)** classification. While all ternary blended cement concrete mixes exhibited either low or very low permeability of chlorides. Sulfate test results are included in **Fig. 8**. The results show that all binary blended cement except this contained Fly ash exhibited higher expansion than **(ASTM C1012, 2018)** limit for six months sulfate expansion, especially for the mortar included (Sla) due to greater Al_2O_3 content and the lesser fineness of (Sla). In contrast, all ternary mixtures exhibited a high ability to reduce the sulfate expansion to lower than the ASTM limit.

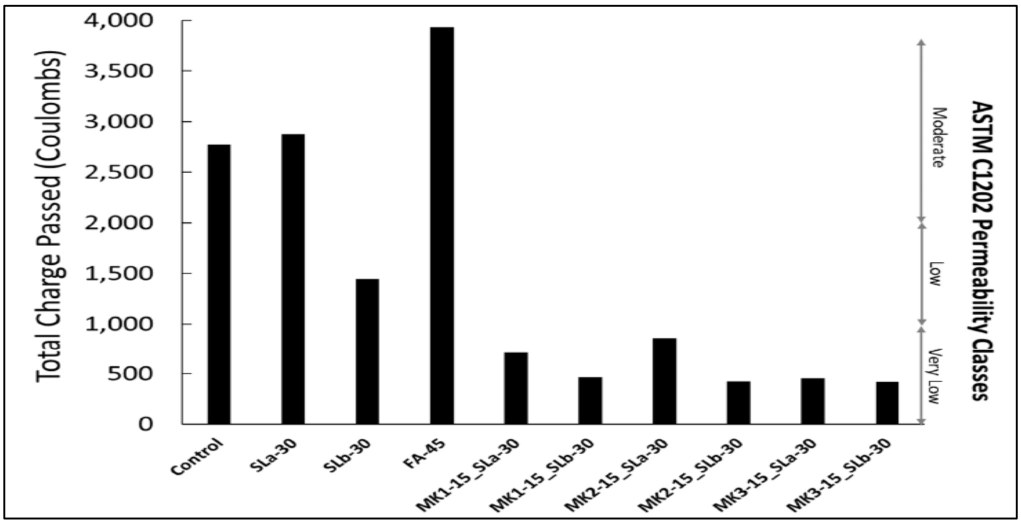

Figure 7. Permeability of all mixes by (RCPT) **(Sullivan, et al., 2020)**.

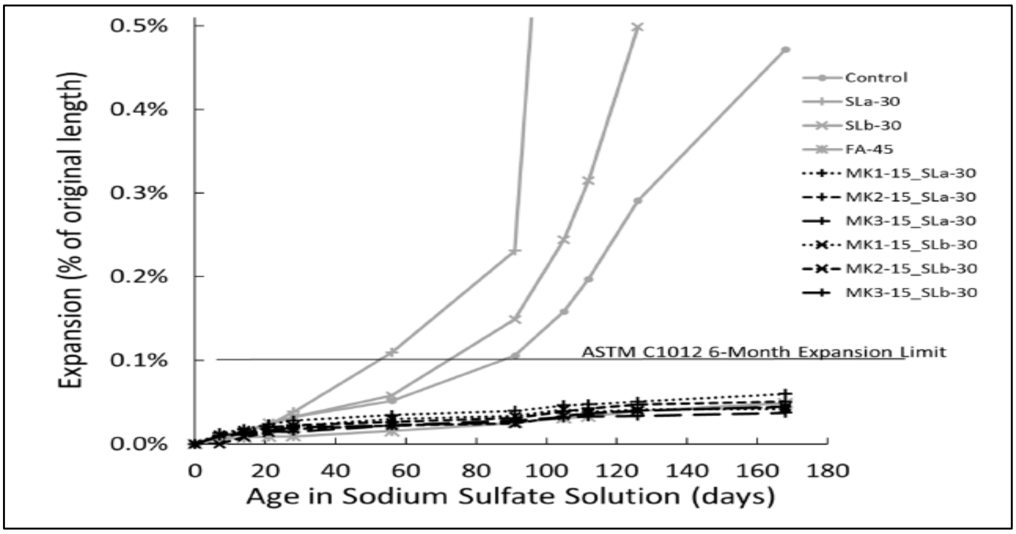

Figure 8. Expansions of all mortar mix in sodium sulfate solution **(Sullivan, et al., 2020)**.

3. CONCLUSIONS

After reviewing the literature, the following conclusions were obtained:-

1- Workability and dosage of superplasticizer must be detected to obtain a specified slump for ternary blended cement concrete depend on mineral admixtures type and replacement percentages used. Generally, mixes with ternary blended cement exhibited significant effects on cohesiveness and increase segregation resistance of concrete, while the heat of hydration reduces due to reducing cement content.

2- An addition of fly ash or slag to binary blended cement concrete mix contained mineral admixture with high surface area such as silica fume, high reactivity attapulgite, and metakaolin can improve workability and pump ability without needing to increase water content or superplastisizer dose due to spherical particle shape of fly ash and slow reactivity of slag.

3- An addition of mineral admixture with low or slow reactivity such as class F fly ash or slag to binary blended cement mixes containing high reactivity mineral admixture such as silica fume, metakaolin, and class C fly ash is very necessary to reduce the heat of hydration and extend setting time of concrete. This is very useful in hot weather concreting and placing of mass concrete and sophisticated concrete work.

4- Efficiency factor (k) of ternary blended cement exhibited a significant increasing relative to control mixes, and corresponding binary blended cement mixes. By increasing (k), higher replacement percentages of mineral admixture by weight of cement can be utilized.

5- Concrete with ternary blended cement depending on types of mineral admixtures used, replacement percentages by weight of cement and age, illustrated higher improvement in strength when compared with both control mixes and corresponding binary blended cement mixes due to synergic effects of mineral admixtures when used together in ternary blended cement.

6- An addition of mineral admixture with high reactivity such as silica fume, metakaolin, high reactivity attapulgite, and class C fly ash or limestone powder with high fineness to binary blended cement mixes consisting of low reactivity mineral admixture such as class F fly ash and slag to produce ternary blended cement mixes is very necessary to improve early age strength of concrete. This is very beneficial when high early-age strength is required.

7- A significant improvement in the durability of concrete with ternary blended cement concrete was obtained due to the reduction of permeability of concrete, which is a decisive factor in concrete durability. The improvement of durability by reducing concrete permeability when ternary blended cement mixes are used can be attributed to strengthened aggregate-matrix interface, denser microstructure, increasing water tightness, and decreasing micro cracks. By reducing concrete permeability, ingress of detrimental salts and acids can cause sulfate attack, corrosion of reinforcement bars, penetration of chloride ions, and carbonation can be reduced.

8- Utilization of ternary blended cement concrete leads to a significant reduction in expansive cracks resulting from sulfate attack and alkali-silica reaction due to this type of concrete's superior ability to consume higher $Ca(OH)_2$ content than both binary blended cement and cement only concrete by its pozzolanic reactions.

9- More sustainable concrete can be produced when ternary blended cement concrete is used because by using ternary blended cement, high content of CO_2 emissions related to the cement manufacturing process can be reduced due to reducing of cement content in concrete mixes. In addition to reduce the maintenance works of concrete due to accomplished properties of this type of concrete.

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