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ARTICLE

Experimental Assessment of Reinforced Concrete Incorporating Waste Tile Powder and Metakaolin under Aggressive Environmental Conditions

Mohammad Kazem Sharbatdar [1*], ***Samaneh Alizadeh*** [2]

[1] *Faculty of Civil Engineering, Semnan University, Semnan 35131-19111, Iran*

[2] *Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal*

ABSTRACT

Concrete deterioration in aggressive environments poses significant challenges for the durability of reinforced concrete structures. The incorporation of supplementary cementitious materials offers a promising strategy to enhance performance while reducing cement consumption. This experimental study investigates the effects of metakaolin and waste ceramic tile powder as partial cement replacements on the compressive and flexural behavior of reinforced concrete members exposed to aggressive environmental conditions. Ten concrete mix designs were prepared with replacement levels of 10%, 20%, and 30% using metakaolin and waste tile powder. A total of 120 concrete cubes (100 mm) and 56 reinforced concrete slabs (40 × 200 × 600 mm) were cast and subjected to both standard curing and aggressive exposure regimes, including continuous immersion and alternating wet–dry cycles. The results demonstrate that the pozzolanic activity of metakaolin became more pronounced after 3–6 months, leading to enhanced mechanical performance. All mixtures containing waste tile powder exhibited higher compressive strength than the control mix. An increase of up to 11% in flexural capacity was observed for slabs incorporating 20% metakaolin, while slabs with 30% waste tile powder achieved an 8% improvement compared to lower replacement levels. Notably, specimens with 30% waste tile powder showed a significant increase in the experimental-to-nominal flexural capacity ratio, reaching

*CORRESPONDING AUTHOR:
Mohammad Kazem Sharbatdar, Faculty of Civil Engineering, Semnan University, Semnan 35131-19111, Iran; Email: msharbatdar@semnan.ac.ir

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values of 1.57 and 1.50 at 90 and 180 days, respectively. Overall, the combined use of metakaolin and waste tile powder improved durability and structural performance under aggressive conditions, indicating their potential for sustainable construction and rehabilitation of reinforced concrete structures.

Keywords: Waste Ceramic Tile Powder; Metakaolin; Reinforced Concrete Durability; Aggressive Environmental Exposure; Structural Performance

1. Introduction

Today, the use of concrete is increasing in various construction projects, and the need for a better understanding of its constituent materials, along with advancements in construction technology, is widely recognized in engineering communities. The high energy costs involved in cement production, coupled with the pollutants generated during its manufacturing, of which CO_2 is one of the most significant, have led to extensive efforts to reduce cement production and find alternative materials to replace it [1]. Pozzolans are one such group of materials that have become the focus of many of these efforts. Pozzolans are defined as siliceous or siliceous-aluminous materials that, on their own, do not possess cementitious properties [2]. However, when finely ground, they chemically react with lime (released from the hydration of Portland cement) in the presence of moisture at ambient temperature to form compounds with cementitious properties. Although the use of metakaolin in the concrete industry is only about 20 years old, it has rapidly gained acceptance as an effective pozzolanic material. Its pozzolanic capacity is high due to its strong demand for CH (calcium hydroxide) to form CAH gels (calcium alumino-silicate hydrates) [3]. Research shows that the partial replacement of cement with metakaolin improves the strength and durability of concrete [4,5]. Social, economic, and environmental necessities compel us to pay attention to the recycling industry across various dimensions. Traditional methods, inadequate equipment, inefficient systems, and insufficient regulations cannot meet our needs in waste management. Given the rise in construction and the production of waste materials in recent years, recycling and reusing materials have become essential, especially when considering the benefits of conserving natural resources and minimizing waste. This approach is particularly relevant to concrete, the most important material used in construction. with concrete being a material of global significance and high consumption, it is crucial to consider its economic, environmental, and performance aspects. Construction and demolition waste includes concrete, asphalt, wood, metals, glass, plaster, brick, stone, polymers, mosaics, ceramics, tiles, and roofing materials. Ceramic and tile waste, which are non-biodegradable industrial wastes, pose a significant environmental challenge due to their long biodegradation periods. As ceramic waste represents a substantial portion of industrial byproducts, recycling it is a major issue. One natural solution to reuse this waste is to incorporate it into the production of building materials, particularly as raw materials in concrete production. This approach has positive environmental effects, reducing waste accumulation and limiting the extraction of natural resources. In recent years, the use of metakaolin and waste ceramic tiles in concrete as partial replacements for cement has gained attention [6].

Studies on the mechanical properties and durability of concrete have shown that appropriately replacing cement with metakaolin improves these properties. In research examining the impact of metakaolin on high-strength concrete, samples containing 10% metakaolin showed the highest compressive strength and reduced water and chloride permeability compared to other samples [7]. Reviews of ceramic waste use in concrete production showed that replacing 30% of cement with ceramic tile powder increased compressive strength and decreased chloride permeability. Using tile as a pozzolan in concrete, when applied at appropriate replacement levels, not only increases the compressive strength of the concrete but also offers environmental and economic benefits [8]. Concrete produced with waste sanitary ceramics and combined with nano silica as a partial cement replacement demonstrated that ceramic waste alone reduced compressive strength at early ages and lowered water absorption. However, the combination of ceramic powder and brick waste with nano silica in high-strength concrete significantly improved compressive strength. In another study, samples containing 30% ceramic powder initially showed lower strength compared to control samples, but their strength increased over time [9]. Manthena and Boddepalli explored the influence of broken tiles and fly ash (0–40% as partial replacements in equal intervals) on the properties of self-compacting concrete (SCC) [10]. Their findings revealed that a 30% replacement provided the optimum balance of strength and durability in hardened concrete. Darweesh investigated the use of glass waste nanoparticles as a partial replacement (up to 20% by weight) in floor tile production, examining water absorption, firing temperature, shrinkage, and physical, mechanical, and thermal properties [11]. Results indicated decreased water absorption and porosity up to 1,100 °C, along with increased bulk density and slight increases in firing shrinkage at elevated temperatures. Bansal et al. studied the development of dry mix mortars incorporating supplementary cementitious materials (SCMs) and assessed strength parameters at varying water-to-cement ratios [12]. They observed consistent strength at 15, 30, and 60 days, with improved calcium silicate hydrate (C-S-H) gel distribution. Chandru et al. reviewed various studies on SCC utilizing industrial wastes as replacements for conventional materials, emphasizing their optimal dosages for enhancing strength and durability [13]. Hou et al. [14] evaluated the effects of metakaolin and silica fume on workability, compressive strength, and chloride penetration resistance. They reported that metakaolin enhanced early and long-term strength, while both metakaolin and silica fume improved resistance to chloride penetration. Comparisons of high-strength concrete with recycled aggregate (RAC) incorporating SF and MK demonstrated significant benefits [15]. Samadi et al. [16] examined the flexural behavior of reinforced concrete beams with recycled ceramic as cement and aggregate replacements, comparing them with conventional concrete. Recycled aggregate beams achieved up to 99% of the ultimate load of control specimens, with a 43% reduction in deflection. Jwaida et al. [17] reviewed the use of waste ceramics in concrete production, including waste disposal, ceramic raw materials, production processes, and types of waste ceramics utilized. Studies characterized waste ceramics as suitable replacements for aggregates or cement [18]. Experimental research demonstrated both positive and negative effects of waste ceramics on fresh and hardened concrete properties [19], with particular effectiveness in enhancing durability and mitigating alkali-silica reaction (ASR) [20]. Additionally, specific ceramic demolition waste materials were identified as potential components for eco-cement production, contributing to reduced carbon footprints in cement manufacturing [21]. Sharbatdar et al. have conducted several experimental tests on the effects of silica fume, zeolite, and a suggested Afghan natural pozzolan as a replacement for or complementary to cement [22–24].

Ambrose et al. investigated the performance of concrete incorporating recycled ceramic tile (RCT) as fine aggregate, analyzing its mechanical and durability properties, including density, slump, compressive strength, water absorption, chloride ion ingress, and acid attack resistance [25]. Their experimental findings showed that using RCT as fine aggregate produced lighter-weight concrete compared to river sand, and that as the RCT content increased, workability decreased while compressive strength increased proportionally. In terms of durability, specimens containing RCT exhibited improved resistance to water absorption, chloride ion ingress, and acid attack. Nasr et al. conducted experimental tests on the combined influence of zeolite and ceramic powder as supplementary cementitious materials on the mechanical and durability performance of concrete [26], while Tariq et al. carried out an experimental investigation using ceramic waste powder as a partial fine aggregate replacement in concrete [27]. Ismail et al. employed metakaolin and palm oil fuel ash to investigate the durability of concrete under cyclic environmental exposure [28]. Cheng et al. examined the effect of complete and semi-immersion modes on the durability of a metakaolin (MK)-based geopolymer mortar in a chloride–sulfate environment, using granulated blast furnace slag (GBFS) at various dosage rates (10–50%) [29]. Geu et al. reviewed the physical, mechanical, and durability performance of metakaolin concrete [30], and Raveendran et al. assessed the engineering performance and environmental impact of sustainable concrete incorporating nano-silica and metakaolin as cementitious materials [31]. Finally, Garg et al. conducted a mechanical strength and durability analysis of mortars prepared with fly ash and nano-metakaolin [32].

Although several studies have investigated metakaolin and waste tile powder and their effects on concrete properties, limited research has been conducted on the structural behavior of this type of concrete in combination with steel reinforcement. This paper therefore aims to address this gap. This study presents an experimental investigation in which metakaolin was added as a supplementary cementitious material and tile powder was used as a waste material, replacing 10, 20, and 30% of cement in concrete cubes and reinforced slabs. The results of compressive and flexural strength tests, along with the flexural capacity and durability of the concrete at 90 and 180 days, are discussed. Metakaolin and waste ceramic tile powder as partial cement replacements enhanced both compressive and flexural performance of reinforced concrete members under aggressive environmental exposure. Pozzolanic activity of metakaolin became increasingly pronounced after 3–6 months, with 20% replacement yielding up to 11% improvement in flexural capacity compared to the control mix. All waste tile powder mixtures surpassed the control mix in compressive strength, with 30% replacement achieving an experimental-to-nominal flexural capacity ratio of up to 1.57 after 90 days of aggressive exposure. The combined use of metakaolin and waste tile powder demonstrated strong potential for sustainable construction and rehabilitation of reinforced concrete structures in durability-critical applications.

2. Materials and Methods

2.1. Materials and Mix Designs

The aggregates used in this research were sourced from quarries, and the grading test, used to determine the distribution of aggregate particle sizes, was performed using sieves according to ASTM C33 standards [33]. The cement used was Type I Portland cement with chemical properties (from XRD tests) as specified in **Table 1** and a Blain value of 3,000 (cm^2/gr). The standard metakaolin shown in **Figure 1** was procured from the Company, and its chemical properties were determined by XRD tests, as listed in **Table 2**, with a Blain value of approximately 2,500 (cm^2/gr). The ceramic tiles used in this study were waste materials from the Tile Factory and were utilized in the form of tile powder or crushed waste (smaller than 4 mm replaced with sand. For grading, some of the tile and ceramic waste was crushed using the Los Angeles testing machine, and then sieved according to ASTM C33 standards, with material passing through a No. 200 sieve being considered as tile powder with a Blain value of approximately 1,500 (cm^2/gr), as shown in **Figure 2**. Given the large amount required, the necessary quantity of powder was prepared by the factory. The chemical properties of the tile and ceramic materials were obtained from the Tile Factory laboratory (from XRD tests) and are presented in **Table 3**. As shown in **Table 3**, the total percentage of the three oxides SiO_2 + Al_2O_3 + Fe_2O_3 in this material is approximately 88.76%, which meets the minimum requirement for a pozzolanic material as per ASTM C618 [34], where the threshold is 70%. Additionally, the SO_3 content of this material is 0.06%, which is well below the maximum limit of 3% specified by the standard. The loss on ignition (LOI) is 4.55%, which is also with in the maximum allowable limit of 10% according to the standard. Therefore, based on the above information, it can be concluded that this material satisfies the chemical requirements of ASTM C618.

Table 1. The chemical composition of Portland cement.

Chemical Profile	Percent (%)
K_2O	0.51
Na_2O	0.32
MgO	1.51
CaO	63.36
Fe_2O_3	3.96
Al_2O_3	4.42
SiO_2	21.11

Figure 1. Standard Metakaolin.

Table 2. The chemical composition of Metakaolin.

Chemical Profile	Average (%)
SiO_2	74.32
AL_2O_3	14.23
Fe_2O_3	2.26
CaO	1.53
MgO	1.2
SO_3	0.04
K_2O	3.09
Na_2O	0.76
LOI	0.93

Figure 2. Tiles powder.

Table 3. Chemical composition of the tile factory.

Chemical Profile	Percent (%)
MnO	0.002
P_2O_5	0.1
K_2O	3.97
Na_2O	0.68
MgO	0.7
CaO	0.04
TiO_2	0.9
Fe_2O_3	3.29
Al_2O_3	20.31
SiO_2	65.16
LOI	4.55
SO_3	0.06

The details of the mix designs are given in **Table 4**. M, TP, and TC indicate the Metakaoline, tile powder, and tile crushed at three different percentages of 10, 20, and 30%.

2.2. Experiments and Specimens

The compressive strength loading system was performed on 120 cubic specimens using a fully automated compressive testing machine with a capacity of 2,000 kN. The loading of the samples was carried out according to ASTM C39 standards [35]. In this study, cube-shaped specimens measuring 100 × 100 × 100 mm were used for measuring compressive strength. The compressive strength (in MPa) for each specimen was calculated by dividing the force P_{max} (in N) by the specimen's surface area A (in mm^2). The flexural strength loading system, as shown in **Figure 3**, was performed using a fully automated flexural testing machine with a capacity of 200 kN. This test was carried out according to ASTM C78-94 standards [36]. The samples (a total of 56) were placed on two supports with in a rigid frame, and the machine applied force at the midpoint. The force and the resulting displacement were recorded by the machine. To measure the maximum flexural force, reinforced concrete slabs were made with dimensions of 40 × 202 × 606 mm. To reinforce the slabs, the minimum reinforcement was used, following the ACI 318-25 [37]. So, two ribbed bars, size 8 mm with yielding strength 420 MPa, were placed 10 mm above the bottom of the mold, maintaining the required cover all around. Additionally, due to the large number of samples, two specimens were made for each type of concrete, and the average force was used in the calculations. Although many previously published studies tested only one or two structural specimens, we aimed to include additional specimens to provide adequate statistical reliability. However, due to equipment and cost limitations, only two slabs were tested for each mix design. As shown in **Figure 3**, the universal testing machine operates on a displacement-controlled mechanism, where a slab with free supports is subjected to a vertical load at the midpoint. Two reaction forces occur at the supports, while a direct load is applied at the middle of the slab. The support distance for the concrete slab is 500 mm, and the loading is performed at a constant rate.

Table 4. Mix design (for 1 m3).

Concrete Type	Cement (kg)	Water (kg)	Gravel (kg)	Sand (kg)	Metakaolin		Tile Powder		Tile Crushed	
					(%)	(kg)	(%)	(kg)	(%)	(kg)
T0	400	220	802	980	0	0	0	0	0	0
M10	360	220	802	980	10	40	0	0	0	0
M20	320	220	802	980	20	80	0	0	0	0
M30	280	220	802	980	30	120	0	0	0	0
TP10	360	220	802	980	0	0	10	40	0	0
TP20	320	220	802	980	0	0	20	80	0	0
TP30	280	220	802	980	0	0	30	120	0	0
TC10	400	220	802	882	0	0	0	0	10	98
TC20	400	220	802	784	0	0	0	0	20	196
TC30	400	220	802	686	0	0	0	0	30	294

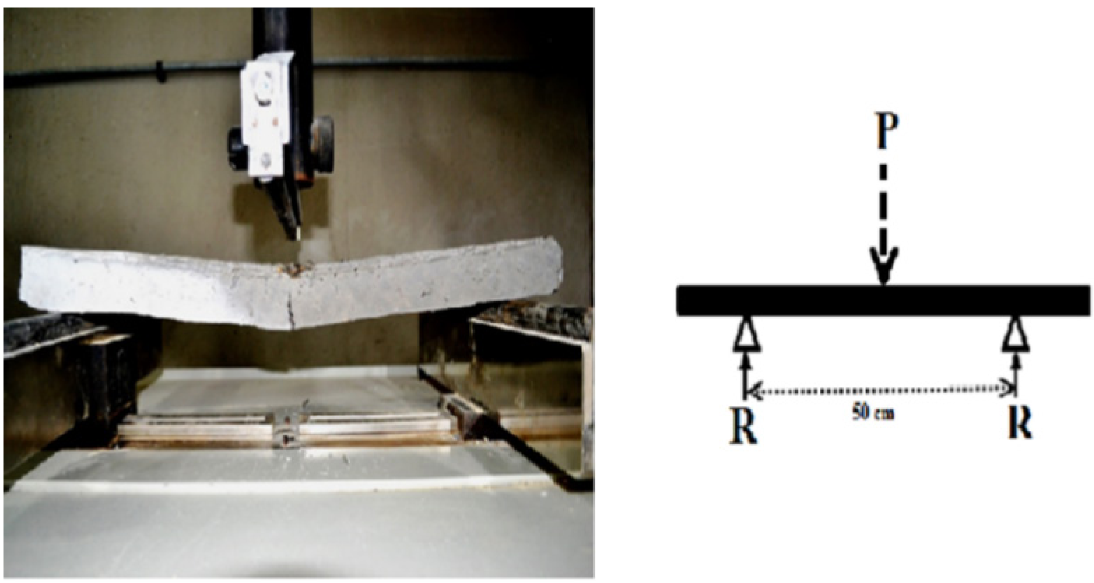
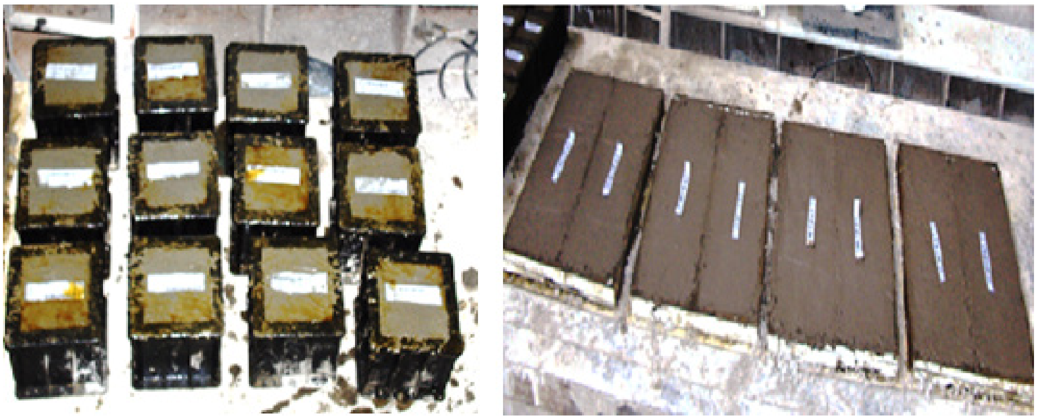


Figure 3. Test setup for flexural strength.

Since metakaolin and tile powder participate in the chemical reactions at later ages, the samples were tested at 60, 90, and 180 days to observe the effect of these pozzolans on the behavior of the specimens. After casting the concrete, the samples were demolded after 24 h and kept in tanks of ordinary water. For the curing of samples in a controlled environment, a pond containing potable water from the university was used, with ambient temperatures maintained at 25–30 °C. Compressive and flexural specimens, as well as slabs, were cured and maintained for the specified duration (60, 90, and 180 days) in two environments, regular and aggressive, before being subjected to loading. The process of casting concrete and filling molds, demolding specimens, and curing of cubic and reinforced slabs is shown in **Figure 4**.

The aggressive environment consisted of a basin filled with municipal drinking water, while the aggressive environment was a chloride-rich environment with a sodium chloride solution at a concentration similar to that of the salt concentration in Lake Urmia, approximately 300 g/L. Owing to the limited laboratory testing period (three months), most researchers adopt accelerated simulation methods, in which the chloride concentration is increased relative to actual field conditions to expedite the durability assessment.

The samples were positioned in the environment such that the cubic specimens and reinforced slabs were fully submerged in water. The curing process involved alternating wet and dry cycles, where the water from each environment was pumped back and forth using a pump. Each 24-h period constituted a wet-dry cycle, with each cycle comprising 12 h of soaking and 12 h of drying at an ambient temperature of 25–30 °C. The results of the chemical analysis of certain ions present in the test environment's water, along with a comparison to the destructive waters of Iran and drinking water, are presented in **Table 5**.



(**a**) Casting cubic and slab specimens.

(**b**) Demoulding and curing specimens.

Figure 4. Casting and curing process of specimens.

Table 5. Available ions of different waters (PPM).

Ions	Drinking Water	Persian Gulf	Kish Island	Lake Urmia	This Research
K^+	2.6	450	397	1,404	146,750
Ca^{2+}	8.01	430	450	1,360	0
Mg^{2+}	3.9	1,460	1,600	12,418	367
SO_4^{2-}	0	2,720	3,070	22,752	1,310
Na^+	78	12,400	11,400	86,066	976
Cl^-	99.26	21,450	3,070	143,704	150,490
Total	191.7	38,910	19,987	267,704	299,892

3. Results and Discussion

3.1. Compressive Strengths

The compressive strength test was conducted using a compression jack, and the compressive strength of the samples was measured at 60, 90, and 180 days after being placed in the two different environments. It is worth noting that three cubic samples were prepared and tested for each case, and the average results were reported. **Tables 6** and **7** show the average compressive strength of the samples. According to the results in **Table 5**, at 60 days, the highest strength was observed in the cube samples containing 10% metakaolin. However, over time, at 180 days, the samples containing 30% tile powder exhibited the highest strength. According to **Table 8**, in the regular environment, the sample containing 10% metakaolin exhibited the highest strength compared to the control sample at the age of 60 days. Additionally, at 90 and 180 days, it showed the highest strength with increases of 4% and 9%, respectively. The sample containing 30% metakaolin had the lowest strength compared to the control sample at 60 days. However, over time, at 90 and 180 days, its strength increased by 46% and 55%, respectively, compared to the control sample. Also, the sample containing 30% tile powder showed the highest strength compared to the control sample at the age of 60 days. Additionally, at 90 and 180 days, it demonstrated the highest strength with increases of 7% and 15%, respectively. The sample containing 20% tile powder had the lowest strength compared to the control sample at 60 days. However, over time, at 90 and 180 days, its strength increased by 1% and 17%, respectively, compared to the control sample. Moreover, the sample containing 20% crushed tile exhibited the highest strength compared to the control sample at 60 days. Additionally, at 90 and 180 days, it showed the highest strength with increases of 6% and 16%, respectively. The sample containing 10% crushed tile had the lowest strength compared to the control sample at 60, 90, and 180 days. For the sample containing 30% crushed tile, strength increased over time, with increases of 9% and 15% at 90 and 180 days, respectively.

Table 6. The average compressive strengths of cubic specimens (MPa), regular environment.

Concrete Type	60 Day	90 Day	180 Day
T0	25.9	27	27.9
M10	31	32.3	33.7
M20	22.8	23.3	26.2
M30	19.2	28	29.7
TP10	28	28.8	29.8
TP20	26.7	27.1	31.2
TP30	29.4	31.6	33.9
TC10	16	18.7	20.9
TC20	32.4	34.4	37.6
TC30	31.5	34.3	36.2

Table 7. The average compressive strengths of cubic specimens (MPa), aggressive environment.

Concrete Type	60 Day	90 Day	180 Day
T0	25.9	25.5	25.3
M10	29	32	31.1
M20	22.5	23.4	23.7
M30	24.4	27.9	28.5
TP10	26.5	22.5	28.8
TP20	24.1	24.7	26.4
TP30	24.7	29.7	30.5
TC10	21.8	27	29.5
TC20	32.1	34.3	38.6
TC30	27.4	30.4	33.6

Table 8. Effectiveness of age on compressive strength in a regular environment.

Concrete Type	$f_{cu,i,60}$ (MPa)	$f_{cu,i,90}$ (MPa)	$f_{cu,i,90}/f_{cu,i,6}$	$f_{cu,i,180}$ (MPa)	$f_{cu,i,180}/f_{cu,i,60}$
T0	25.9	27	1.04	27.9	1.08
M10	31	32.3	1.04	33.7	1.09
M20	22.8	23.3	1.02	26.2	1.15
M30	19.2	28	1.46	29.7	1.55
TP10	28	28.8	1.03	29.8	1.06
TP20	26.7	27.1	1.01	31.2	1.17
TP30	29.4	31.6	1.07	33.9	1.15
TC10	16	18.7	1.17	20.9	1.31
TC20	32.4	34.4	1.06	37.6	1.16
TC30	31.5	34.3	1.09	36.2	1.15

Table 9 shows the effect of adding various percentages of mineral additives on the 60, 90, and 180-day compressive strength of concrete in a regular environment. The sample containing 10% metakaolin exhibited increases of 20% in strength at 60, 90, and 180 days, respectively, compared to its control sample, while the samples containing 20% metakaolin showed decreases in strength of 12%, 14%, and 6%, respectively. The sample with 30% metakaolin showed a 25% reduction in strength at 60 days, but at 90 and 180 days, its strength increased by 4% and 6%, respectively, compared to the control sample. For the sample containing 30% tile powder, strength increased by 14%, 17%, and 22% at 60, 90, and 180 days, respectively, compared to the control sample. The sample with 20% tile powder showed an increase over time, reaching a 12% increase in strength at 180 days compared to the control. At 60, 90, and 180 days, the sample with 20% crushed tile showed strength increases of 25%, 27%, and 34%, respectively, while the samples containing 10% crushed tile showed decreases of 38%, 31%, and 25%, respectively, compared to the control sample. The sample with 30% crushed tile showed a 19% decrease in strength at 60 days, but increases of 27% and 30% at 90 and 180 days, respectively, compared to the control sample.

Table 9. The effect of various percentages of mineral additives on the compressive strength of concrete in a regular environment.

Age (Days)	T_0 (MPa)	$f_{cu,i,10\%}$ (MPa)	$f_{cu,i,10\%}/f_{cu,T0}$	$f_{cu,i,20\%}$(MPa)	$f_{cu,i,20\%}/f_{cu,i,T0}$	$f_{cu,i,30\%}$(MPa)	$f_{cu,i,30\%}/f_{cu,i,T0}$
		Samples Containing Metakaolin					
60	25.9	31	1.2	22.8	0.88	19.2	0.75
90	27	32.3	1.2	23.3	0.86	28	1.04
180	27.9	33.7	1.21	26.2	0.94	29.7	1.06

Table 9. *Cont.*

Age (Days)	T_0 (MPa)	$f_{cu,i,10\%}$ (MPa)	$f_{cu,i,10\%}/f_{cu,T0}$	$f_{cu,i,20\%}$(MPa)	$f_{cu,i,20\%}/f_{cu,i,T0}$	$f_{cu,i,30\%}$(MPa)	$f_{cu,i,30\%}/f_{cu,i,T0}$
		Samples Containing Tile Powder					
60	25.9	28	1.08	26.7	1.03	29.4	1.14
90	27	28.8	1.07	27.1	0	31.6	1.17
180	27.9	29.8	1.07	31.2	1.12	33.9	1.22
		Samples Containing Tile Crushed					
60	25.9	16	0.62	32.4	1.25	20.9	0.81
90	27	18.7	0.69	34.4	1.27	34.3	1.27
180	27.9	20.9	0.75	37.6	1.34	36.2	1.30

3.2. Flexural Strength

This test was conducted using a universal testing machine with a 500 mm support span, with measurements taken 90 and 180 days after sample curing in two different environments. For each condition, two reinforced slabs containing only cement, metakaolin, or tile powder were prepared and tested, with the average results reported. **Table 10** shows the average maximum flexural force of the samples. According to **Table 10**, at 90 days, all samples exhibited flexural force higher than the control sample. In samples containing 20% metakaolin and 30% tile powder, flexural strength increased at 180 days due to the pozzolanic properties of these materials. At 90 days, as seen in **Table 10**, the samples with 10% tile powder exhibited the lowest flexural force with a 5% reduction, while the samples with 10% metakaolin and 30% tile powder showed the highest flexural force with a 19% increase. However, at 180 days, the samples with 10% tile powder and 20% metakaolin had the lowest flexural force, showing a 3% reduction, whereas the samples with 30% tile powder exhibited the highest flexural force with an 18% increase. **Table 11** shows the effect of adding various percentages of mineral additives on the 90- and 180-day flexural force of concrete slabs in a regular environment.

Table 10. The average flexural force of beam specimens (kN).

Concrete Type	90 Days	Increase/Decrease the Percentage of Each Specimen to T0–90	180 Days	Increase/Decrease the Percentage of Each Specimen to T0–180
T0	10.6	0	11.2	0
M10	12.6	19	12.9	15
M20	10.7	1	10.9	−3
M30	11.2	6	11.8	6
TP10	10.1	−5	11	−2
TP20	11.2	5	12	7
TP30	12.8	20	13.2	18

Table 11. The effect of various percentages of mineral additives on the flexural force of concrete slabs in a regular environment.

Age (Days)	T_0 (kN)	$P_{i,10\%}$ (kN)	$P_{i,10\%}/P_{T0}$	$P_{i,20\%}$ (kN)	$P_{i,20\%}/P_{T0}$	$P_{i,30\%}$ (kN)	$P_{i,30\%}/P_{T0}$
		Samples Containing Metakaolin					
90	10.6	12.6	1.19	10.7	1.01	11.2	1.06
180	11.2	12.9	1.15	10.9	0.97	11.8	1.06
		Samples Containing Tile Powder					
90	10.6	10.1	0.95	11.2	1.06	12.8	1.20
180	11.2	11	0.98	12	1.07	13.2	1.18

3.3. The Durability of Specimens in an Aggressive Environment

Some compressive and flexural specimens were cured and maintained for the specified duration (60, 90, and 180 days) in an aggressive environment before being subjected to loading. In this section, the results of these specimens are presented and compared with the results of specimens cured in a regular environment in **Tables 12** and **13**.

Table 12. Comparison of compressive strength of concrete cubes in regular and aggressive environments.

Environment	T (MPa)	M10 (MPa)	M20 (MPa)	M30 (MPa)	TP10 (MPa)	TP20 (MPa)	TP30 (MPa)	TC 10 (MPa)	TC20 (MPa)	TC30 (MPa)
					60 Days					
Aggressive	23.6	29.8	22.2	20.0	26.5	24.8	26.9	17	31.0	28.4
Regular	25.9	31	22.8	19.2	28	26.7	29.7	16	32.4	31.5
Aggressive to regular	0.91	0.96	0.97	1.04	0.95	0.93	0.90	1.06	0.95	0.90
					90 Days					
Aggressive	23.7	31.0	23.0	27.2	25.5	24.2	28.0	19.5	32.2	30.0
Regular	27	32.3	23.3	28	28.8	27.1	31.6	18.7	34.3	34.3
Aggressive to regular	0.88	0.95	0.99	0.97	0.89	0.90	0.87	1.04	0.94	0.87
					180 Days					
Aggressive	23,1	31.1	23.8	28.0	26.0	26.4	29.5	22	35.2	31.0
Regular	27.9	33.7	26.2	29.7	29.8	31.2	33.9	21	38	36
Aggressive to regular	0.82	0.92	0.91	0.94	0.87	0.85	0.87	1.04	0.92	0.86

Table 13. Comparison of the flexural force of concrete slabs in regular and aggressive environments.

Environment	T (kN)	M10 (kN)	M20 (kN)	M30 (kN)	TP10 (kN)	TP20 (kN)	TP30 (kN)
				90 Days			
Aggressive	9.6	11.4	9.9	10.2	9.2	10.5	10.8
Regular	10.6	12.6	10.7	11.2	10.1	11.2	12.8
Aggressive to regular	0.90	0.91	0.93	0.91	0.91	0.94	0.85
				180 Days			
Aggressive	9.3	11.5	9.5	9.9	9.5	10.4	11.9
Regular	11.2	12.9	10.9	11.8	11.0	12	13.2
Aggressiveto regular	0.83	0.89	0.87	0.84	0.86	0.87	0.91

Table 12 shows that, over time, a decrease in compressive strength is observed in the reference sample (T0), with reductions of 9%, 12%, and 18% occurring after 60, 90, and 180 days, respectively, when compared to samples of the same age. However, with the addition of supplementary materials, such as metakaolin, tile powder, or tile crushed, the decline in compressive strength in samples after 60, 90, and 180 days was less pronounced. Samples containing metakaolin, tile powder, and tile crushed demonstrated the best performance in an aggressive environment, in that order. The compressive strength of samples containing 10% and 30% metakaolin, 10% and 30% tile powder, and 20% and 30% tile crushed even exceeded the 60-day strength of the reference sample T0, at 25.9 MPa, after 90 and 180 days in an aggressive environment, highlighting the effectiveness of using mineral additives and recycled materials from tile manufacturing. **Table 13** shows that, over time, a decrease in the flexural force of reinforced concrete slabs is observed in the reference sample (T0), with reductions of 10% and

17% occurring after 90 and 180 days, respectively, when compared to samples of the same age. However, with the addition of supplementary materials, such as metakaolin and tile powder, the decline in flexural force in samples after 90 and 180 days was less pronounced, around 7% and 9% for metakaolin with 20% and tile powder with 20%. Samples containing metakaolin and tile powder demonstrated the best performance in an aggressive environment, in that order.

3.4. Comparison of Nominal and Experimental Moment Capacity

The nominal flexural moment of the reinforced slabs was theoretically calculated using Equation (1) based on ACI-318-25, and the experimental load-bearing capacity was determined through Equation (2). These moments are compared in two different environments in **Tables 14** and **15**.

$$M_n = A_s \cdot f_y \cdot (d - \frac{a}{2}),\ a = \frac{A_s \cdot f_y}{(0.85 f_c) \cdot b} \quad (1)$$

$$M_E = \frac{P \cdot L}{4} \quad (2)$$

Where:

M_n = Nominal Moment (kN·m), f_y = Yielding strength (420 MPa), A_s = Steel bar area (100 mm^2);

M_E = Experimental Moment (kN·m), a = compression block height (mm), P = Flexural force (kN);

L = Support length (500 mm), d = Effective height (26 mm), f'_c = Concrete compressive strength (MPa);

b = The width of the slab (mm).

Table 14. The comparison of the nominal and experimental moments in the regular environment.

Concrete Type	f'_c (MPa)	a (mm)	M_n (kN·m)	P (kN)	M_E (kN·m)	M_E/M_n
			90 Days			
T0	27	9.1	0.9	10.6	1.33	1.47
M10	32.3	7.6	0.93	12.6	1.58	1.69
M20	23.3	10.5	0.87	10.7	1.33	1.53
M30	28	8.7	0.91	11.2	1.4	1.54
TP10	28.8	8.5	0.91	10.1	1.26	1.38
TP20	27.1	9	0.9	11.2	1.4	1.55
TP30	31.6	7.7	0.93	12.8	1.6	1.72
			180 Days			
T0	27.9	8.8	0.91	11.2	1.4	1.54
M10	33.7	7.3	0.94	12.9	1.6	1.72
M20	36.2	6.8	0.95	10.9	1.36	1.43
M30	29.7	8.2	0.92	11.8	1.48	1.60
TP10	29.8	8.2	0.92	11	1.38	1.5
TP20	31.2	7.8	0.93	12	1.5	1.62
TP30	33.9	7.2	0.94	13.2	1.65	1.75

Table 15. The comparison of the nominal and experimental moments in the aggressive environment.

Concrete Type	f'_c (MPa)	a (mm)	M_n (kN·m)	P (kN)	M_E (kN·m)	M_E/M_n
			90 Days			
T0	25.5	9.6	0.89	9.6	1.2	1.35
M10	32	7.6	0.93	11.4	1.43	1.53
M20	23.4	10.5	0.87	9.9	1.24	1.42
M30	27.9	8.8	0.91	10.2	1.28	1.4
TP10	22.5	10.9	0.86	9.2	1.15	1.33
TP20	24.7	9.9	0.88	10.5	1.31	1.48
TP30	29.7	8.2	0.92	10.8	1.35	1.47

Table 15. *Cont.*

Concrete Type	f'_c (MPa)	a (mm)	M_n (kN·m)	P (kN)	M_E (kN·m)	M_E/M_n
			180 Days			
T0	25.3	9.7	0.89	9.3	1.16	1.3
M10	31.1	7.9	0.93	11.5	1.44	1.55
M20	23.7	10.3	0.87	9.5	1.19	1.36
M30	28.5	8.6	0.91	9.9	1.23	1.36
TP10	28.8	8.5	0.91	9.5	1.19	1.3
TP20	26.4	9.3	0.89	10.4	1.3	1.45
TP30	30.5	8	0.93	11.9	1.49	1.61

According to **Table 14**, at 90 and 180 days, the flexural moment for all test samples in the regular environment exceeded the theoretical calculations. However, the flexural moment capacity of specimens was increased from 38 to 72% at 90 days, and from 43 to 75% at 180 days. The lowest flexural moment was observed at 90 days in the sample with 10% tile powder, which still exceeded the theoretical value by 38%. In contrast, the lowest flexural moment was observed at 180 days in the sample with 20% metakaolin, which still exceeded the theoretical value by 43%. At both 90 and 180 days, the sample containing 30% tile powder showed the highest flexural moment, bearing 72% and 75% more than the theoretical calculation, respectively. Therefore, **Table 14** demonstrates that all experimental moment capacities of the beams incorporating waste tile powder exceed the theoretical moments predicted by the available design codes. This confirms that the proposed concrete conforms to the existing assumptions and theoretical framework for calculating the nominal moment capacity, with safety factors greater than 1.4. According to **Table 15**, at 90 and 180 days, the flexural moment for all test samples in the aggressive environment exceeded the theoretical calculations. However, the flexural moment capacity of specimens was increased from 33 to 53% at 90 days, and from 30 to 61% at 180 days. The lowest flexural moment at 90 and 180 days was observed in the sample with 10% tile powder, which still exceeded the theoretical value by 30%. At both 90 and 180 days, the sample containing 30% tile powder showed the highest flexural moment, bearing 47% and 61% more than the theoretical calculation, respectively. Metakaolin and tile powder help concrete decrease permeability and also increase its capacity in aggressive environments.

The results presented in **Tables 14** and **15** indicate that both metakaolin and waste tile powder, as sustainable materials, enhanced the compressive strength, durability, and particularly the long-term structural performance of the concrete. Therefore, these materials are suitable for use in new sustainable infrastructure as well as in the rehabilitation of existing concrete structures. Tile powder is an industrial waste material with a low cost compared to cement, making it an economical alternative; moreover, it is capable of increasing the concrete compressive strength by up to 70% under normal environmental conditions. The reference concrete with out tile powder exhibited a reduction in compressive strength of up to 17% when subjected to the aggressive environment. Consequently, the use of tile powder, with its high initial strength, can compensate for this reduction and prove effective in providing enhanced durability under aggressive environmental conditions.

4. Conclusions

By selecting seven mix designs, including standard concrete and concretes with varying percentages of metakaolin and waste tile powder, and creating 56 cubic and reinforced concrete slab samples, compressive strength and flexural capacity were tested and analyzed over long-term periods of 3 and 6 months. The following general conclusions can be drawn:

- The sample containing tile powder acted as a pozzolanic additive, achieving the highest compressive strength at 180 days. The strength of all samples with tile powder was higher than that of the control sample.
- At 60 days, the highest strength was observed in the cube sample containing 10% metakaolin. At 90 and 180 days, due to the pozzolanic chemical reaction,

the sample with 30% tile powder endured the highest flexural load compared to the samples with 10% and 20%.

- At 90 days, the sample with 20% metakaolin bore a flexural load similar to the control but less than the other two samples; however, with aging, its pozzolanic properties became evident, leading to increased load-bearing capacity.
- In all samples containing tile powder, the experimentally measured flexural moment exceeded theoretical calculations, and the flexural capacity of samples with 20% metakaolin and 30% tile powder exceeded the nominal flexural capacity (ACI-318) by 42% and 50%, respectively.
- The samples with 20% metakaolin and 30% tile powder showed greater durability at 180 days due to their increased weight.
- Both metakaolin and waste tile powder enhanced the compressive strength, durability, and long-term structural performance of concrete, with tile powder increasing the compressive strength by up to 70% under normal conditions.
- As an economical and sustainable industrial waste, tile powder effectively compensated for the strength reduction observed in aggressive environments, making it suitable for new sustainable infrastructure and the rehabilitation of existing structures.

Author Contributions

Conceptualization, M.K.S. and S.A.; material preparation, S.A.; testing, S.A.; data collection, S.A.; analysis, S.A.; writing—original draft preparation, S.A.; writing—review and editing, M.K.S.; supervision, M.K.S. Both authors have read and agreed to the published version of the manuscript.

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The authors declare that they have no competing interests, financial or otherwise, that could have influenced the research outcomes or interpretations presented in this study.

AI Use Statement

During the preparation of this manuscript, the authors used Claude solely for language refinement. No AI tools were used for data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of the work.

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