

## Evaluation of Limestone from Bekhme Formation for Metakaolin, Alkaline-Resistant Glass, and Hybrid Steel Fiber Concrete Reinforcement in Kurdistan Region of Iraq

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### Abstract

The limestone from the Bekhme Formation within the Hareer Anticline has been utilized as a concrete aggregate. X-ray fluorescence was carried out for eighteen limestone samples to determine the major oxide compositions of CaO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MgO, Na<sub>2</sub>O, K<sub>2</sub>O, Cl, TiO<sub>2</sub>, SO<sub>3</sub>, P<sub>2</sub>O<sub>5</sub>, MnO, and loss on ignition. The results showed that only 195m out of a 255m thickness of the Bekhme limestone met the chemical standards for concrete aggregates. Mechanical characterization using the Los Angeles abrasion test yielded a 29% wear value, which is within the acceptable range for concrete aggregate quality. Two standard concrete mix designs were adopted: 1:1.5:3 (M20) with a water content of 23–28.5 L and 1:2:4 (M15) with a water content of 22–25.5 L. A total of 32X3 concrete cubes measuring 15 cm<sup>3</sup> were prepared for testing, using suitable proportions of cement, fine aggregate ( $\leq 4.75$  mm), coarse aggregate ( $\leq 12.5$  mm), and water. To enhance mechanical performance, alkali-resistant glass fiber (0.10%), hybrid steel fiber (0.50%), and metakaolin (10%) were used, the latter replacing an equivalent portion of cement by weight. The concrete comprising metakaolin exhibited higher compressive strength than that reinforced with glass or steel fibers. This improvement is attributed to the pozzolanic reactivity of metakaolin, which promotes the formation of additional calcium silicate hydrate (C–S–H) gel. An economic assessment of the upper Bekhme Formation, based on the total limestone volume, indicated that the reserve is sufficient to sustain long-term concrete production; metakaolin provides a cost-effective alternative, whereas glass and steel fibers act solely as mechanical additives without offsetting cement usage.

**Keywords:** Metakaolin; Concrete; AR-glass fiber; Reserve Estimation; Hybrid steel fiber

### 1. Introduction

The Bekhme Formation represents a major geological unit in the Kurdistan region that hosts extensive resources. These limestones are generally fine-grained, dense, and mostly composed of calcite (Sissakian, 2000; Al-Bahadily, 2014). Limestone was employed as a primary aggregate in place of natural sand and gravel due to its partial solubility and reactive surface, which improve bonding with the cement paste through physico-chemical interactions during hydration. The limestone's alkaline nature neutralizes acidic compounds, contributing to the durability of the hardened matrix (ASTM D4791, 2023). The angular and rough texture of crushed limestone provides mechanical interlocking compared

to the smoother surfaces of natural river aggregates, thereby reducing voids and packing density and enhancing the workability of fresh concrete (Mindess et al., 2003).

In order to enhance the concretes strength to dynamic loading and cracking conditions the incorporation of metakaolin (MK) that sourced from Injana Formation in Smaq-Shirin area in East of Erbil City (NE of Iraq), alkali-resistant glass fiber (ARG) and hybrid steel fiber (HS) where bought from Erbil North Construction Material Factories, they were mixed within limestone aggregate to enhance both mechanical and durability characteristics (ASTM A820M, 2022; ASTM C1666M, 2023). Metakaolin, thermally activated at approximately 800 °C, is used to improve the compressive strength through its high pozzolanic reactivity and the formation of additional calcium silicate hydrate (C–S–H) gel (Dhandapani et al., 2025). Steel fibers, on the other hand, are added to improve the ductility, impact resistance, and energy absorption capacity (Banthia & Gupta, 2004; Afroughsabet et al., 2018), while alkali-resistant glass fibers are added to control microcracks under alkaline exposures (Yin et al., 2015; Song et al., 2005). Jomaa'h (2012) reported that Al-Sinea limestone achieved a compressive strength of 32.11 MPa, thereby reducing structural dead load and cost. Hakeem (2016) assessed Shiranish and Pilaspi limestones for concrete production using chemical and petrographic analyses, while Fatah (2020) confirmed the high-grade quality of Aqra Formation limestone for Portland cement (>95% CaCO<sub>3</sub>). Hamawandy et al. (2022) concluded that the Bekhme Formation carbonates are highly suitable for cement manufacture. Hosseini (2021) and Aziz and Mohammed (2022) reported that glass and steel fibers enhance concrete strength, toughness, and crack resistance, with hybrid fibers further improving performance. Hadeed et al. (2023) found that hybrid fibers, including glass and polypropylene, improve compressive, tensile, and flexural strengths in high-strength and lightweight concretes. Dhandapani et al. (2025) showed that higher metakaolinite content in calcined clay enhances pozzolanic reactivity, producing additional C-A-S-H gel and improving mechanical and durability properties.

This study aims to evaluate the compressive strength of MK, ARG, and HS and their effects on the workability of Bekhme limestone-based concrete. In addition, an economic assessment was conducted using reserve estimates derived from the volumetric analysis of limestone resources.

## 2. Materials and Methods

### 2.1. Geological Setting

The studied section is situated within the Bekhme Formation exposed in the Hareer Anticline, which lies in the High Folded Zone of the Zagros Fold–Thrust Belt (Alavi, 2004), approximately 50 km northeast of Erbil Governorate. The geographic coordinates of the study area are 36° 28' 32" N and 44° 26' 35" E Fig.1. Columnar section developed for the Bekhme Formation of Campanian to Early Maastrichtian, showing sampling locations and the thickness of the studied strata Fig. 2. The Bekhme Formation is composed of intraformational conglomerate and brecciated limestone and dolomite in the lowermost units, comprising about 20m, then extends to a thin dolomitic and dolomitic limestone bed of 14m. The middle unit is composed of a 36 m fossiliferous limestone bed, then thickens to a massive limestone of 100m. The upper units are composed of alternating marly limestone and thin shale beds totaling about 45m, which extend to dolomitic limestone in the uppermost unit of 40m. The total stratigraphic thickness of Bekhme at Harreer anticline was approximately 255 m. The Bekhme Formation was deposited in an open-marine to outer-platform environment, conformably underlying the Shiranish Formation and unconformably overlying the Qamchuqa Formation (Ameen and Karim, 2008).

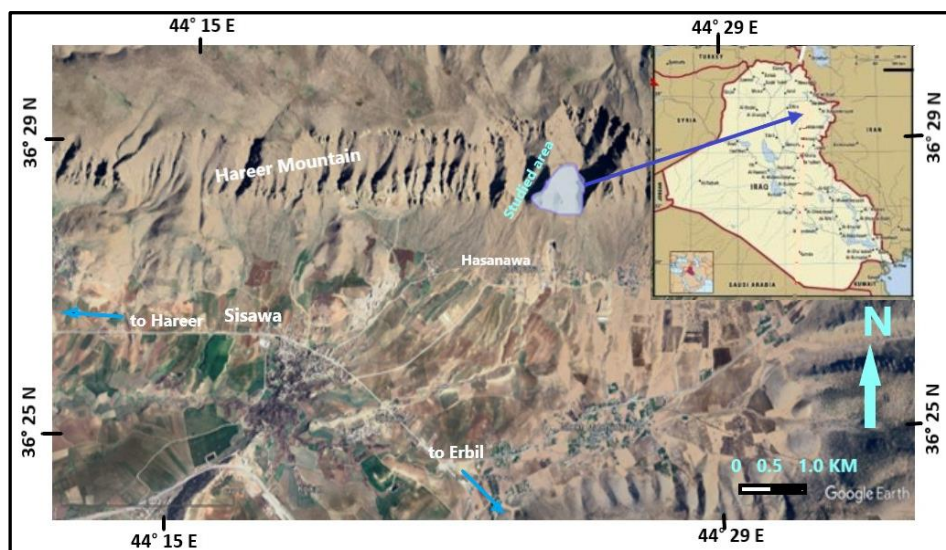


Fig.1. Satellite image showing the location and area of the studied section

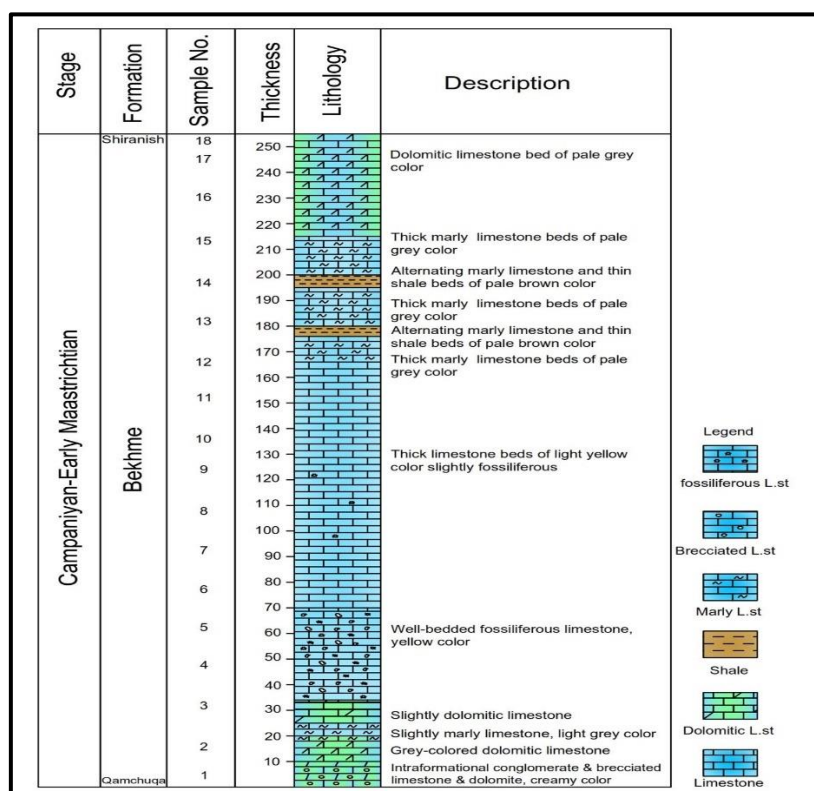


Fig. 2. Columnar section of the Bekhme Formation encountering samples and their thickness

## 2.2. Sampling and Sample Preparation

Limestone samples were systematically collected from the Bekhme Formation exposed at Hareer Mountain in northern Iraq using channel sampling techniques at 18 representative stations. Geochemical analyses were performed using X-ray fluorescence (XRF) to quantify the major and minor oxides, including CaO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MgO, Na<sub>2</sub>O, K<sub>2</sub>O, Cl, TiO<sub>2</sub>, SO<sub>3</sub>, P<sub>2</sub>O<sub>5</sub>, MnO, and loss on ignition (LOI), which aimed to assess the chemical composition and suitability of the Bekhme limestone for use

as an aggregate in concrete production. The analytical procedures were conducted at the Kansaran Binaloud Laboratory, Iran.

### 2.3. Chemical Analysis

Aggregates with CaO content exceeding 45% are considered high-purity limestone suitable for concrete applications (Table 1). The SiO<sub>2</sub> of > 10% leads to potential risk for alkali–silica reaction (ASR) by impurities of quartz, chert, or clay, the SiO<sub>2</sub> within all 18 samples are within the standard range, however the sample No. 1, 12, 13, 14, 15, 16, 17, and 18 shows higher values than other samples, and this is due to the marly limestone in the lowermost units and alternating marly limestone and shale units in the upper units Fig. 2. The Al<sub>2</sub>O<sub>3</sub> of < 3% accepted, however, sample No. 1, 15, 16, 17, and 18 shows higher Al<sub>2</sub>O<sub>3</sub> values due to the marly limestone units that indicates increased argillaceous content, that is undesirable for concrete.

Fe<sub>2</sub>O<sub>3</sub> of < 1% are preferred. Samples No. 15, 16, 17, and 18 show higher iron oxide values, which lower the durability of concrete. MgO of <5% accepted; it may lead to deleterious expansion of the concrete matrix. The lowermost units of Bekhme Formation that exhibits sample NO.1 & 2 of 46.34% and 49.08% CaO that is within the standard range, however their MgO% is >5% which is not within the standard range, and the uppermost units of sample No. 15, 16, 17, and 18 have lower CaO% value and higher MgO% values than the standard range Fig. 2. For this reason, only the lower and middle unit of 12 stations that exhibits 195m were accepted for concrete manufacturing the other lowermost 2 samples and uppermost 4 samples that exhibits 20m and 40m being neglected from the total 255m Bekhme thickness. Na<sub>2</sub>O and K<sub>2</sub>O at <0.3% (Na<sub>2</sub>O) or <0.5% (K<sub>2</sub>O) are accepted. Samples No. 15, 16, 17, and 18 have higher values than the standard range, which can increase the risk of alkali–silica reaction. A chloride content < 0.02% is acceptable to prevent corrosion of the reinforcement. TiO<sub>2</sub> of <0.2% accepted to prevent inert mineral impurities. SO<sub>3</sub> <0.3% accepted to prevent cracking in the hardened concrete. P<sub>2</sub>O<sub>5</sub> of < 0.2% accepted to prevent the formation of non-reactive surface films that weaken the interfacial transition zone (ITZ). MnO of < 0.05% is accepted. These findings are consistent with the specifications outlined in ASTM C33 (2011), ASTM C295 (2004), BS 882 (1983), and Iraqi Standard 13-87 (1989).

**Table 1.** Major oxide composition and relative proportions of the Bekhme Formation determined by X-ray fluorescence (XRF) analysis

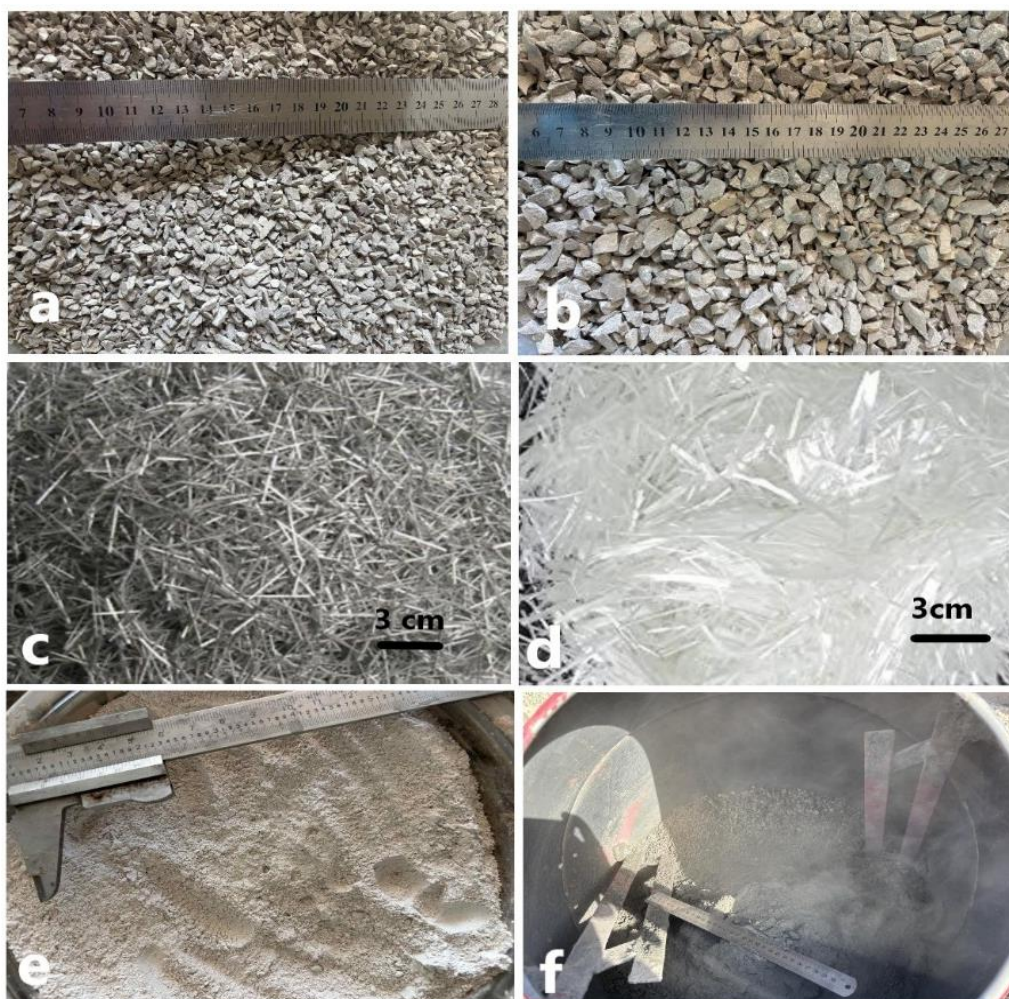
| No | CaO<br>% | SiO <sub>2</sub><br>% | Al <sub>2</sub> O <sub>3</sub><br>% | Fe <sub>2</sub> O <sub>3</sub><br>% | MgO<br>% | Na <sub>2</sub> O<br>% | K <sub>2</sub> O<br>% | Cl<br>% | TiO <sub>2</sub><br>% | SO <sub>3</sub><br>% | P <sub>2</sub> O <sub>5</sub><br>% | MnO<br>% | LOI<br>% |
|----|----------|-----------------------|-------------------------------------|-------------------------------------|----------|------------------------|-----------------------|---------|-----------------------|----------------------|------------------------------------|----------|----------|
| 1  | 46.34    | 7.34                  | 3.04                                | 0.81                                | 5.16     | 0.18                   | 0.27                  | 0.01    | 0.12                  | 0.19                 | 0.11                               | 0.02     | 37.44    |
| 2  | 49.08    | 4.12                  | 1.54                                | 0.60                                | 5.08     | 0.12                   | 0.10                  | 0.01    | 0.07                  | 0.11                 | 0.09                               | 0.01     | 40.02    |
| 3  | 53.32    | 0.16                  | 0.25                                | 0.64                                | 3.12     | 0.07                   | 0.09                  | 0.01    | 0.05                  | 0.03                 | 0.01                               | 0.01     | 43.3     |
| 4  | 53.89    | 0.19                  | 0.28                                | 0.82                                | 2.35     | 0.11                   | 0.23                  | 0.01    | 0.08                  | 0.03                 | 0.01                               | 0.02     | 42.03    |
| 5  | 53.12    | 0.17                  | 0.35                                | 0.7                                 | 2.05     | 0.09                   | 0.1                   | 0.01    | 0.05                  | 0.09                 | 0.09                               | 0.01     | 43.27    |
| 6  | 53.9     | 1.05                  | 1.06                                | 0.4                                 | 1.22     | 0.06                   | 0.1                   | 0.01    | 0.04                  | 0.05                 | 0.07                               | 0.01     | 42.04    |
| 7  | 52.6     | 1.75                  | 1.09                                | 0.48                                | 1.56     | 0.08                   | 0.13                  | 0.01    | 0.05                  | 0.07                 | 0.07                               | 0.01     | 42.12    |
| 8  | 52.19    | 2.02                  | 1.27                                | 0.52                                | 1.95     | 0.08                   | 0.16                  | 0.01    | 0.07                  | 0.07                 | 0.09                               | 0.01     | 41.56    |
| 9  | 51.66    | 2.45                  | 1.32                                | 0.56                                | 2.08     | 0.09                   | 0.19                  | 0.01    | 0.11                  | 0.09                 | 0.1                                | 0.02     | 41.32    |
| 10 | 50.97    | 2.87                  | 1.51                                | 0.53                                | 2.5      | 0.11                   | 0.18                  | 0.01    | 0.09                  | 0.07                 | 0.11                               | 0.02     | 41.05    |
| 11 | 48.72    | 3.48                  | 2.09                                | 0.7                                 | 2.08     | 0.2                    | 0.21                  | 0.01    | 0.14                  | 0.12                 | 0.13                               | 0.03     | 41.22    |
| 12 | 46.58    | 6.87                  | 2.30                                | 0.74                                | 2.47     | 0.21                   | 0.19                  | 0.01    | 0.14                  | 0.17                 | 0.1                                | 0.03     | 37.42    |
| 13 | 46.41    | 7.94                  | 2.43                                | 0.72                                | 3.37     | 0.2                    | 0.21                  | 0.01    | 0.16                  | 0.22                 | 0.12                               | 0.03     | 35.82    |
| 14 | 46.33    | 7.54                  | 2.22                                | 0.84                                | 3.53     | 0.2                    | 0.19                  | 0.01    | 0.14                  | 0.19                 | 0.1                                | 0.02     | 35.75    |
| 15 | 42.56    | 9.65                  | 3.71                                | 2.12                                | 5.09     | 0.25                   | 0.34                  | 0.01    | 0.21                  | 0.22                 | 0.1                                | 0.02     | 34.44    |
| 16 | 39.95    | 8.93                  | 3.99                                | 2                                   | 6.11     | 0.23                   | 0.27                  | 0.01    | 0.19                  | 0.2                  | 0.14                               | 0.03     | 36.97    |
| 17 | 38.72    | 8.99                  | 4                                   | 2.11                                | 7.23     | 0.25                   | 0.31                  | 0.01    | 0.2                   | 0.22                 | 0.15                               | 0.03     | 37.8     |
| 18 | 37.98    | 9                     | 5.23                                | 2.15                                | 7.39     | 0.25                   | 0.34                  | 0.02    | 0.21                  | 0.26                 | 0.15                               | 0.03     | 38.99    |

## 2.4. Aggregate Preparation and Los Angeles Test

The limestone sample No. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14 were subjected to Los Angeles abrasion (LAA) testing to evaluate aggregate durability according to the procedures in ASTM C131-01 (2001) and ASTM C131 (2006), the aggregates were sieved into fine (4.75 mm) (Fig. 3a) and coarse fractions (12.5 mm) (Fig. 3b). The abrasion resistance was determined by calculating the percentage of mass loss, the obtained values were compared with standard (grade B) criteria from AASHTO T96 & 99 (2022). The HS of short (10–20 mm) and long (30–40 mm) fibers mix used that are low carbon stainless steels to control micro and macro cracks in concrete Fig. 3c. The ARG with zirconia ( $\text{ZrO}_2 \geq 16\%$ ) used which makes them chemically stable in concrete they resist alkali attack from the cement matrix Fig. 3d, since fresh concrete exhibits a highly alkaline environment (pH 12–13) due to cement hydration, which rapidly degrades conventional glass fibers. In contrast, alkali-resistant glass fibers maintain stability under these conditions, thereby enhancing tensile capacity, controlling plastic-shrinkage cracking, improving impact resistance, increasing durability, and providing lightweight, well-bonded reinforcement within the cementitious matrix. MK was activated at 800 °C (Fig. 3e). It is employed in concrete as a high-reactivity pozzolan that actively consumes calcium hydroxide to generate supplementary C–S–H, leading to a denser and more refined microstructure. Its incorporation elevates mechanical performance, significantly decreases permeability, and enhances resistance to deleterious chemical processes, thereby improving both the durability and overall quality of high-performance cementitious systems. Cement is added to bond the materials. The ingredients are mixed in the electrically rotating drum (Fig. 3f) to obtain a more homogeneous mixture.

## 2.5. Concrete Mix Design and Unconfined Compressive Strength Test

A total of 32X3 concrete cubes of 15 cm<sup>3</sup> were prepared from the limestone sample No. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14 using two nominal mix ratio designs were adopted of 1:1.5:3 (M20) with a water content of 23–28.5 L, and 1:2:4 (M15) with 22–25.5 L of water, respectively, the amount of water kept standard at the beginning of the procedure when mixed inside rotating drum Fig. 4a, according to ACI Committee 318, 2019 during working the amount of water have been increased when adding MK and ARG in concrete mixtures compared to HS containing mixtures Table 2, since MK is an ultrafine porous pozzolanic material with a hydrophilic high specific surface area which enhances the rate of cement hydration but simultaneously increases the water requirement to maintain workability (Sabir et al., 2001; Justice & Kurtis, 2007). Similarly, ARG possesses a hydrophilic rough surface that improves bonding with the cement matrix but reduces workability. To ensure uniform dispersion and prevent fiber clumping, extra water is often needed (Banthia & Gupta, 2004). In contrast, HS have a non-porous lower surface area and fewer fibers per unit volume that do not interfere with the flow of the cement paste (Naaman, 2003). The mixture is then poured into molds in three steps. They were forced to vibrate between steps to obtain a homogeneous mixture (Fig. 4b). Concrete specimens were demolded after 24 hours of casting and subsequently cured in distilled water (ASTM C192M, 2025). Compressive strength tests were performed on M20 and M15 grade concretes after 7 and 28 days of curing (Fig. 4c and d) at the Civil Engineering Department, College of Engineering, Salahaddin University–Erbil. The concrete cubes exhibited minimal deterioration under compressive loading (Fig. 4e), and the embedded steel fibers remained free of corrosion even after 28 days of curing (Fig. 4f). This performance is attributed to the alkaline nature of limestone-based concrete, which reduces the likelihood of steel–water reactions.



**Fig. 3.** Fundamental materials incorporated in concrete formulation a) fine limestone aggregates (4.75mm); b) coarse limestone aggregates (12.5 mm); c) steel fiber (3cm); d) glass fiber (3cm); e) metakaolinite; f) the aggregate-cement mixture inside a rotating mixing drum.

**Table 2.** Mix design variables and curing schedules for control and additive-enhanced M20 and M15 concrete

| Conc<br>rete<br>name | Additive type               | Additive<br>amount % | Mix M15<br>(Cement, Fine, &<br>Coarse) water | Mix M20 (Cement,<br>Fine, & Coarse)<br>water | cement ratio<br>replaced by<br>additives % | Curing<br>Period<br>(Days) |
|----------------------|-----------------------------|----------------------|----------------------------------------------|----------------------------------------------|--------------------------------------------|----------------------------|
| N                    | -                           | -                    | 1 : 2 : 4<br>22 liters                       | 1 : 1.5 : 3<br>23 liters                     | -                                          | 7, 28                      |
| MK                   | metakaolin                  | 10                   | 1 : 2 : 4<br>24 liters                       | 1 : 1.5 : 3<br>27 liters                     | 10                                         | 7, 28                      |
| HS                   | Hybrid steel fiber          | 0.50                 | 1 : 2 : 4<br>23 liters                       | 1 : 1.5 : 3<br>26 liters                     | 0.50                                       | 7, 28                      |
| ARG                  | Glass fiber                 | 0.10                 | 1 : 2 : 4<br>24 liters                       | 1 : 1.5 : 3<br>26 liters                     | 0.10                                       | 7, 28                      |
| SG                   | Steel + Glass fiber         | 0.50+0.10            | 1 : 2 : 4<br>24.5 liters                     | 1 : 1.5 : 3<br>26.5 liters                   | 0.6                                        | 7,28                       |
| SM                   | Steel fiber +<br>Metakaolin | 0.50+10              | 1 : 2 : 4<br>24.5 liters                     | 1 : 1.5 : 3<br>27.5 liters                   | 10.5                                       | 7,28                       |
| GM                   | Glass fiber +<br>Metakaolin | 0.10+10              | 1 : 2 : 4<br>25 liters                       | 1 : 1.5 : 3<br>28 liters                     | 10.1                                       | 7,28                       |
| SGM                  | Steel + Glass<br>Metakaolin | 0.50+0.10+10         | 1 : 2 : 4<br>25.5 liters                     | 1 : 1.5 : 3<br>28.5 liters                   | 10.6                                       | 7,28                       |



**Fig.4.** a) The aggregate-cement paste while mixing; b) the mixture inside the molds on the vibrator; c) the concrete cube under unconfined compressive strength; d) the concrete cubes (15cm); e) the concrete cubes after compressive strength test remained compacted with little fractures; f) After 28 days of curing, the steel fibers remained free from observable rust formation, indicating stable performance within the concrete matrix

### 3. Results

#### 3.1. Mechanical Analysis

The LAS test showed 29% wear, which refers to the Bekhme limestone aggregates capability to endure wear and degradation resulting from friction, impact, and load-induced stresses during mixing, handling, and the service life of concrete, also contributing to a strong interfacial bond within the cement paste, according to ASTM C131 (2006), which refers to wear% of <45%.

The strength results showed that the concrete mixtures are suitable for concrete masonry at 9-25% and for columns, roofs, and foundations at >25%, according to ASTM C90 (1970) and I.Q.S. 10-77 (1987). It's obvious that M20 showed higher strength values than M15, which may be due to a higher cement content relative to the aggregate, leading to more hydration products that bond the aggregate particles together and reduce voids. Table 3 shows that the addition of MK, HS, and ARG was at the

same ratio in both mixtures. The combined incorporation of ARG, HS, and MK yields the maximum strength improvement, according to ASTM C39/C39M (2023). The 28th-day strength is higher than the 7th-day strength because the 7th-day strength is typically 65–75% of the 28th-day strength for all mixes by 28 days. By 28 days, cement hydration is mostly complete, and the concrete has achieved about 90–100% of its potential strength. It's considered the representative final strength for design and quality control. For this purpose, the use of each of N, MK, HS, ARG, SG, SM, GM, and SGM is dependent on the standard strength of the 28th day of curing.

**Table 3.** Unconfined compressive strength based on the average 3X concrete samples

| Concrete name | Compressive strength of M15 mixture (MPa) |                   | Compressive strength of M20 mixture (MPa) |                   |
|---------------|-------------------------------------------|-------------------|-------------------------------------------|-------------------|
|               | 7 days of curing                          | 28 days of curing | 7 days of curing                          | 28 days of curing |
| N             | 9.12                                      | 14.04             | 12.34                                     | 20.62             |
| MK            | 14.53                                     | 19.17             | 17.09                                     | 25.67             |
| HS            | 13.46                                     | 18.67             | 16.06                                     | 23.41             |
| ARG           | 12.47                                     | 17.20             | 15.01                                     | 21.33             |
| SG            | 14.00                                     | 18.67             | 21.08                                     | 25.59             |
| SM            | 15.80                                     | 20.00             | 22.67                                     | 35.36             |
| GM            | 15.36                                     | 19.96             | 21.58                                     | 35.90             |
| SGM           | 16.78                                     | 21.66             | 22.09                                     | 39.12             |

### 3.2. Economic Analysis

Reserve estimation of the upper and middle units of the Bekhme Formation in the Hareer Anticline, with a thickness of 195 m and an area of 4.175 km<sup>2</sup>, indicates a total volume of approximately  $798.5 \times 10^6$  m<sup>3</sup> and a corresponding mass of  $1.89 \times 10^9$  tons, assuming an average density of 1.56 tons/m<sup>3</sup>. Comparative analysis of limestone and cement consumption in M15 and M20 concrete mixtures shows that M20 requires about 10–15% more aggregate and cement, resulting in a shorter reserve lifespan than M15. Although at a production capacity of 500 m<sup>3</sup>/day (Table 4), the reserves can remain sustainable for over 11 years (M20) or 8 years (M15), indicating long-term economic importance. MK (10%), HS (0.5%), and ARG (0.1%) are released annually, with annual requirements ranging from 11.7 t to 5,840 t, depending on plant size.

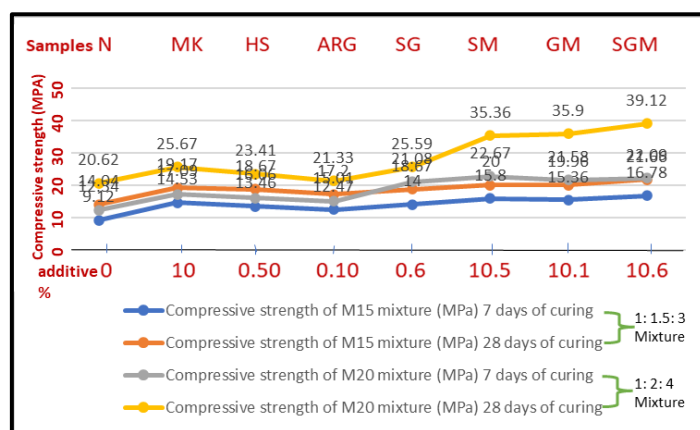
**Table 4.** Annual Consumption of Limestone, Cement, and MK, HS, and ARG Additives with Estimated Lifespan for M15 and M20 Concrete at Different Plant Capacities

| Plant capacity |                                   | 100 m <sup>3</sup> /day | 250 m <sup>3</sup> /day | 500 m <sup>3</sup> /day |
|----------------|-----------------------------------|-------------------------|-------------------------|-------------------------|
| M20            | Limestone consumption (tons/year) | 62,694                  | 156,735                 | 313,470                 |
|                | Cement consumption (tons/year)    | 11,680                  | 29,200                  | 58,400                  |
|                | Lifespan (years)                  | 32                      | 15                      | 11                      |
| M15            | Limestone consumption (tons/year) | 51,246                  | 128,115                 | 256,230                 |
|                | Cement consumption                | 10,038                  | 25,095                  | 50,190                  |
|                | Lifespan                          | 34                      | 17                      | 8                       |
|                | Concrete m <sup>3</sup> /year     | 36,500                  | 91,250                  | 182,500                 |
|                | MK consumption (tons/year)        | 1,095                   | 2,737.5                 | 5,475                   |
|                | HS consumption (tons/year)        | 54.75                   | 136.875                 | 273.75                  |
|                | ARG consumption (tons/year)       | 10.95                   | 27.375                  | 54.75                   |

#### 4. Discussion

Based on the XRF results, only twelve samples of No. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14 of Bekhme Formation encountered the standard chemical composition values as concrete aggregates Table 1, since the lower and middle unit was deposited in a shallow open-marine carbonate platform characterized by low terrigenous inflow, allows the accumulation of well-sorted calcite carbonates with minor silicate or clay impurities. In contrast, the lowermost and uppermost units displays restricted lagoonal environment, recurrently affected by siliciclastic and Mg-rich fluids, resulting in greater argillaceous and dolomitization accumulation, from which magnesium rich fluids replaced calcium shortly after deposition of limestone and the lower beds remained in contact with these fluids for longer period than upper beds, so as the sediments were buried under compaction led to the pressure driven fluid movements to increase dolomitization, while the upper part of Bekhme Formation is mostly open shelf carbonate wackestones that remained calcitic (Al-Shareeda & Al-Ghreear, 2022; Salih et al., 2019; Mansurbeg et al., 2016).

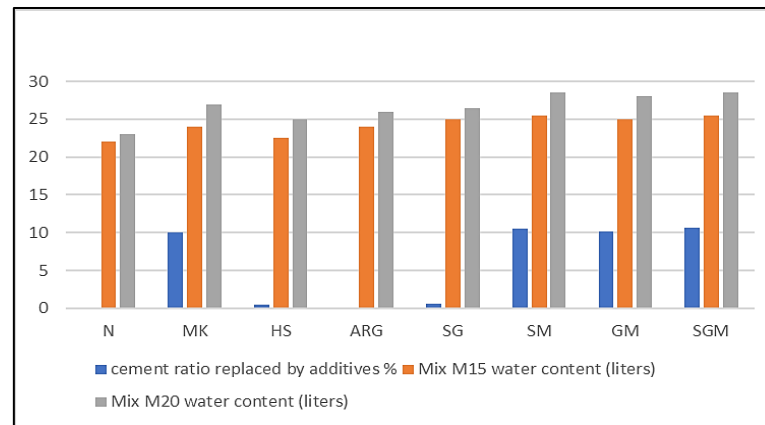
There is direct relationship between compressive strength values and additive amounts, as the additives of NK (10%), SM (10.5%), GM (10.1%), and SGM (10.6%) shows higher compressive strength values compared to N (0%), HS (0.50%), ARG (0.10%), SG (0.6%) that shows lower compressive strength values, the M15 mixture of 7 days curing showed lower compressive strength, the M15 of 28 days and M20 of 7 days are relatively similar to each other shows moderate compressive strength values, while M20 mixture of 28 days showed higher compressive strength values (Fig. 5) since the M20 mixture contributes to 18.18% cement and 81.82% limestone aggregates, while the M15 mixture contributes to 14.29% cement and 85.71% aggregate, therefore the M20 mixture showed higher compressive strength value than M15 mixture due to higher cement ratio that binds the particles together and fills the voids. However, the high cement content in the M20 mixture is insufficient to achieve high compressive strength. It's clear that the addition of MK significantly increased compressive strength, especially in the M20 mixture, with 28-day curing at additive ratios of 10.5, 10.1, and 10.6. It demonstrates that the addition of MK enhances the blending efficiency between cement and limestone aggregate.



**Fig. 5.** Relation between percentage of additives (N control mixture, MK, HS, ARG, SG, SM, GM, and SGM) and compressive strength (MPa) values of concrete samples

The M20 mixture concrete generally requires a higher water dosage than an M15 mixture, due to the higher cement ratio in relation to aggregate (Fig. 6). However, the M20 mixture is proportioned with a lower water-to-cement (w/cm) ratio to achieve greater compressive strength, whereas the M15 mixture is a lower-grade mixture with lower cement content and less strict strength requirements. It's obvious

that even M20 required more water dosage by liters than M15, however its inadequate to allow for a standard water dosage to be added for each mixture as the standard water content can be observed in control mixture (N) concrete sample which corresponds to 22 L in M15 and 23 L in M20 mixtures Table 2, Since the water content was adjusted during mixing when HS, AR glass fiber, and metakaolin (MK) were added to the cement–aggregate paste showed that the addition of MK required higher water dosage, ARG required slightly higher dosage of water, but HS required a very low dosage (Fig. 5), due to the hydration nature of MK and hygroscopic nature of ARG (Sabir et al., 2001; Banthia & Gupta, 2004).



**Fig. 6.** Relationship between the percentage of additives (N control mixture, MK, HS, ARG, SG, SM, GM, and SGM) and water content (L)

The control mixture (N) exhibited relatively low compressive strength, whereas incorporating MK, HS, and ARG resulted in a moderate strength. The SG mixture exhibited moderate to high strength, making it suitable for general structural applications under moderate loading conditions. In contrast, mixtures incorporating MK and fibers (SM, GM, and particularly SGM) achieved high to very high strength, and their usages are shown in Table 5, meeting the criteria for high-performance concrete as defined by EN 206 (2013) and ACI 318-19 (2019). The superior performance of MK-modified concretes is attributed to the extremely fine particle size of MK ( $>1\text{--}2\text{ }\mu\text{m}$ ), which effectively fills the micro voids between cement grains, leading to a denser interfacial transition zone (ITZ) between the cement paste and aggregates. Additionally, MK acts as a highly reactive pozzolan, rich in  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$ , which reacts with  $(\text{Ca}(\text{OH})_2)$  released during cement hydration to form additional calcium silicate hydrate (C–S–H) gel, which is responsible for a strong binding phase in the concrete, hence higher compressive strength values (Victor, 2019; Bentur and Mindess, 2007).

**Table 5.** Typical usage of various concrete types based on the 28<sup>th</sup> day compressive strength

| Concrete name | Approx. 28-day Strength | Typical Usage                                                                                                              |
|---------------|-------------------------|----------------------------------------------------------------------------------------------------------------------------|
| N             | Low                     | Plain concrete, non-load-bearing works                                                                                     |
| MK            |                         |                                                                                                                            |
| HS            | Moderate                | Reinforced concrete, impact-resistant floors, crack-resistant slabs, pavements, and beams                                  |
| ARG           |                         |                                                                                                                            |
| SG            | Moderate-High           |                                                                                                                            |
| SM            |                         |                                                                                                                            |
| GM            | High                    | Heavy load structural elements, durable slabs, beams in harsh environments, High-performance concrete, bridges, and decks. |
| SGM           | Very High               |                                                                                                                            |

Replacing 10% of cement with MK in M20 mixtures reduces consumption from 58,400 t/year to 52,560 t/year Table 6, demonstrating the cost-effectiveness and sustainability benefits of MK utilization in large-scale concrete production.

**Table 6.** Concrete cement Consumption (tons/year) when replaced by 10% Metakaolin for M20 and M15 Concrete at varying plant capacities

|                                                        | Mixtures | Plant Capacity          |                         |                         |
|--------------------------------------------------------|----------|-------------------------|-------------------------|-------------------------|
|                                                        |          | 100 m <sup>3</sup> /day | 250 m <sup>3</sup> /day | 500 m <sup>3</sup> /day |
| Cement consumption (tons/year) when 10% replaced by MK | M20      | 10,512                  | 26,280                  | 52,560                  |
|                                                        | M15      | 9,034.2                 | 22,585.5                | 45,171                  |

## 5. Conclusions

The lower and middle units of the Bekhme limestones are identified by high CaO% and relatively low MgO and SiO<sub>2</sub> contents. In contrast, the lowermost and uppermost Bekhme strata display higher MgO and clay-related impurities. These compositional variations reflect the combined effects of diagenetic modification and depositional energy on the lithological differentiation between the upper and lower units. The 195m-thick Bekhme limestone bed is suitable for high-quality concrete aggregate and requires only mechanical crushing into fine and coarse fractions, without thermal processing, thereby minimizing energy consumption. Furthermore, incorporating HS into the concrete successfully prevented corrosion, and the fibers remained rust-free even after 28 days of curing. The incorporation of ARG increased the concrete's structural durability by yielding in more compact cubes that preserved their overall shape with only minor cracking even after applying compressive load, the incorporation of MK increases the mechanical efficiency of concrete due to the formation of (C–S–H) gel, and keeping cost efficiency, as it replaces 10% of cement content rather than working only as a reinforcing additive like HS and ARG fibers. The SGM exhibited very high strength that can be maintained in heavy-load structural concrete performances.

## Recommendations

The economic analysis in this study assumed that 100% of the rock volume is recoverable. In practice, for a continuously operating limestone quarry producing concrete aggregate, detailed measurements of the area, recovery/recovery factor, losses (during transportation and processing), quality zones, and cut-off depths that reduce usable aggregate tonnage should be taken into account.

## Author Contributions: CRediT

The author entirely contributed to the conceptualization, data curation, formal analysis, investigation, methodology, resources, validation, visualization, writing-original draft, writing-review, and editing.

## Declaration of Competing Interest

I declare that I have no competing financial interests or personal relationships that could influence the work reported in this study.

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## Data Availability

The data of findings in this study were generated by the author through laboratory experiments and are available from the corresponding author upon reasonable request.

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