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EFFECT OF METAKAOLIN ACTIVATION AND ALCCOFINE ON THE MECHANICAL STRENGTH OF CONCRETE AT ELEVATED TEMPERATURE

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ABSTRACT

This research examines the possibility of chemically activating MK (Metakaolin) to increase the MK ratio with strength improvement at both standard and elevated temperatures. Besides, cement was replaced by AF (Alccofine) with a ratio of up to 15 % to improve concrete workability and strength. MK was tested with ratios ranging from 0% to 30%, with a 5% increase. MK was activated chemically using two activators: 2.5% Na_2SO_4 and 4% Aquis Na_2SiO_3. AF was investigated at 5%, 10%, and 15% ratios. 0.7% glass fibres (GF) were added to improve concrete ductility. According to the results of the tests, MK. up to a ratio of 15% without an activator improved concrete strength. After 28 days, the increase in strength was more pronounced. After the 15% ratio, the concrete strength improvement was rapidly declined. The Aquis Na_2SiO_3 activator increased the strength of the concrete while diminishing its workability. AF improved workability and concrete strength when subjected to normal and after being exposed to elevated temperatures. Using GF at a weight ratio of 0.7% on activated 30% MK with Aquis Na_2SiO_3 and 10% AF improved splitting and flexural strength at normal and increased temperatures Furthermore, GF avoided the spalling of concrete samples induced by the application of AF. Correlations between different mechanical parameters of concrete using multiple regression analysis. A good agreement between the predicted equations' outputs and the experimental results for compressive, splitting, and flexural strengths. Further, a cost analysis was conducted for the suggested mix by comparing it with a high-strength concrete mix of the same grade, and workability.

KEYWORDS: Metakaolin, Alccofine, Glass fibers, Fire resistance, Chemical activation, Workability.

تأثير تنشيط الميتاكولين والألكوفين على الخصائص الميكانيكية للخرسانة عند درجة الحرارة المرتفعة

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الملخص

إستخدام الميتاكولين والألكوفين كبديل جزئي للأسمنت في الخرسانة يقلل من التلوث البيئي ، ويحافظ على الموارد الطبيعية ويحسن قوة الخرسانة. يوضح هذا البحث إمكانية زيادة نسبة استبدال الأسمنت بـالميتاكولين حتى نسبة 30٪. تم استكشاف التحفيز الكيميائي لـلميتاكولين لتحقيق الزيادة في نسبة الميتاكولين مع تحسين مقاومة الخرسانة في درجات الحرارة العادية والمرتفعة. إلى جانب ذلك ، تم استبدال الأسمنت بـالألكوفين بنسبة تصل إلى 15٪ لتحسين قابلية تشغيل الخرسانة ومقاومتها. تم دراسة استخدام الميتاكولين بنسب من 0٪ إلى 30٪ ؛ بزيادة قدرها 5٪. تم تحفيز الميتاكولين كيميائيًا باستخدام منشطين كيميائيين ؛ كبريتات الصوديوم 2.5 % و 4 % ميتاسيليكات الصوديوم . تم فحص عينات الخرسانة باستخدام الألكوفين بنسب 5٪ و 10٪ و 15٪. مع اضافة الألياف الزجاجية بنسبة 0.7٪ لتحسين مرونة الخرسانة. أشارت نتائج الاختبار إلى أن الميتاكولين تصل إلى نسبة 15٪ بدون التحفيز زاد من مقاومة الخرسانة ، وكان زيادة مقاومة الخرسانة أكثر أهمية بعد 28 يومًا ، بعد أن انخفضت نسبة تحسين مقاومة الخرسانة بنسبة 15٪ تدريجيًا. كان منشط ميتاسيليكات الصوديوم المائية هو الأفضل في ضوء مقاومة الخرسانة وقوة الشد والانحناء ولكنه قلل من قابلية التشغيل. وعمل الالكوفين على تحسين قابلية

التشغيل وزيادة مقاومة الخرسانة في درجات الحرارة العادية والمرتفعة. استخدام الألياف الزجاجية بنسبة 0.7٪ من الوزن على خرسانة بنسبة 30٪ الميتاكولين المنشط باستخدام ميتاسيليكات الصوديوم المائية و نسبة 10٪ الألكوفين حسن مقاومة الشد ولانحناء في درجات الحرارة العادية والمرتفعة ، بالإضافة إلى ذلك ، منع الألياف الزجاجية انفجار الخرسانة الناتجة عن استخدام الألكوفين. تم عمل الارتباطات بين العوامل الميكانيكية المختلفة للخرسانة باستخدام تحليل الانحدار المتعدد. أظهر البحث وجود توافق جيد بين مخرجات المعادلات المتوقعة والنتائج التجريبية لمقاومة الضغط والشد الانحناء. علاوة على ذلك ، تم إجراء تحليل التكلفة للخلطة المقترحة من خلال مقارنته بخلطة خرسانية عالية المقاومة من نفس الرتبة ، وقابلية التشغيل

الكلمات المفتاحية : ميتاكولين ، ألكوفين ، ألياف زجاجية ، مقاومة حريق للخرسانة ، التحفيز الكيميائي للميتاكولين ، قابلية تشغيل الخرسانة.

1. INTRODUCTION

Kaolin clay is a hydrated aluminum disilicate, $Al_2\ Si_2O_5\ (OH)_4$. Thermally treated between 600 °C and 850 °C under carefully controlled conditions converts it to an amorphous phase named MK ($Al_2(OH)_4Si_2O_5$) [1]. Above this temperature, Kaolin clay creates mullite, a non-pozzolanic material. The optimal duration and temperatures for thermal activation of kaolin vary depending on the author [2]. stating that the temperatures ranged from 450 to 850 °C, while the calcination times ranged from 30 min to 3 hours.

Another often-used way of activating kaolin clay is chemical activation. Compared to the competition, it is superior at increasing strength [3] and has the lowest-cost-to strength ratio. Alkali and sulfate activation are typically the two different chemical activation strategies evaluated. The most popular methods for chemical activation for pozolans include sulfate activation using $CaSO_4\ 2H_2O$ or Na_2SO_4 [4] and alkali activation using $Ca\ (OH)_2$ or NaOH. The activation processes $CaCl_2$, Na_2SiO_3, and CaO [4-8] are other methods.

The hydrate of Na_2SiO_3 could maintain the concentration of alkali in solution, and on the other side its product, silica gel, would change to gel with solid properties when the gel loses water gradually. In fact, this gelatinization is the process of transformation from linear structure to reticular structure [8]. To address the issue of insufficient heat activation and improve the process of activation operations, chemical activation of kaolin clay can be performed after thermal activation. Chemical activation offers the opportunity to raise the MK content in concrete.

Adding MK to concrete with (0 to 30 %) improves the mechanical properties, it was concluded that 20% MK replaced OPC in concrete accelerated OPC hydration [9]. When using MK, the pozzolanic reaction strengthened the desire beyond 14 days [9]. In addition, chemical composition and changes to the paste microstructure significantly reduce permeability and can dramatically improve the durability of concrete [1].

Furthermore, by consuming $Ca\ (OH)_2$ and recrystallizing C-S-H, thermally activated kaolin clay to concrete reduces the paste's initial and final setting times. It improves the microstructure of the formed hydrates. Furthermore, thermally activated kaolin clay poses high compressive strength values at earlier ages [1].

The significance of employing MK on concrete strength with different w/c ratios on concrete strength after 28 and 90 days was investigated [10]. They found that MK concrete at a w/b of 0.3 has a lower porosity and smaller pore sizes than the control (plain) concrete. It was found that MK influence was optimal at 10% and 15% MK levels [11,12].

Adding MK to concrete improves concrete fire resistance [8, 13, 14]. MK consumes $Ca\ (OH)_2$ in concrete which is reasonable for vapor pressure when concrete is exposed to fire [8, 13]. The compressive strength at 200 °C was enhanced by replacing Portland cement with 0, 5, 10, and 20% MK. At higher temperatures, the MK concrete suffered a greater loss in compressive strength than the corresponding SF, FA, and OPC concretes [15]. Explosive spelling was observed in both normal and high strength MK concretes and the frequency increased with higher MK contents. This spalling is forecasted as result of lower porosity and smaller pore sizes occurs when using higher MK contents [10].

Alccofine 1200 exists in three series: 1201, 1202, and 1203, and the particle size for each series is fine, microfine, and ultrafine, respectively. It is used in concrete to increase the numbers of fines, achieve self-compatibility, and improve fresh and hardened concrete qualities because of its distinctive chemistry and ultrafine particle size. AF offers a high-range water reducer with up to a 70% replacement ratio, which enhances the strength and workability of concrete [16-21].

Using AF as a mineral additive boosted concrete's strength, decreased the water/cement ratio, and improved workability [18]. The substitute level of cement by 10% AF increased compressive and flexural strength of concrete at all curing ages to an enormous extent [18]. The strength increased rapidly at early ages; latterly, it increased gradually. If the ratio of AF is extended beyond this limit, it acts as a filler material and yields high workability to the concrete.

In self-compacted concrete (SCC), the cement substitution by 15% MK had reached the ideal compressive, split tensile, and flexural strengths [22]. Additionally, the 12% MK and 12% AF cement substitution also reached their peak compressive, split tensile, and flexural strength [16].

The use of AF powder was investigated to increase the number of fines and achieve self-compatibility. The properties of SCC containing AF were investigated by replacing cement with AF by 5%, 10%, and 15%. Test results illustrated that the fresh and hardened properties of SCC with 10% AF produced greater compressive strength than SCC with 5% or 15% AF [20].

Test results suggest that using MK and AF in concrete production significantly saves cost and energy and enhances the concrete’s strength and durability properties. MK and AF replacement levels were 5%, 7.5%, 5%, 10%, and 15% by weight of cement, respectively. It was concluded that the compressive and flexural strengths increased with MK and AF replacement levels [21].

Several types of researches dealt with the impact of using MK on concrete; most of these researches highlight that the optimum replacement ratio of cement with MK is 15% [23-31], Above this ratio the strength starts to decline. This research investigated the possibility of using high proportions of MK up to 30% to achieve the optimal saving of cement in concrete. Chemical activation of MK was explored to realize the increase in MK ratio with strength improvement at normal and elevated temperatures. Besides MK, cement was replaced by AF with a ratio of up to 15 % to achieve a larger replacement ratio of cement, reduce environmental pollution, save natural resources and produce economic concrete. Concrete strength was investigated for all concrete mixes at normal and after exposure to elevated temperature.

The main purpose of this study is to develop high-strength concrete with superior fire resistance using chemically activated natural pozzolans (MK) and artificial pozzolans (AF) with a total replacement ratio of up to 45 percent cement. Two activators were investigated for MK: Sodium sulfate (Na_2SO_4) and Aquas Sodium Silicate (Na_2SiO_3).

2. EXPERIMENTAL STUDY

The research includes three stages: Stage investigating the effect of cement replacement by MK besides the effect of chemical activation of metakaolin, this stage involved replacing a portion of the cement with MK at ratios of 10%, 15%, 20%, 25%, and 30%. Two activators were investigated: 2.5% Na_2SO_4 and 4% aquis Na_2SiO_3 to activate MK. The concrete's compressive, splitting, and flexural strengths were investigated under normal conditions and after exposure to elevated temperatures. Whereas Stage II investigates the effect of adding Alccofine to the suggested MK concrete mix for chemical activation. Concrete's compressive, splitting, and flexural strengths were evaluated under normal conditions and after exposure to high temperatures. Finally, Stage III investigated the impact of adding GF to chemically activated MK concrete with AF. Concrete compressive, splitting, and flexural strengths were tested at normal and increased temperatures.

2.1 Materials

Cement, metakaolin, aggregate, Alccofine 1203, glass fibers, superplasticizer, sodium sulphate (Na_2SO_4), and aquis sodium silicate (Na_2SiO_3) were employed in this experiment. The used cement was ordinary Portland cement (CEM I 42.5 N) complying with ES 4756-1/ 2009 [32]. Metakaolin is a fine powder manufactured from the dihydroxylation of kaolin clay. MK was generated by thermally activating Egyptian kaolin clay extracted from the southwestern Sinai quarries (Essela). The activation was by heating the kaolin clay in a muffle furnace for 3 hours at temperatures ranging from ambient temperature to 850 °C. The author established the preparation method and type based on previous research [33]. The kaolin clay was treated to the finest possible fineness following calcination to fulfill ASTM C618 standards. Tables 1 and 2 exhibit the chemical and physical properties, respectively.

Table 1: Metakaolin Physical Properties

Property	Test result
Brightness	60 hunters
Specific Gravity	2.5
Color	Off white
Specific surface area (cm^2/g)	60220

Table 2: Metakaolin Chemical Properties

Chemical component	Chemical analysis (%)
SiO_2	63.10
Al_2O_3	32.12
S_2O_3	1.20
TiO_2	0.83
K_2O	0.50
SO_3	0.10
N_2O	0.02
$K_2O + Na_2O$	0.61
CaO	0.10
Mn_2O_3	0.02
Loss On Ignition	0.50

The used natural siliceous sand has a fineness modulus of 2.85 and stone with particle sizes; S1 (5 to 20 mm) and S_2 (10 to 25 mm). The Alccofine was a slag-based ultrafine, low-calcium silicate product with a high glass content and strong reactivity produced through controlled granulation. Table 3 displays the chemical characteristics of Alccofine. The glass fibers were E-glass single filament fibers with diameters of 13 microns, lengths of 6 mm, and 18 mm with a ratio of 1:1. The superplasticizer complying with ASTM C 494 Type F, was used. The used Sodium silicate Manufactured directly in a solution from by the wet process where the silica leached out under pressure by concentrated caustic soda solution. The percentages of Na_2O and SiO2 of Liquid sodium silicate were 14.7 and 29.4 and density of the activator was 1.5 g/cm^3. The sodium hydroxide solution of NaOH was prepared by dissolving sodium hydroxide pellets with a purity of 97% in deionized water at least 1 day prior to mixing.

Table 3: Alccofine 1203 Chemical Constituent

Chemical component	Chemical analysis (%)
SiO_2	33-35
CaO	32-34
Al_2O_3	18-20
Fe_2O_3	1.8-2
SO_3	0.2-0.7
MgO	8-10

2.2. Mix Proportions

Twenty-two concrete mixes were performed for the study. Six mixes were made to evaluate the impact of partially substituting cement with MK at amounts from 0 to 30% with an increment of 5% by weight. Another ten mixtures were performed to explore the effect of the chemical activation of MK. Two chemical activators were utilized in these combinations: 2.5 % Na_2SO_4 and 4% aquis Na_2SiO_3.

Based on the results of stage I, three more concrete mixes were executed to investigate the effect of replacing cement with Alccofine. The replacement percentages with AF were 5%, 10%, and 15% by cement weight. Before adding water, Alccofine was well mixed with the cement. Finally, 0.7% by cement weight GF was added to the stage II selected mix. The GF ratio was chosen based on the previous research.

The w/c ratio for all concrete mixtures was 0.45 (160.7 liters/m^3). A superplasticizer was applied to enhance and sustain continuous workability. The sand and crushed stone weights were 550 and 1100 Kg/m^3, respectively; other proportions are reported in Table 4.

Table 4: Mix Proportions (Kg/m^3)

ID*	Cement	Metakaolin	Alccofine	Glass fibers	Super plasticizer	Activator	
						Type	Dose
C	375	-	-	-	7.75	-	-
MK10	337.5	37.5	-	-	8.05	-	-
MK15	318.75	56.25	-	-	8.08	-	-
MK20	300	75	-	-	8.10	-	-
MK25	281.25	93.75	-	-	8.15	-	-
MK30	262.5	112.5	-	-	8.20	-	-
AMK101	337.5	37.5	-	-	8.05	2.5 % Na_2SO_4	9.4
AMK151	318.75	56.25	-	-	8.05		9.4
AMK201	300	75	-	-	8.10		9.4
AMK251	281.25	93.75	-	-	8.15		9.4
AMK301	262.5	112.5	-		8.20		9.4
AMK102	337.5	37.5	-	-	8.05	4% Aquis Na_2SiO_3	15.0
AMK152	318.75	56.25	-	-	8.05		15.0
AMK202	300	75	-	-	8.10		15.0
AMK252	281.25	93.75	-	-	8.15		15.0
AMK302	262.5	112.5	-	-	8.20		15.0
AAMK5	243.75	112.5	18.75	-	7.90		15.0
AAMK10	225.00	112.5	37.50	-	7.80		15.0
AAMK15	206.25	112.5	56.25	-	7.70		15.0
AAMG5	243.75	112.5	18.75	2.63	8.15		15.0
AAMG10	225.00	112.5	37.50	2.63	8.00		15.0
AAMG15	206.25	112.5	56.25	2.63	7.75		15.0

* **C:** Control Mix **MK:** Inactivated Metakaolin **AMK:** Chemically Activated Metakaolin
AAMK: Alccofine and Chemically Activated Metakaolin
AAMG: Alccofine, Chemically Activated Metakaolin and Glass Fibers

2.3. Test Procedures

The concrete's intended slump was 100 mm. The compressive strength was evaluated using cubic samples 100mmx100mmx100mm prepared by E.S.S 1658, and the splitting tensile strength was determined using cylinders 100mmx200 mm prepared by ASTM C 496-90. Prisms 100mmx100mmx500 mm were used to measure the flexural strength by ASTM C 78 - 02. Concrete samples were stored in the molds for 24 hours at room temperature before being de-molded and stored in water at (20 ± 2) °C until testing. For each test, three samples were cast. Compression, splitting, and flexure tests were performed at ages 3, 7, 28, 56, and 180 days. Specimens were burned in an electric oven at a heating rate of 5°C /min for 3 hours until 600°C was attained. Before testing, specimens were allowed to cool to room temperature.

3. RESULTS AND DISCUSSION

3.1. MK Effect on Concrete Strength

Tables 5, 6 and 7 indicate the results of compressive, splitting and flexural strengths respectively for MK concrete mixes; at ages 7, 28, 56, and 180 days at normal temperature.

Table 5: Compressive Strength for MK (N/mm^2)

Age	Control (C)	MK10	MK15	MK20	MK25	MK30
3	18.0	18.0	19.7	19.4	18.7	17.8
7	27.0	27.1	29.1	28.6	28.1	26.7
28	40.0	45.1	49.2	46.4	44.5	43.6
56	41.0	47.3	51.6	48.6	46.2	43.8
180	45.0	48.4	52.8	49.7	47.8	46.8

Pozzolanic materials increase the strength of concrete through three main features. These features are filler, acceleration within 24 hours, and pozzolanic effects. As illustrated in Table 5, the compressive strength increased up to a dose of 15% cement weight. The increase in strength was more significant after 28 days, when the average compressive strength of concrete (MK15) increased by 23.0%, from 40.0 MPa to 49.2 MPa. The increase in strength after 7 days was 7%, from 27.0 MPa to 29.1 MPa. A further increase in MK content starts to reduce the strength enhancement. This is because the mixture lacked enough $Ca(OH)_2$ [8,13] for the pozzolanic reaction, and MK was only used as a filler. Besides, the tested mixture had a low water-cement ratio; at w/c = 0.45, part of the cement will remain un-hydrated [34]. As a result, higher MK doses require a higher water-cement ratio, resulting in more $Ca(OH)_2$.

Table 6: Splitting Tensile Strength for MK (N/mm^2)

Age	C	MK10	MK15	MK20	MK25	MK30
3	1.8	1.9	2.1	2.0	2.0	1.9
7	2.7	2.8	3.1	3.0	3.0	2.8
28	4.1	4.7	5.2	4.9	4.7	4.6
56	4.4	5.0	5.4	5.1	4.8	4.6
180	4.6	5.1	5.5	5.2	5.0	4.9

Table 7: Flexural Strength for MK (N/mm^2)

Age	C	MK10	MK15	MK20	MK25	MK30
3	3.2	3.3	3.6	3.9	3.8	3.7
7	4.9	5.0	5.4	5.8	5.7	5.6
28	7.3	8.1	8.9	9.7	9.2	8.8
56	7.7	8.5	9.4	10.2	9.6	9.1
180	8.3	8.7	9.6	10.5	9.8	9.5

Similarly, replacing cement with MK with a ratio of up to 15 % significantly increased splitting and flexural strength after 28 days as indicated in Tables 6 and 7. With 15% MK, the splitting and flexural strength were enhanced at age 28 days by 30.0% and 23.6%, respectively. Further improvement in strength occurred up to 180 days.

Table 8 presents the test findings of concrete samples following exposure to elevated temperatures at the ages of 56 and 180 days.

Ibrahim, S.S. concluded that the intensity of the calcium hydroxide peaks $Ca(OH)_2$ of ordinary cement paste with 10% replacement of cement by MK was lower than in the case of neat ordinary cement paste, whereas the peak of the hydration products of calcium silicate hydrates and calcium aluminates silicate hydrates was higher in the OPC-MK10 samples. This conclusion was based on the X-ray diffractometry analyses [35]. As a result, using MK enhanced the strength of concrete significantly. This increase in strength is due to the interaction of MK with $Ca(OH)_2$ [35].

The increase in C-H-S gel development, the principal component of the concrete structure is responsible for imparting high residual strength after the fire. Furthermore, increased MK concentrations limit concrete's thermal conductivity and shield the internal concrete layers from heat damage [36]. Compared to the control mix, cement replacement with 30% MK delivered the biggest strength gain after exposure to harsh temperatures; it enhanced compressive, splitting, and flexural strengths at age 180 days by 62%, 47%, and 54%, respectively.

Table 8: Compressive, Splitting Tensile, and Flexural Strength for MK (N/mm^2)

Strength	**Age**	**C**	**MK10**	**MK15**	**MK20**	**MK25**	**MK30**
Compressive Strength	56	22.0	26.0	31.0	33.1	34.2	35.5
	180	24.0	26.6	31.7	32.3	35.3	38.9
Splitting Tensile	56	2.4	2.6	3.1	3.3	3.4	3.5
	180	2.6	2.7	3.2	3.2	3.5	3.9
Flexural Strength	56	4.1	4.7	5.6	6.0	6.2	6.4
	180	4.5	4.8	5.7	5.8	6.4	7.0

3.2 Chemical Activation Of MK

The results for compressive, splitting tensile and flexural strength tests for control mix C, chemically activated MK concrete by employing 2.5 % Na_2SO_4 and 4% Aquis Na_2SiO_3 at normal temperature are illustrated in Tables 9, 10 and 11, respectively.

Table 9: Compressive Strength for AMK (N/mm^2)

Age	Activator	AMK10	AMK15	AMK20	AMK25	AMK30
3	2.5 % Na_2SO_4	21.9	23.9	28.0	33.0	33.7
7		30.5	32.8	38.5	46.4	47.4
28		47.1	51.4	57.1	65.4	69.0
56		51.1	55.7	61.5	68.1	66.9
180		52.3	55.4	61.8	67.6	70.4
3	4% Aquis Na_2SiO_3	25.2	27.5	32.3	37.0	38.8
7		34.5	37.0	43.5	52.5	53.5
28		48.5	52.9	58.8	67.3	71.1
56		53.6	58.5	64.6	72.2	72.6
180		55.4	58.8	65.5	73.3	73.9

Table 10: Splitting Strength for AMK (N/mm^2)

Age	Activator	AMK10%	AMK15%	AMK20%	AMK25%	AMK30%
3	2.5 % Na_2SO_4	2.2	2.4	2.8	3.3	3.4
7		3.0	3.3	3.9	4.6	4.7
28		4.7	5.1	5.7	6.8	6.9
56		5.1	5.6	6.1	6.8	7.0
180		5.2	5.5	6.2	6.7	7.0
3	4% Aquis Na_2SiO_3	2.5	2.8	3.2	3.7	3.9
7		3.4	3.7	4.4	5.2	5.4
28		4.8	5.3	5.9	7.0	7.1
56		5.4	5.9	6.5	7.1	7.3
180		5.5	5.9	6.5	7.0	7.3

Table 11: Flexural Strength for AMK (N/mm^2)

Age	Activator	AMK10	AMK15	AMK20	AMK25	AMK30
3	2.5 % Na_2SO_4	3.9	4.3	5.0	5.9	6.1
7		5.5	5.9	6.9	8.4	8.5
28		8.5	9.2	10.3	12.2	12.4
56		9.2	10.0	11.1	12.3	12.6
180		9.4	10.0	11.1	12.0	12.7
3	4% Aquis Na_2SiO_3	4.5	5.0	5.8	6.7	7.0
7		6.2	6.7	7.8	9.4	9.6
28		8.7	9.5	10.6	12.5	12.8
56		9.7	10.5	11.6	12.7	13.1
180		10.0	10.6	11.8	12.6	13.2

When using MK at high substation ratios, greater than 15%, $Ca(OH)_2$ will not be sufficient to react with MK. As a result, MK particles operate as a filler or are aggregated to form crumbles. These crumbles created weak spots in the concrete, limiting its strength. Chemical activators improve concrete strength at all ages by reacting with the surplus MK particles.

As demonstrated in Table 9, both the utilized chemical activators provide high early strength; Aquis Na_2SiO_3 was the greatest in enhancing concrete strength; the compressive strength for AMK 30% mix utilizing Aquis Na_2SiO_3 was doubled at age 3 and 7 days when compared with inactivated MK. The strength enhancement was progressively diminished after 7 days; the enhancement was 80% at age 28 days when compared with inactivated MK 30%. However, the inclusive improvement in compressive strength after 180 days by substituting cement by 30% by AMK was enhanced by 63% compared to the control mix.

In terms of compressive strength enhancement, the effect of the Na_2SO_4 activator is less than that of Aquis Na_2SiO_3. Compressive strength for AMK, 30% mix, activated with Na_2SO_4 reduced by 13% and 12% at 3 and 7 days, respectively. At 28, 56, and 180 days, these levels were lowered to 3%, 8%, and 5%, respectively. Although MK mixes activated with Na_2SO_4 demonstrated lower strength improvement than Aquis Na_2SiO_3, Na_2SO_4 imparted higher workability. Similar patterns were discovered for splitting and flexural strengths, as reported in Tables 10 and 11.

Table 12 illustrates the results for compressive, splitting tensile and flexural strength tests for chemically activated MK concrete by employing 2.5 % Na_2SO_4 and 4% Aquis Na_2SiO_3 after exposure to elevated temperature.

Table 12: Compressive, Splitting Tensile, and Flexural Strengths for AMK (N/mm^2)

Activator	Strength	Age	MK10	MK15	MK20	MK25	MK30
2.5 % Na_2SO_4	Compressive	56	28.1	33.4	40.0	47.7	48.8
		180	28.7	33.9	40.2	48.3	51.4
	Splitting	56	2.8	3.3	4.0	4.3	4.9
		180	2.9	3.4	4.1	5.0	5.3
	Flexural	56	5.1	6.0	7.2	8.6	8.8
		180	5.2	6.2	7.3	8.7	9.4
Aquis Na_2SiO_3	Compressive	56	29.5	35.1	42.0	50.5	53.1
		180	30.6	35.8	42.6	51.3	54.3
	Splitting	56	3.2	3.6	4.3	5.1	5.3
		180	3.7	3.7	4.4	5.1	5.6
	Flexural	56	5.3	6.3	7.6	9.1	9.6
		180	5.6	6.5	7.8	9.4	9.8

The inclusion of AMK considerably enhanced concrete strength, which might be due to the interaction of MK with Ca $(OH)_2$ degraded at high temperatures. This resulted in the creation of additional C-H-S gel, the critical element of concrete construction responsible for high residual strength after the fire. For AMK 20%, AMK 25%, and AMK 30%, noticeable spalling occurred at temperatures exceeding 450 °C. It was prevalent in Aquis Na_2SiO_3-activated concrete mixtures. This spalling was created by excessively high-water pressure triggered by reduced concrete permeability because silica particles filled concrete gaps when Aquis Na_2SiO_3 was applied.

As indicated in Table 12, activating MK 30% with Aquis Na_2SiO_3 enhanced compressive, splitting, and flexural strength by 40%, 44%, and 40%, respectively, after 180 days when compared to inactivated MK 30%. When the Na_2SO_4 activator is employed, this effect is somewhat lessened. On the other hand, the Na_2SO_4 activator was employed to minimize concrete spelling.

Based on earlier test results and discussions, it is evident that the Aquis Na_2SiO_3 activator is the best activator for MK in enhancing concrete strength at normal and elevated temperatures. consequently, AF was added to the chemically activated AMK 302% using Aquis Na_2SiO_3 activator to increase concrete workability and splitting strength.

3.3. Effect Of Alccofine

The effect of replacing cement with AF by ratios 5%, 10%, and 15% on the proposed chemically activated concrete mix (AMK302%) at normal temperature is illustrated in Table 13.

Table 13: Compressive, Splitting Tensile, and Flexural Strengths for AAMK (N/mm^2)

Strength	Age	3	7	28	56	180
Compressive	AAMK5	41.9	58.4	77.5	79.9	82.0
	AAMK10	43.1	60.1	80.6	83.1	85.6
	AAMK15	43.7	60.7	81.4	83.1	85.7
Splitting	AAMK5	4.3	6.0	8.1	8.3	8.5
	AAMK10	4.4	6.2	8.3	8.5	8.8
	AAMK15	4.6	6.1	8.6	8.6	9.1
Flexural	AAMK5	7.8	10.7	14.1	14.1	15.0
	AAMK10	7.8	10.8	14.6	15.3	15.7
	AAMK15	7.9	10.9	14.6	15.3	15.8

As illustrated in Table 13, the strength increased rapidly at early ages; after that, the increase was gradual. Adding Alccofine by 5% enhanced the early strength; it improved compressive strength at age 3 days by 8%, and this enhancement was increased gradually up to 11% at 180 days. Increasing Alccofine to 10% improved compressive strength by 11% at age 3 days; this ratio increased to 16% at 180 days. When increasing the ratio of Alccofine to 15%, a minor improvement occurred. Similar trends have occurred for splitting and flexural strength.

Adding Alccofine increased strength, workability, filling and passing ability, and resistance to segregation. Furthermore, AF will be economical in high-performance concrete.

The compressive, splitting tensile and flexural strength tests after fire exposure at ages 56 and 180 days are illustrated in Table 14. Alccofine's high pozzolanic reaction significantly boosted concrete strengths. At a 10% Alccofine substitution ratio, the improvement was significant. Compressive, splitting, and flexural strengths were enhanced after 180 days by 15%, 20%, and 19%, respectively. Due to the significant void-filling capacity of Alccofine particles, explosive spalling occurred at 300ºC when concrete samples were exposed to fire. Maximum spalling occurred at 15% AF. To remedy this problem, 0.7% GF was added to the concrete mix.

Table 14: Compressive, Splitting Tensile, and Flexural Strengths for AAMK at Elevated Temperature (N/mm^2)

Strength	Age	AAMK5	AAMK10	AAMK15
Compressive	56	58.3	59.8	56.5
	180	59.3	61.9	57.7
Splitting	56	6.1	6.2	5.6
	180	6.2	6.4	5.8
Flexural	56	10.5	10.8	10.2
	180	10.7	11.4	10.4

3.4 Glass Fiber (GF)

Table 15 illustrates concrete strength for mixes containing 0.7% GF by weight of cement. GF was added to concrete mixes containing activated MK 30% using Aquis Na_2SiO_3 and Alccofine with ratios from 5% to 15% at normal temperature.

Table 15: Compressive, Splitting Tensile, and Flexural Strengths for AAMG (N/mm^2)

Strength	Age	3	7	28	56	180
Compressive	AAMG5	37.3	51.4	64.3	66.3	67.2
	AAMG10	38.4	52.9	66.9	68.9	71.0
	AAMG15	38.9	53.4	67.6	68.9	71.2
Splitting	AAMG5	4.6	6.7	8.6	9.0	9.6
	AAMG10	4.9	6.8	8.6	9.2	9.7
	AAMG15	5.0	6.9	8.7	9.1	9.5
Flexural	AAMG5	8.4	12.0	15.2	15.8	15.7
	AAMG10	8.6	12.6	15.9	16.6	17.0
	AAMG15	7.7	12.0	12.8	16.9	17.3

It was clarified that the addition of GF decreased compressive strength. At ages 3, 28, and 180 days, the reduction for AAMG5% was 11%, 17%, and 18%, respectively. AAMG10% and AAMG15% showed identical reductions. When GF fibers were used to prevent micro-crack localization into macro-cracks, the splitting strength was dramatically boosted, increasing by 7%, 7%, and 13% at 3, 28, and 180 days, respectively, when compared to mixes without fibers. Flexural strength showed identical improvement.

Table 16 and Figures 1–3 show the results at 56- and 180-days following exposure to increased temperatures. It is established that the addition of GF significantly enhanced the strength of concrete at 180 days of age. This behavior is most likely due to GF's lower thermal conductivity when compared to the concrete matrix. As a result, GF protects the interior matrix of concrete from thermal degradation. Furthermore, it remains under elevated temperature for extended periods and saves connecting the matrix, restricting crack spread and heat interference over cracks.

Table 16: Compressive, Splitting Tensile, and Flexural Strengths for AAMG at Elevated Temperature (N/mm^2)

Strength	Age	AAMG5	AAMG10	AAMG15
Compressive	56	59.0	60.7	60.7
	180	60.5	62.5	64.0
Splitting	56	6.0	6.2	6.2
	180	6.2	6.4	6.5
Flexural	56	10.8	11.1	11.1
	180	11.1	11.5	11.8

The strength improvement with GF was limited for AAMG5 and AAMG5 mix, as indicated in Table 16, compared to the exact mixes shown in Tables 14 and 15. At 180 days, the improvement was 10% for AAMG15. Adding GF to all mixtures reduces sample spalling for all concrete mixes.

The increasing consequence of temperature on strength is demonstrated in Figures 1 to 3**.** The early strength increases up to about 200 °C is noticeable, and it could be considered to be due to MK activation in the MK30% mix. The strength allows for a stability stage between 150 and 450 degrees Celsius. Following that, a significant decrease in strength is detected. The presence of GF had a significant impact on reducing strength loss, particularly for splitting and flexural strengths. Similar patterns were seen for GF in Figures 1–3; compressive strength was limited by 30%, 10%, 12%, and 8% for C mix, MK30, AMK30, and AAMG10, respectively, following exposure to increased temperature at 500 °C. Similarly, for the control mix, MK30, AMK30, and AAMG10, splitting strength was reduced by 32%, 14%, 20%, and 10%, respectively, while flexural strength was lowered by 25%, 16%, 20%, and 14%, respectively.

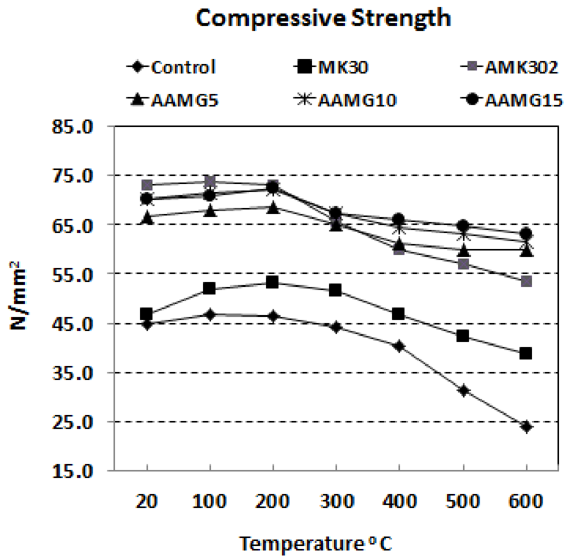


Fig. 1: Compressive Strength

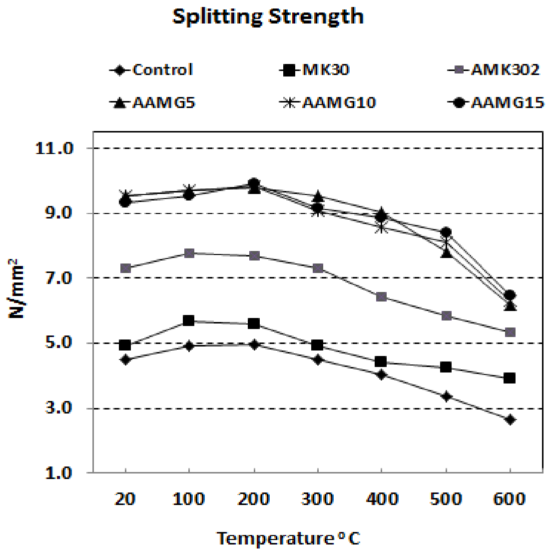


Fig. 2: Splitting Tensile Strength

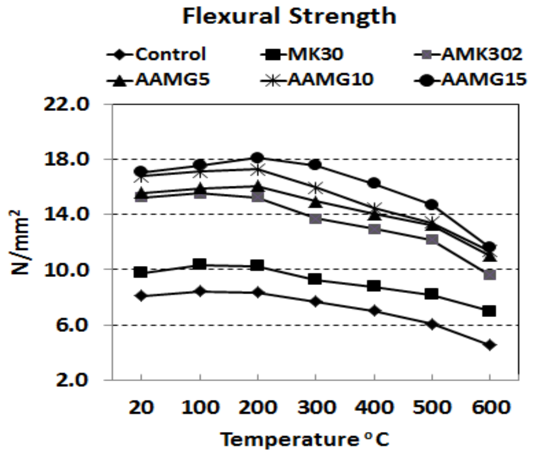


Fig. 3: Flexural Strength

4. MECHANICAL STRENGTH CORRELATIONS

The mechanical properties of concrete containing metakaolin as a partial replacement for cement depend on various factors. It has been concluded that these factors are the percentage of metakaolin, the age of the concrete (days), the water–cement ratios, and other factors related to the activation and chemical composition of metakaolin [37]. In this study, the water-to-cement ratio was constant for all mixes and the admixture was varied to attain relatively similar workability.

Multiple regression analysis was performed on the experimental study results concerning the metakaolin and Alccofine effects. Table 17 presents the factors for predicting the equations to estimate the compressive, splitting, and flexural strengths at ages 3, 7, and 28 days for Metakaolin and Alccofine. at a normal temperature and after exposure to an elevated temperature.

Table 17: Factors of the Predicted Equations for Estimating Compressive, Splitting, and Flexural Strength

Age (days)	Parameter	Compressive strength (N/mm^2)		Splitting strength (N/mm^2)		Flexural strength (N/mm^2)	
		Factor	R^2	Factor	R^2	Factor	R^2
Metakaolin (MK mix) At Normal Temperature							
3,7,28	Constant	19.54	0.95	2.051	0.95	2.978	0.95
	MK%	-0.07		-0.008		0.028	
	Age	1.00		0.105		0.197	
56,180	Constant	50.89	0.45	5.344	0.45	7.924	0.57
	MK%	-0.21		-0.022		0.059	
	Age	0.013		0.001		0.003	
Metakaolin (MK mix) After Exposure to Elevated Temperature							
56,180	Constant	21.668	0.96	2.295	0.92	4.017	0.95
	MK%	0.486		0.042		0.084	
	Age	0.009		0.001		0.002	
Alccofine (AAMK Mix) At Normal Temperature							
3,7,28	Constant	41.62	0.90	4.220	0.92	7.792	0.90
	AF %	0.27		0.030		0.027	
	Age	1.31		0.140		0.234	
56,180	Constant	77.50	0.84	7.866	0.94	13.629	0.82
	AF %	0.35		0.045		0.100	
	Age	0.02		0.003		0.005	
Alccofine (AAMK Mix) After Exposure to Elevated Temperature (600 °C)							
56,180	Constant	4.220	0.92	7.866	0.93	7.792	0.90
	AF%	0.030		0.045		0.027	
	Age	0.140		0.003		0.234	
Alccofine (AAMG Mix) After Exposure to Elevated Temperature (20 to 600^{o}C)							
180	Constant	68.341	0.83	10.382	0.72	16.639	0.83
	AF%	0.388		0.004		0.160	
	Temp.	-0.017		-0.005		-0.009	

Based on the predicted factors in Table 17, the compressive, splitting, and flexural strengths are calculated and reported in Tables 18-20 for mixtures at normal temperature and subjected to increased temperature. In addition, the differences between the predicted and the experimental strengths were displayed.

Table 18: Comparison Between Experimental and Predicted Values for Compressive, Splitting, and Flexural Strength at Normal Temperature

Mix Type	Age	Compressive strength (N/mm^2)			Splitting strength (N/mm^2)			Flexural strength (N/mm^2)		
		Exp.	Cal.	Dif.%*	Exp.	Cal.	Dif.%*	Exp.	Cal.	Dif.%*
MK10	3	18.0	21.8	21.0	1.9	2.3	17.3	3.3	3.8	14.1
	7	27.1	25.8	-4.7	2.8	2.7	-4.9	5.0	4.6	-7.2
	28	45.1	46.9	4.1	4.7	4.9	3.9	8.1	8.8	7.4
	56	47.3	49.6	4.8	5.0	5.2	4.6	8.5	8.7	1.8
	180	48.4	51.2	5.7	5.1	5.4	5.4	8.7	9.0	3.2
MK15	3	19.7	21.5	8.9	2.1	2.3	8.2	3.6	4.0	10.5
	7	29.1	25.5	-12.5	3.1	2.7	-14.3	5.4	4.8	-12.4
	28	49.2	46.6	-5.3	5.2	4.9	-5.6	8.9	8.9	-0.3
	56	51.6	48.5	-5.9	5.4	5.1	-6.3	9.4	9.0	-4.5
	180	52.8	50.1	-5.0	5.5	5.3	-5.3	9.6	9.3	-3.1
MK20	3	19.4	21.1	9.0	2.0	2.2	8.2	3.9	4.1	5.5
	7	28.6	25.1	-12.2	3.0	2.6	-14.0	5.8	4.9	-17.3
	28	46.4	46.2	-0.3	4.9	4.9	-0.3	9.7	9.0	-7.7
	56	48.6	47.5	-2.3	5.1	5.0	-2.3	10.2	9.3	-10.4
	180	49.7	49.1	-1.3	5.2	5.2	-1.3	10.5	9.6	-9.0
MK25	3	18.7	20.7	10.7	2.0	2.2	9.7	3.8	4.3	10.2
	7	28.1	24.7	-12.1	3.0	2.6	-13.7	5.7	5.1	-12.1
	28	44.5	45.8	3.0	4.7	4.8	2.9	9.2	9.2	0.1
	56	46.2	46.5	0.6	4.8	4.9	0.6	9.6	9.6	-0.7
	180	47.8	48.1	0.6	5.0	5.0	0.6	9.8	9.9	0.4
MK30	3	17.8	20.4	14.6	1.9	2.1	12.7	3.7	4.4	15.9
	7	26.7	24.4	-8.7	2.8	2.6	-9.5	5.6	5.2	-7.2
	28	43.6	45.5	4.3	4.6	4.8	4.1	8.8	9.3	5.5
	56	43.8	45.4	3.7	4.6	4.8	3.6	9.1	9.8	7.2
	180	46.8	47.0	0.5	4.9	4.9	0.5	9.5	10.2	7.1
AAMK5	3	41.9	46.9	11.85	4.3	4.8	11.4	7.8	8.6	10.6
	7	58.4	52.1	-10.80	6.0	5.3	-10.9	10.7	9.6	-10.6
	28	77.5	79.5	2.59	8.1	8.3	2.2	14.1	14.5	2.7
	56	79.9	80.3	0.5	8.3	8.2	-0.7	14.1	14.4	2.1
	180	82	77.7	-5.2	8.5	8.6	0.9	15	15.0	0.0
AAMK10	3	43.1	48.2	11.83	4.4	4.9	12.3	7.8	8.8	12.3
	7	60.1	53.4	-11.11	6.2	5.5	-11.3	10.8	9.7	-10.2
	28	80.6	80.8	0.30	8.3	8.4	1.6	14.6	14.6	0.1
	56	83.1	75.6	-9.0	8.5	8.5	-0.4	15.3	14.9	-2.6
	180	85.6	77.7	-9.2	8.8	8.8	0.0	15.7	15.5	-1.3
AAMK15	3	43.7	49.5	13.35	4.6	5.1	10.6	7.9	8.9	12.6
	7	60.7	54.8	-9.79	6.1	5.6	-7.4	10.9	9.8	-9.8
	28	81.4	82.2	0.95	8.6	8.6	-0.2	14.6	14.7	1.0
	56	83.1	75.6	-9.0	8.6	8.7	1.1	15.3	15.4	0.7
	180	85.7	77.7	-9.3	9.1	9.0	-0.8	15.8	16.0	1.3

* Dif.% = 100*(Cal.- Exp.)/ Exp.

Table 19: Comparison Between Experimental and Predicted Values for Compressive, Splitting, and Flexural Strength After Exposure to Elevated Temperature (MK Mixes)

Mix Type	Age	Compressive strength (N/mm^2)			Splitting strength (N/mm^2)			Flexural strength (N/mm^2)		
		Exp.	Cal.	Dif.%*	Exp.	Cal.	Dif.%*	Exp.	Cal.	Dif.%*
MK10	56	26	27.06	4.07	2.6	2.4	-1.9	4.7	4.9	5.2
	180	26.6	28.22	6.11	2.7	2.9	7.6	4.8	5.1	7.1
MK15	56	31	29.49	-4.87	3.1	2.8	6.6	5.6	5.4	-4.3
	180	31.7	30.66	-3.29	3.2	3.1	-2.7	5.7	5.6	-2.4
MK20	56	33.1	31.92	-3.56	3.3	3.0	-3.9	6	5.8	-3.7
	180	32.3	33.09	2.44	3.2	3.3	3.8	5.8	6.0	3.1
MK25	56	34.2	34.35	0.45	3.4	3.2	-3.4	6.2	6.2	-0.1
	180	35.3	35.52	0.62	3.5	3.5	0.9	6.4	6.4	-0.1
MK30	56	35.5	36.78	3.62	3.5	3.4	-0.1	6.4	6.6	3.3
	180	38.9	37.95	-2.44	3.9	3.7	-4.1	7	6.8	-2.7

Table 20: Comparison Between Experimental and Predicted Values for Compressive, Splitting, and Flexural Strength After Exposure to Increased Temperature (AAMG and AMK302 Mixes)

Mix Type	Temp. °C	Compressive strength (N/mm^2)			Splitting strength (N/mm^2)			Flexural strength (N/mm^2)		
		Exp.	Cal.	Dif.%*	Exp.	Cal.	Dif.%*	Exp.	Cal.	Dif.%*
AAMG5	20	67.2	69.2	2.9	9.6	9.4	-1.8	15.7	17.3	9.7
	100	68.59	67.9	-1.1	9.81	9.1	-7.6	16.0	16.5	2.9
	200	69.26	66.2	-4.4	9.90	8.6	-13.4	16.2	15.6	-3.8
	300	65.90	64.5	-2.0	9.62	8.1	-15.7	15.1	14.7	-2.8
	400	61.86	62.9	1.7	9.14	7.6	-16.5	14.1	13.8	-2.9
	500	60.52	61.2	1.2	7.88	7.1	-9.3	13.3	12.8	-4.0
	600	60.5	59.6	-1.5	6.2	6.7	7.2	11.1	11.9	7.2
AAMG10	20	71.0	70.3	-1.0	9.7	10.0	4.0	17.0	18.1	6.2
	100	72.44	69.0	-4.7	9.85	9.7	-2.0	17.3	17.3	-0.1
	200	73.16	67.4	-7.9	9.95	9.2	-7.7	17.5	16.4	-6.4
	300	68.18	65.7	-3.6	9.18	8.7	-5.1	16.1	15.5	-4.2
	400	65.34	64.1	-2.0	8.69	8.2	-5.4	14.6	14.6	-0.5
	500	63.92	62.4	-2.4	8.21	7.7	-5.6	13.6	13.6	0.2
	600	62.5	60.8	-2.8	6.4	7.3	14.1	11.5	12.7	10.8
AAMG15	20	71.2	71.5	0.5	9.5	10.6	12.4	17.3	18.9	9.0
	100	71.88	70.2	-2.3	9.65	10.3	6.3	17.8	18.1	1.7
	200	73.30	68.5	-6.5	10.0	9.8	-2.5	18.3	17.2	-6.2
	300	68.32	66.9	-2.1	9.28	9.3	0.3	17.8	16.3	-8.6
	400	66.90	65.2	-2.5	8.99	8.8	-1.8	16.4	15.4	-6.5
	500	65.47	63.6	-2.9	8.52	8.4	-2.0	14.8	14.4	-2.9
	600	64.0	61.9	-3.3	6.5	7.9	20.5	11.8	13.5	14.9
AMK302	20	73.9	68.0	-7.9	7.4	8.8	19.7	15.8	16.5	4.3
	100	74.6	66.7	-10.6	7.8	8.5	8.0	16.1	15.7	-2.3
	200	73.9	65.0	-12.0	7.8	8.0	2.9	15.8	14.8	-6.2
	300	66.5	63.4	-4.7	7.4	7.5	1.6	14.2	13.9	-2.3
	400	60.6	61.7	1.9	6.5	7.0	8.1	13.4	13.0	-3.4
	500	57.6	60.1	4.2	5.9	6.5	10.8	12.6	12.0	-4.6
	600	54.3	58.4	7.6	5.6	6.1	8.6	9.8	11.1	13.7

From the preceding tables, it is noticeable that there is a reasonably good agreement between the predicted equations results and the experimentally, which demonstrates the reliability of the equation in predicting the values of compressive, splitting, and flexural strengths.

5. COST ANALYSIS:

Although using MK in concrete significantly improves concrete strength [38-43]; One of the most crucial factors in determining the feasibility of adopting a certain type of concrete is its economic extent. This economy depends on the availability of concrete ingredients. To demonstrate the economics of the recommended mix (AAMG15), a cost analysis comparison with a high-strength concrete mix (HSC) of the same grade and workability was undertaken. Furthermore, the AMK302 mix was compared due to its superior strength at normal temperatures. The cost of all the mix's ingredients is estimated based on the most recent market prices in Egypt.

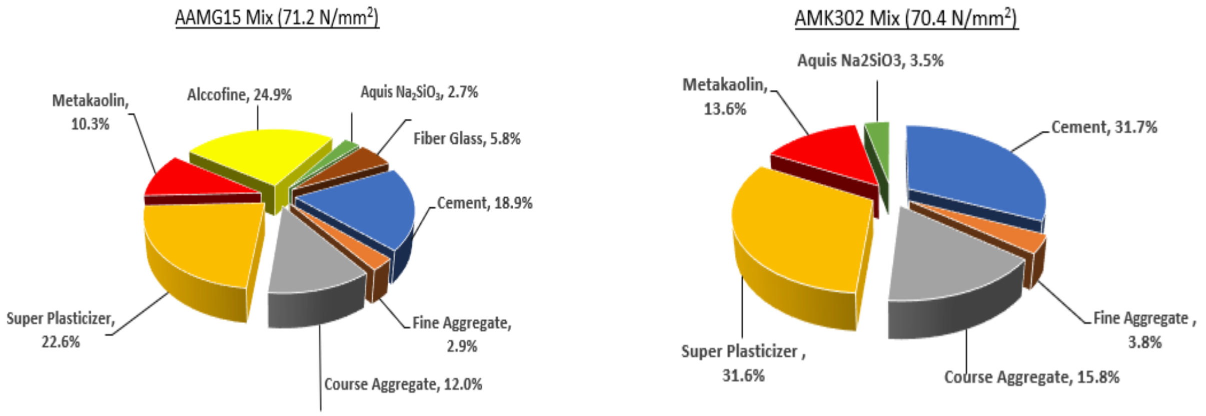
Table 21 assesses the calculation of the cost for one cubic meter of mixes: AAMG15, AMK302, and HSC mix. The table illustrates the ingredients, cost (US$/t), and quantity (Kg). The cost contribution of each material is calculated and illustrated in Fig. 4.

Table 21: Cost of Production of 1 m^3 of Concrete

Ingredients	Cost (US$/t)	AAMG15 Mix		AMK302 Mix		HSC Mix	
		Cement +AF+MK+GF		Cement + MK		Cement + Silica Fume	
		Quantity (Kg)	Cost (US$)	Quantity (Kg)	Cost (US$)	Quantity (Kg)	Cost (US$)
Cement	61.9	206.25	12.77	262.5	16.25	475	29.40
Fine Aggregate	3.7	525.0	1.93	525.0	1.93	510	1.88
Coarse Aggregate	7.4	1100.0	8.10	1100.0	8.10	1080	7.95
Super Plasticizer	1973.9	7.75	15.30	8.2	16.19	12.0	23.69
Metakaolin	61.9	112.5	6.96	112.5	6.96	-	-
Alccofine	300.0	56.25	16.88	-	-	-	-
Aquis Na_2SiO_3	120.0	15.0	1.80	15	1.80	-	-
Silica Fume	200.0	-	-	-	-	50.0	10.00
Fiber Glass	1486.9	2.63	3.91	-	-	-	-
Total Cost		67.64		51.20		72.90	

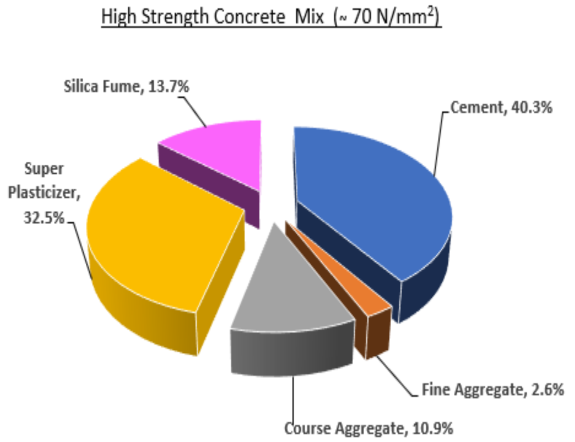
Despite the extremely low temperature needed to convert Egyptian kaolin clay to the reactive metakaolin phase (850 °C), the manufacturing cost of metakaolin in Table 21 is assumed to be equivalent to the cost of cement manufacturing due to the evident absence of plants that are enabled to produce different treatment operations for kaolin clay. However, once metakaolin is approved as a construction material in the industry, its price is predicted to be cheaper than cement due to its natural availability as well as the difference in the processing temperature (1450 °C for cement and 850 °C for metakaolin).

The overall cost of generating 1 m^3 of AAMG15 mix and AMK302 mix was less than HSC mix by 7.2% and 29.7%, respectively. The main problem occurring when HSC is exposed to fire is a massive explosion causes large losses in humans and buildings. This problem could well be prevented when using the AAMG15 mix. Thus, this attitude offers a significant economic value to the suggested mixture.



a) AAMG15 Mix

b) AMK302 Mix



c) HSC. Mix

Fig. 4: Cost Contribution of Each Material

Despite the Alccofine cost is 24.9% of the AAMG15 ingredient cost, as illustrated in Fig. 4, when comparing the cementitious ingredients for AAMG15 mix and HSC mix; cement, Alccofine, and metakaolin in the AAMG15 mix and cement and silica fume in the HSC mix, the costs were 36.61 $ and 39.40 $, respectively.

The cost of the AAMG15 mix is 32.1% greater than AMK302 cost; this increment was a result of using Alccofine and glass fibers in the first mix. Despite AMK302 is considered more economical at normal temperature, the AAMG15 mix is better at high temperatures (600 ºC). in addition, AAMG15 has a notable splitting and flexural strength at normal and high temperature.

6. CONCLUSION

Substitution of cement with MK up to a dose of 15% of cement weight considerably enhances the strength of concrete. The increase in strength was more significant after 28 days; the average compressive strength, splitting strength, and flexural strength of concrete (MK15) increased by 23.0%, 30.0%, and 23.6%, respectively, after 28 days. When the MK ratio is increased to 30%, the strength ratio enhancement is lowered to 9.2%, 12.0%, and 11.1%. After exposure to harsh temperatures, the ratio of 30% MK produced the highest strength; it enhanced the compressive, splitting, and flexural strengths at age 180 days by 62%, 47%, and 54%, respectively.

For increasing concrete strength, Aquis Na_2SiO_3 is the higher activator for MK. When compared by Na_2SO_4 activator and Aquis Na_2SiO_3, the compressive strength for AMK, (30% mix) activated with Na_2SO_4 is lower by 13% and 12% at 3 and 7 days, respectively. At 28, 56, and 180 days, these levels were lowered to 3%, 8%, and 5%, respectively.

Adding Alccofine leads in cost savings and better concrete strength. Adding Alccofine up to 10% improved compressive strength by 11% at age 3 days; this ratio increased to 16% at 180 days. At increased temperatures, compressive, splitting, and flexural strengths were enhanced after 180 days by 15%, 20%, and 19%, respectively. Similar trends have occurred for splitting and flexural strength. When the Alccofine ratio was increased to 15%, there was a minor improvement at normal temperature and explosive spalling at 300 ºC. Adding 0.7% GF can remedy this problem since it greatly increases splitting and flexural strength and tremendously enhances concrete strength after exposure to extreme temperatures.

A good agreement occurs between the predicted equations' outputs and the experimental data for compressive, splitting, and flexural strengths using multiple regression analysis, although the water-cement ratio is not explored.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

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