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Mechanical Properties of Metakaolin-based Concrete Exposed to Elevated temperature

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Abstract

As buildings are often exposed to high temperatures due to fire, understanding the thermal resilience of construction materials is critical. This research highlights the need for further exploration of building materials that can withstand extreme temperatures to ensure structural integrity and safety. Four concrete mixes were produced with locally available materials of ordinary Portland cement (OPC), metakaolin (MK), crushed fire brick as fine aggregate, and crushed dolomite as coarse aggregate. These concrete mixes were tested for physical and mechanical properties at room temperature and after exposure to elevated temperature of 250 °C, 500°C, 750 °C, 1000 °C, 1250 °C and 1500 °C.The results demonstrate that compressive strength generally increases with temperature up to 1000 °C, with the K20 mix (20% MK) exhibiting the highest strength at this temperature. These findings indicate that metakaolin incorporation significantly enhances concrete's thermal performance, suggesting that K20 is a promising candidate for fire-resistant construction applications.

Keywords: Metakaolin, elevated temperature, refractory brick, thermal concrete.

1. Introduction

Concrete structures are often exposed to fire during their service life, which can severely impact their structural performance and safety, potentially leading to catastrophic failure in extreme cases [1, 2]. Exposure to fire elevates the temperature of the structure, which can result in spalling, significantly compromising the structural integrity of the concrete and adversely affecting its mechanical properties, particularly its compressive strength. This spalling may become a critical factor in the collapse of key structural elements [3, 4].
The primary mechanisms behind explosive spalling include the build-up of pore pressure due to water vaporization and uneven thermal stress distribution. When concrete is exposed to high temperatures, the water retained within its internal structure vaporizes and moves toward the exterior. This migration can be hindered by denser surface layers, which, in turn, increase the internal pore pressure. If the heating rate is rapid and the concrete has a low-permeability structure, the vapor pressure may rise to critical levels, leading to spalling and potential disintegration of structural components if the tensile capacity of the concrete is inadequate [5].
Figure 1 illustrates the increase in pore pressure that can cause spalling under thermal conditions [6]. Another contributing factor is the development of thermal gradients at high temperatures [7]. As the surface temperature of the concrete rises, compressive stresses parallel to the heated surface develop, while tensile stresses occur perpendicularly. If these differential stresses exceed the tensile strength of the concrete, spalling occurs, as shown in Figure 2.
Further to these factors, the accelerated heating of concrete may lead to cracking due to the decomposition of hydrates, differential shrinkage of the paste, thermal instability, and the expansion of coarse aggregates. The mismatch in thermal expansion between aggregates and the cementitious matrix at elevated temperatures can cause cracking within the interfacial transition zone (ITZ), contributing to overall degradation .Reinforced concrete structures are particularly vulnerable to fire damage during their service life. It is well established that molecular structures remain stable only up to specific temperatures; fluctuations beyond these can compromise their stability. The degree of temperature, combined with the duration of exposure and heating rate, critically influences the molecular structure of concrete, leading to its degradation. The mechanical properties and stiffness of concrete are notably reduced at elevated temperatures, primarily due to physical and chemical alterations [7, 8]. These changes, coupled with microstructural stresses, result in a significant reduction in mechanical properties, such as compressive strength.

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In severe fire incidents, ordinary Portland cement (OPC) concrete can undergo rapid spalling, causing the loss of surface layers and exposing internal reinforcements to high temperatures, which may lead to structural failure [7]. This strength loss is closely associated with the dehydration of calcium hydroxide $Ca(OH)_2$ between 400–500°C and the continuous dehydration of calcium-silicate-hydrate (C-S-H) starting at approximately 105°C in the OPC concrete matrix. Differential thermal expansion or contraction between the aggregate and cement paste matrix generates interfacial stresses that result in significant cracking, further contributing to the reduction in stiffness and mechanical strength. Additionally, thermal gradients exacerbate the poor performance of OPC concrete at high temperature.

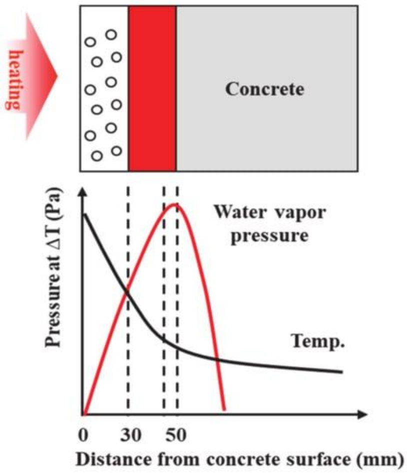

Fig. 1. Relation between water vapor pressure in concrete and temperature [9].

1.2 Research Objective

The primary objective of this research is to investigate the properties of metakaolin-based concrete after exposure to elevated temperatures up to 1500°C, focusing on compressive strength, tensile strength, and elastic modulus.

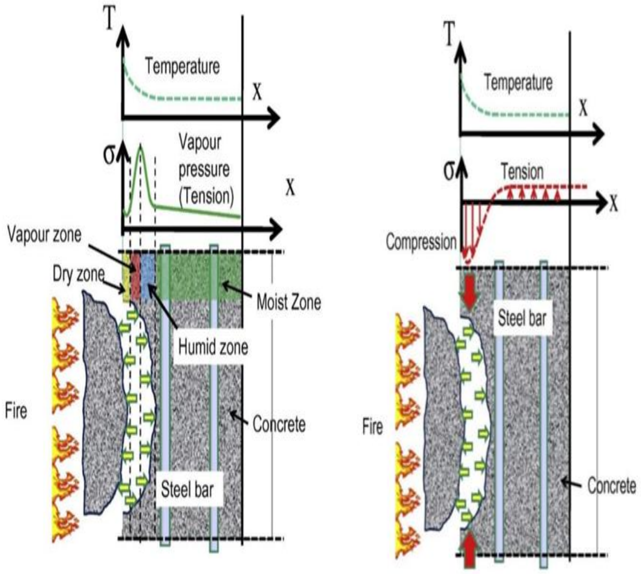

Fig.2. Spalling of concrete due to vapor pressure and thermal dilation [10].

2. Experimental Study

2.1 Materials

Detailed information about the economically available materials and their characteristics are given in this section. Crushed dolomite of maximum size of 12 mm was used herein as coarse aggregate, and crushed refractory brick with fineness modulus 2.82 was used as fine aggregate. Physical properties, and sieve analysis of used aggregate are shown in Table 1 and Fig.3, Respectively.

Table 1. Physical Properties of coarse aggregate

Physical Property	Value
Specific Gravity of oven dry	2.83
Dry rodded weight (SSD)kg / m^3	1640
Nominal max.size	12
Soundness %(Na_2SO_4)	3.1
Absorption by weight %	1.7

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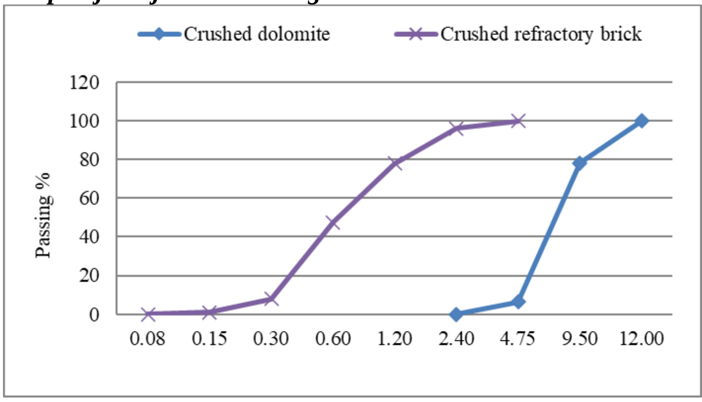

Fig. 3. Grading of aggregate

	…	0.04
ignition	2.06	2.74
gravity	3.15	2. 7

The types and properties of cementitious materials used in the study are presented in as follows:

Cement: Ordinary Portland cement CEM I 42.5 N, that meets the ASTM C150 [11] was selected considering compressive strength, fineness, and heat of hydration.

Metakaolin: (MK) is a reactive aluminosilicate, which is formed by the dehydroxylation of kaolinite (Al2O3.2SiO2. 2H2O). Metakaolin has a specific gravity of 2.7 and its specific surface area is 3500 cm^2/gm according to Blain test. Table 2, shows the chemical composition of used cementitious materials.

Sikament-163M high range water reducer complies with ASTM C494 [12] type F was used to produce highly workable concrete with low water - cement ratio. Potable tap water has been used in mixing concrete constituents and in curing of hardened concrete. Water to be used in concrete should conform to the requirements of ACI 301 or ASTM C 94 [13].

Table 2.Chemical Composition and Physical Properties of Cementitious Materials

Oxides (%)	Ordinary Portland Cement	Metakaolin
	20.39	58.52
	5.6	35.54
	3.43	1.15
	63.07	1.24
	2.91	0.19
	0.38	0.25
	0.35	0.05
	0.7	0.06
	9.04	…
	….	0.09

2.2 Method

The mix proportions were calculated based on the absolute volume method according to procedures outlined in ACI (211.4R) [14].

Employing the sequence outlined in that standard practice, the quantities of ingredients per cubic meter of concrete given in Table 3.

Mixing, compacting, finishing, and curing are complimentary operations to obtain desired high quality concrete. Mixing was carried out in electric mixer to obtain homogenous mix. Fresh concrete was poured into standard molds for 24 hours. Specimens were removed from molds after 24 hours and cured in basin of clean water for 28 days. Specimens of concrete have been exposed to six degrees of elevated temperature, 250, 500, 750, 1000, 1250 °C and 1500 °C. After two hours of exposure to elevated temperature, specimens were then cooled to room temperature before tested.

2. 3Test Specimens

Unit Weight: Cube specimens of 10 cm side length have been used for density measurement. The unit weight loss percentage for each type of concrete was calculated.

Compressive Strength: Standard cubic molds of 10 cm side length have been used for preparing the needed specimens for each mix. Cylindrical specimens of 15*30cm have been used for determining splitting tensile strength. Test was performed according to ASTMC 496-85[15]. Modulus of Elasticity: Cylindrical specimens of 15×30 cm were used in determining modulus of elasticity of the different concrete mixes.

Table 3. Concrete Mix Proportions (kg / m^3)

Mix designation	Cement	MK	C.Agg.	F.Agg.	Water
K10	360	40	1079	719	160

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K15	340	60	1079	719	160
K20	320	80	1079	719	160
K25	300	100	1079	719	160

2.5 Results and Discussion

2.5.1 Unit Weight

Figure 4, shows the unit weight of concrete mixes at room temperature. It can be seen that use of mixture fine aggregate with 10 % metakaolin results in higher unit weight than unit weight of serpentine concrete contains 10% MK and crushed refractory brickconcrete contains 25% MK by 0.75 % and 0.65% respectively. Also, the results show that the minimum unit weight of crushed refractory brick concrete mix contains 20%MK is higher than unit weight of concrete contains 25% and 15 % MK with fine aggregate of serpentine or mixture fine aggregate by 3.43% and 0.91 % respectively.

Figure 5, shows the unit weight loss of concrete exposed to elevated temperature. It can be seen that at temperature of 250 °C serpentine concrete contains 20% MK loss 5.87 %, while crushed refractory brick concrete contains 25% MK loss 1.97 %. Further, when temperature increased to 500 °C concrete contains 25 % MK with serpentine gave the maximum loss of 7.01%, while gave the minimum loss of 1.96% when mixture fine aggregate were used. At exposure temperature of 750, 1000 and 1250 °C, concrete contains 25% MK have the higher loss of 8.69%, 6.88% and 13.07% for serpentine, crushed refractory brick and mixture fine aggregate respectively. The corresponding minimum losses were 3.25%, 1.65% and 5.55% for crushed refractory brick contains 20% MK. Also Fig.5 shows that concrete of mixture fine aggregate and 15% MK loss 20.15 % when exposed to temperature of 1500 °C, while crushed refractory brick concrete contains the same content of metakaolin (15%) loss only 7.14% when exposed to temperature of 1500 °C.

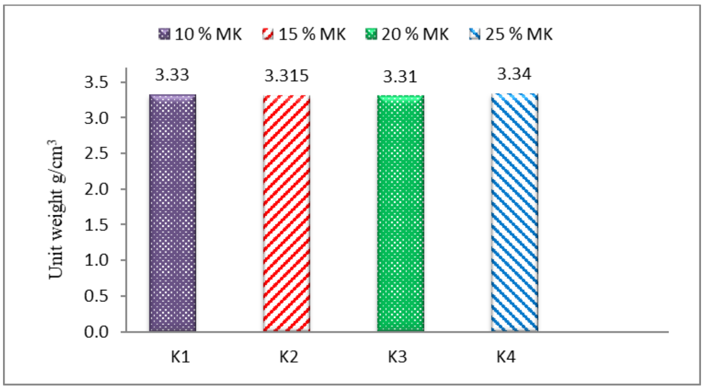

Fig. 4. Unit weight of concrete at room temperature

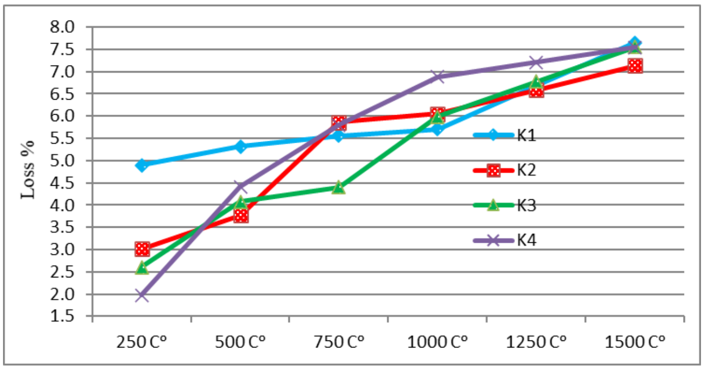

Fig. 5. Unit weight loss of concrete exposed to elevated temperature

2.5.2 Compressive Strength

Figure 6 presents the compressive strength for concrete mixes with fine aggregate of crushed refractory brick after exposure to temperatures of 250, 500, 750, 1000, 1250, and 1500 °C. It is evident that the compressive strengths of K10, K15, K20, and K25 concrete mixes increase with temperature up to 1000 °C (except the strength of K15 concrete, which increases up to 1250 °C), then decreases gradually up to 1500 °C.
The chart also shows that the compressive strengths of the K10 concrete mix are higher than the strengths of K15, K20, and K25 at temperatures of 250, 500, and 750 °C, while at 1000 °C, the compressive strength of K20 (20% MK) is higher than that of K10, K15, and K25. As the exposure temperature increases up to 1250 and 1500 °C, the compressive strength of K15 concrete is higher than that of K10, K20, and K25.
Figure 7 shows the relative compressive strength of concrete mixes with fine aggregate of crushed refractory brick at temperatures of 250, 500, 750, 1000, 1250, and 1500 °C with respect to the original compressive strength at room temperature. Concrete containing 25% MK recorded a lower compressive strength loss of 13%, 26%, and 39% than the strength loss of 10% MK (24%, 34%, and 45%), the loss of 15% MK (26%, 41%, and 56%), and the loss of 20% MK (27%, 41%, and 56%) at temperatures of 1000, 1250, and 1500 °C, respectively.
Also, it indicates that the concrete mixes containing 10%, 20%, and 25% MK with fine aggregate of crushed refractory brick do not experience compressive strength loss up to a temperature of

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1250 °C, while the concrete mix containing 15% MK has a strength loss of 19% at 500 °C. As the exposure temperature increases to 1250 °C and 1500 °C, the concrete mix K20 (20% MK) recorded a lower compressive strength loss of 15% and 53% than the strength loss of 10% MK (25% and 58%), the loss of 15% MK (25% and 61%), and the loss of 25% MK (19% and 60%).
These results indicate that metakaolin plays a vital role in metakaolin-based concrete, primarily due to its high reactivity as a pozzolanic material. Produced by calcining kaolin clay, metakaolin provides essential alumina and silica that react with calcium hydroxide to form a dense concrete matrix, enhancing mechanical properties and structural integrity, especially at elevated temperatures [16]. Its incorporation reduces spalling and thermal cracking, ensuring durability under high heat conditions [17]. Additionally, metakaolin improves the concrete's chemical resistance and long-term performance [18], while also contributing to sustainability by reducing reliance on traditional Portland cement [19]. Overall, metakaolin significantly enhances the performance and environmental footprint of geopolymer concrete in high-temperature applications.

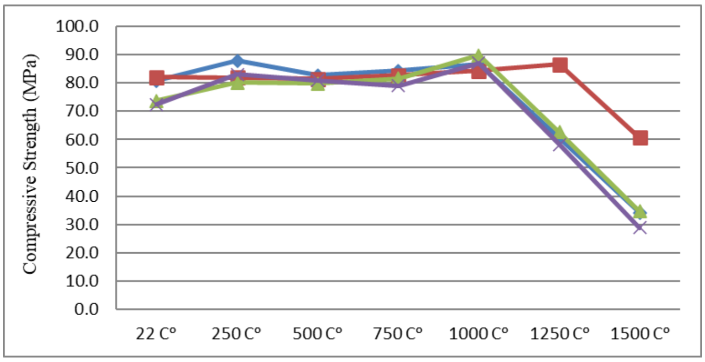

Fig. 6. Compressive Strength at Elevated Temperature

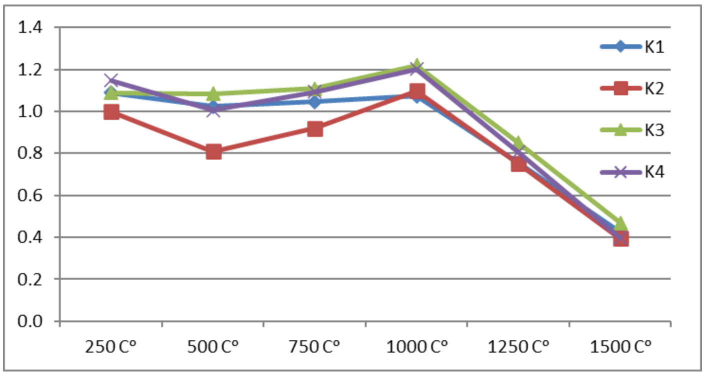

Fig. 7. Relative Compressive Strength of concrete Mixes (fci/fco)

2.5.3 Splitting Tensile Strength

Figure 8 illustrates the development of splitting tensile strength for concrete mixes containing fine aggregate of crushed refractory brick after exposure to temperatures of 250, 500, 750, 1000, 1250, and 1500 °C. It is evident that the splitting tensile strengths of K10, K15, K20, and K25 concrete mixes increase with temperature up to 1000 °C, then decrease gradually up to 1500 °C. The chart also shows that the splitting tensile strengths of the K10 concrete mix are higher than those of K15, K20, and K25 at temperatures of 250, 500, and 750 °C, while at 1000 °C, the K15 concrete mix has the highest tensile strength. As the exposure temperature increases up to 1250 and 1500 °C, the splitting tensile strengths of K10 concrete are higher than those of K15, K20, and K25.
Figure 9 shows the relative tensile strength of concrete mixes with fine aggregate of crushed refractory brick containing 10%, 20%, and 25% metakaolin, which do not experience any loss up to a temperature of 1250 °C, while the concrete mix containing 15% MK has a strength loss of 13% at 500 °C. As the exposure temperature increases to 1250 °C and 1500 °C, the K15 concrete mix (20% MK) recorded a lower splitting tensile strength loss of 10% and 39% than the strength loss of 10% MK (17% and 43%) and the loss of 15% MK (17% and 46%), and it is also lower than the loss of 25% MK (13% and 46%).

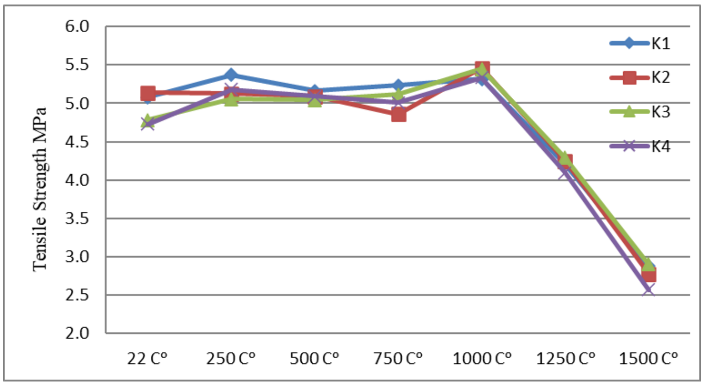

Fig. 8. Splitting Tensile Strength of Concrete Exposed to Elevated Temperature

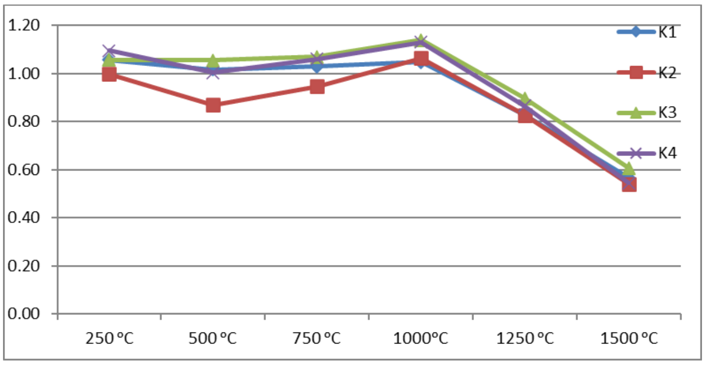

Fig.9. Relative Splitting Tensile Strength of Concrete Mixes (fti/fto)

2.5.4 Modulus of Elasticity

Figure 10 illustrates the development of the elastic modulus for concrete mixes containing crushed refractory brick after exposure to temperatures of 250, 500, 750, 1000, 1250, and 1500 °C. It is clear that the elastic modulus of K10, K15, K20, and K25 concrete mixes increases with temperature up to 1000 °C, and then decreases gradually up to 1500 °C. The chart also shows that the

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elastic modulus of the K10 concrete mix is higher than that of K15, K20, and K25 at temperatures of 250 and 1000 °C, while at 22 °C and 500 °C, the K15 concrete mix has the highest elastic modulus. As the exposure temperature increases up to 1250 and 1500 °C, the elastic modulus of K20 concrete is higher than that of K10, K15, and K25.

Figure 11 shows the relative elastic modulus of concrete mixes with fine aggregate of crushed refractory brick. The K20 concrete mix has the lowest elastic modulus loss of 2% and 3% at temperatures of 500 and 750 °C, respectively, while the K10 concrete mix has the lowest elastic modulus loss of 0%, 15%, and 33% at temperatures of 1000, 1250, and 1500 °C, respectively. As the exposure temperature increases up to 1000, 1250, and 1500 °C, the K25 concrete mix recorded the highest elastic modulus loss of 9%, 23.5%, and 42%, compared to the losses of K10 (0%, 15%, and 33%) and K15 (7%, 23%, and 41%), and it is also higher than the losses of K20 (2%, 16%, and 33%).

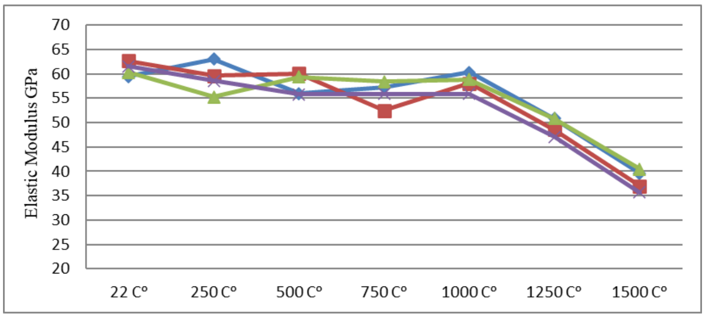

Fig. 10. Elastic Modulus of Concrete Exposed to Elevated Temperature

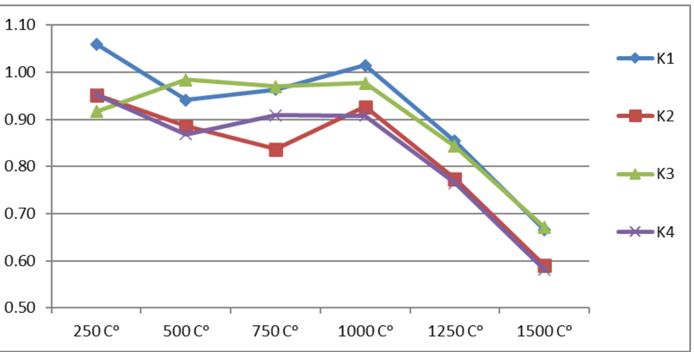

Fig. 11. Relative Elastic Modulus of Concrete Mixes (Ei/Eo)

3. Conclusions

Based on the results obtained from the tests considered in this study some general conclusions may be drawn concerning the effects of the main mix parameters on the mechanical properties of concrete exposed to elevated temperature. The following conclusions can be drawn from the present study:

1. Compressive strength generally increased with temperature up to 1000 °C for most mixes, indicating a potential enhancement in concrete performance under moderate thermal conditions. Notably, the K20 mix (20% MK) exhibited superior strength at 1000 °C compared to other compositions.
2. In terms of relative strength loss, mixes with higher MK content (25% MK) demonstrated the least degradation at elevated temperatures, particularly at 1000 °C, where losses were lower than those in mixes with lower MK percentages. Interestingly, concrete mixes with 10% and 20% MK retained their compressive strength up to 1250 °C, while the K15 mix showed an initial loss at 500 °C, highlighting its vulnerability at lower thermal exposures.
3. Splitting tensile strength and elastic modulus followed similar trends, with increases observed up to 1000 °C before declining. The K15 mix outperformed others in tensile strength at 1000 °C, while K20 maintained the highest elastic modulus at extreme temperatures, underscoring its resilience under thermal stress.
4. Overall, the findings indicate that the incorporation of metakaolin significantly influences the thermal performance of concrete, particularly when exposed to high temperatures. The optimal mix design, particularly K20, suggests that strategic adjustments in MK content can enhance concrete durability and performance in high-temperature applications, making it a viable option for fire-resistant construction materials.

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