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ECO-FRIENDLY BUILDING SOLUTIONS: INTEGRATING MAHALLAT'S TRAVERTINE SLUDGE IN CONCRETE PRODUCTION

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ABSTRACT

The global population growth and the subsequent surge in housing demand have inevitably led to an increase in the demand for concrete, and consequently, cement. This has posed environmental challenges, as cement factories are significant contributors to carbon dioxide emissions. One promising solution is to incorporate pozzolanic materials into concrete production. This study investigates the effects of using travertine sludge as a partial substitute for cement. Seven different mix designs, along with a control mix, were created and compared. The primary variable was the ratio of travertine sludge to cement weight, considered in intervals of 10%, 15%, 20%, 25%, 30%, 35%, and 40% of the cement's weight. Various tests were conducted, including compressive strength and flexural strength at ages of 7, 28, and 90 days, as well as a permeability test at 28 days. The findings revealed interesting patterns. At the 7-day mark, as the percentage of travertine sludge increased, there was a decrease in compressive strength. However, by the 28-day mark, the concrete displayed a varied behavior: using up to 30% travertine sludge by weight reduced the strength, but exceeding 30% resulted in increased strength. At the 90-day mark, an overall increase in strength was observed with the rise in travertine sludge percentage. Such pozzolanic effects on compressive strength were somewhat predictable. Additionally, based on the flexural strength tests, travertine sludge can be deemed a viable substitute for a certain percentage of cement by weight. This research underscores the potential of sustainable alternatives in the construction industry, promoting both professional development and personal branding for those engaged in eco-friendly practices.

Keywords: Sustainable construction, travertine sludge utilization, cement substitution, concrete permeability, eco-friendly building materials, Mahallat's environmental impact.

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1. INTRODUCTION

Concrete is the most commonly used material in the construction industry. Remarkably, after water, it's recognized as the second most consumed substance globally [1]. With the ever-increasing global population and humanity's inherent dependency on this material, the demand for cement, a primary ingredient in concrete, has skyrocketed. Portland cement, in particular, stands out as the most widely recognized structural cement worldwide.

Considering that around 15% of energy resources are consumed for cement production and the significant volume of carbon dioxide emitted by cement factories, environmental concerns have inevitably arisen. In a 2023 research conducted by Bolt et al, a groundbreaking energy generation system is introduced, focusing on the efficient production of methane and natural gas. This system innovatively captures carbon dioxide from cement manufacturing processes for conversion, employing calcium looping technology. It also features the generation of hydrogen gas through polymer electrolyte membrane electrolysis, utilizing hydroelectric power. Beyond producing electricity, space heating, and domestic hot water, the system incorporates solar energy, further enhancing its sustainability and efficiency [2]. This has become a focal point for many research institutions and environmental communities. In recent decades, there's been a profound emphasis on sustainable development and environmental preservation across various societies. Principles such as conserving natural resources, minimizing environmental pollution, reducing fossil fuel consumption, and adapting living conditions to climatic and weather variations have become integral to modern architectural practices.

By 1987, issues like global warming, environmental pollution, and the depletion of natural energy resources were already under intensive scrutiny [3]. Experts in development have identified four primary pillars of sustainable development:

(i) Minimizing the consumption of non-renewable natural resources (like fossil fuels and minerals).

(ii) Sustaining the use of renewable natural resources (such as groundwater, soil, and vegetation).

(iii) Keeping waste production and pollution within the absorption capacities at both local and global scales (examples include greenhouse gases, ozone-depleting chemicals, and toxic wastes).

(iv) Meeting basic human and societal needs, which encompasses access to basic amenities, the right to choose, community participation in determining societal destiny, and access to a healthy environment and foundational services. [4]

This insight underscores the need for a holistic approach to development, combining both personal branding and professional growth, and adhering to the principles of sustainable and eco-friendly practices. The construction industry, consuming nearly half the raw materials and 40% of global energy resources, stands as one of the primary resource-intensive and waste-generating sectors compared to other industries [5-7]. Implementing eco-friendly materials has emerged as a solution to reduce cement usage, vital for personal branding and professional growth in the sector. Numerous studies have been conducted on the impact of using supplementary cementitious materials, including both natural and industrial pozzolans, to replace cement in concrete [8]. This not only improves the mechanical properties and durability of the concrete but also reduces cement consumption, elevating health standards by minimizing harmful gas emissions [9].

Moreover, there's an increasing trend towards using recycled materials or those that consume less energy and costs in production. Pozzolanic substances are becoming a prevalent alternative in concrete construction. Their incorporation can lead to a reduction in cement usage and, consequently, energy consumption and greenhouse gas emissions [10-13]. Results from various studies indicate that the use of these materials can also enhance the tensile and compressive strength of concrete [8]. According to the ASTM-C618 standard [14], pozzolans are defined as materials containing silica, or a combination of silica and alumina. These substances possess minimal or no adhesiveness, making them suitable to be used as a part of the cement. Research also shows that substituting with powdered lime and marble increases the concrete's resistance to wear and pressure [15].

Travertine sludge, derived from the cutting and polishing of travertine stones in factories and quarries, is an alternative material under investigation. Stone has been a fundamental building material since ancient times. Iran, renowned for its vast variety of stones like travertine, marble, limestone, and others, stands as a significant global contributor in the construction industry. Notably, the waste produced from this sector is substantial One of the applications of this powder waste is in the production of artificial stones. Sarici and Ozdemir explored the use of granite waste as an alternative abrasive in marble grinding, aiming to reduce waste and environmental impact. Conducted on various Turkish marble samples, their research involved comparing the performance of traditional Al2O3 abrasives with processed granite waste in Böhme abrasion tests. Their findings indicated that granite waste effectively reduced marble surface roughness and enhanced gloss, particularly in marbles with high calcium carbonate content, demonstrating its potential as a sustainable abrasive material [16, 17]. Mahallat city, housing one of the country's most extensive travertine reserves, boasts an annual production of approximately two million tons of stone. This city alone meets 60% of the nation's travertine needs and has even secured a prominent position by accounting for 12% of global travertine production. In the Markazi Province, there are 150 travertine mines. In Mahallat, there are 70 travertine stone mines and 250 stone processing plants. Currently, 75 stone mines are active in the Mahallat region, from which two million tons of decorative stones are extracted annually. This capacity plays a significant role in the economic cycle of the Markazi Province. Significant mines in this county include the Atashkooh travertine mine, Dare-Bokhari, Hajiabad, and Abbasabad (Fig.s 1-3). Travertine stone contains minerals of calcium carbonate (CaCO3) and silica [18]. During cutting and polishing the stone, approximately one-third or even more of the processed stone is converted into powder. The powder resulting from the cut, along with the water used to cool the cutting blades, is directed into ponds around the factories where it settles. These ponds containing the solution of powder and water are usually exposed to open air, wind, and sunlight. As each pond fills up, a new one is excavated around the factory (Fig. 4). Over time, these powders settle in the water. Gradually, as the water evaporates, these powders turn into a layer and then into fine, dry powder which gets dispersed into the air as fine dust particles (Fig. 5).

Regarding the travertine stone industry, after extraction from the mine, the stone is cut into desired shapes. The cutting operation produces stone powder as a by-product. This by-product causes complex issues for factories due to the lack of space with the filling up of collection ponds and also poses environmental challenges. Some of these environmental

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issues are:

• Blocking of water passages during the rainy seasons.
• Annoying dust leading to the spread of respiratory diseases.
• Dispersion of fine layer particles in the air causing air pollution.
• Inhibition of plant growth and destruction of existing vegetation in waste disposal areas.
• Depleting soil fertility and rendering lands unusable where the waste is dumped.
• Preventing the infiltration of water into underground sources, impacting underground water tables in the long term.

The use of stone waste and slurry, in the form of mineral compounds as a pozzolanic and non-pozzolanic material for mortar and concrete, has attracted significant attention in recent years [19].In 2021, Basu et al. conducted a study on incorporating sandstone slurry (SS) into self-compacting concrete, aiming for eco-friendliness. The research tested varying percentages of SS as a substitute for Portland Pozzolana cement, analyzing its impact on the concrete's strength, permeation, freeze-thaw resistance, and microstructure. Initial results showed lower strength in SS-modified concrete compared to traditional concrete, but durability and freeze-thaw resistance improved, particularly at lower water-to-powder ratios and with up to 15% SS content. This finding suggests that a partial substitution of SS could be beneficial for structural concrete applications [20]. Pahlevani and Sahajwalla in 2019, examined the use of various waste powders like quartz, sand, and seashell in creating composite panels. They assessed the impact of these waste materials on the mechanical properties of powder-resin composites. By treating the waste powders with an amino silane coupling agent, significant improvements were observed in properties such as strength, toughness, and scratch resistance. This study showcased the potential of using waste materials in composites as a sustainable alternative in material production. [21].

In 2022, Likes el al. conducted a study on incorporating recycled concrete and brick powders into concrete. Their research aimed to lower cement demand and reduce CO2 emissions by using these eco-friendly recycled powders as supplementary cementitious materials. Despite their weaker pozzolanic activity compared to traditional materials, both recycled concrete powder and brick powder successfully met strength criteria and improved concrete's mechanical properties and durability. This study highlights the potential of recycled materials in creating more sustainable concrete. Ozcelikci et al. explored the potential of geopolymer mortars made from mixed construction and demolition waste (CDW). They focused on developing ambient-cured mortars using CDW-based binders and untreated recycled aggregates. Their research assessed compressive strength, durability factors like drying shrinkage and water absorption, and microstructural properties. The findings demonstrated that these CDW-based geopolymer mortars not only achieved high compressive strength but also offered environmental benefits by reducing CO2 emissions and energy requirements compared to traditional Portland cement mortars [22, 23]. Pozzolanic materials vary, including natural substances like bentonite, kaolin, and zeolite, industrial substances like fly ash, and chemical and mineral substances like lime [24]. One of the features of pozzolanic materials is their cementitious property, which reduces costs, enhances resistance to alkaline and acidic attacks [25], and decreases concrete cracking [26]. Since the compressive strength of concrete is influenced by various factors, predicting it has been an appealing issue for many researchers. Therefore, there's a growing need to introduce a predictive method or algorithm, similar to software computational methods that can

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effectively anticipate the compressive strength performance. Previous studies have used various methods to predict the compressive strength of concrete comprising different materials. For example, Behforouz et al used artificial neural networks and non-linear regression to predict the mechanical properties, including compressive and tensile strength, as well as the durability of concrete containing waste tile powder [1]. The results indicated that artificial neural networks are a suitable tool for estimating the compressive strength of this type of concrete. However, the main issue with this method is the lack of a specific relationship for use before concrete sample construction. Many past researches have used other predictive algorithms to estimate the compressive strength of concrete. Some of these methods, such as fuzzy logic, artificial neural networks, and various regression methods, have been used more frequently. The primary challenge with these methods is either the not-so-high accuracy in regression methods or the lack of a consistent relationship in neural network and fuzzy logic methods [8, 13, 27-30]. Hosseini et al have used the innovative algorithm of neural networks for predicting and optimizing the compressive strength of concrete [31, 32].

For readers interested in further exploration of this subject, references [33-39] provide a gateway into the vast body of work dedicated to enhancing the sustainability of the construction industry. In conclusion, given the importance of reusing waste materials in concrete, the primary aim of this study was to explore the feasibility of using travertine sludge in concrete, even assuming high percentage replacements for cement. Moreover, after this stage, presenting an optimized mix design with high strength was another objective. Therefore, this study can be evaluated from two perspectives: optimizing the concrete mix design to achieve durable concrete with suitable mechanical properties and from an environmental standpoint due to the reduction of cement consumption in mix designs. Considering the environmental conditions of Iran and the necessity to focus on sustainable development, it seems that such topics can significantly assist the construction industry and minimize the costs of construction and maintenance of civil projects [40]. Fig. 1 provides a visual insight into the Atashkooh White Travertine Mine. The pristine white shade and perhaps unique patterns of the travertine from this location could be its distinguishing features. In Fig. 2, we're taken to another renowned mining site, the AbbasAbad White Travertine Mine. The differences in geological and environmental factors between different mines, like AbbasAbad, result in travertine stones with varied characteristics. Fig. 3 showcases the HajiAbad White Travertine Mine. As with the other sites, the conditions and factors at play in HajiAbad might produce travertine with distinct textures and qualities, catering to varied architectural preferences and demands. Mining activities, however, come with environmental concerns, as highlighted in Fig. 5. This figure captures the dispersion of fine travertine stone particles as dust. Such dust not only affects the environment but can also pose health threats to workers and residents in the vicinity. Implementing advanced methodologies and technologies is crucial to reduce the impact of such issues. Furthermore, the extraction and processing of travertine stone lead to the creation of by-products. One such by-product is the fine powder of travertine. This powder, when not managed properly, can pose environmental challenges. However, as seen in Fig. 4, innovative solutions like gathering travertine sludge in the pools near Stone processing plants can play a role in recycling and utilizing this by-product

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effectively, preventing potential environmental hazards.

Figure 1. Atashkooh white travertine mine

Figure 2. AbbasAbad white travertine mine

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Figure 3. Hajiabad white travertine mine

Figure 4. Gathering travertine sludge in the pools near stone processing plants

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Figure 5. Dispersion of fine travertine stone particles as dust

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2. LABORATORY PLAN

In this section, we initially delve into examining the materials utilized and the characteristics of each. The second part outlines the details of the mixing designs.

2.1. Consumable Materials

The consumable materials in this research include cement, aggregates (gravel and sand), travertine sludge, water, and superplasticizer. Below we introduce their specifications.

2.1.1. Gravel

The gravel employed in this study is sourced from the Mahallat mines and is of the mountainous fractured type. The coarse aggregate used in concrete construction consists of a mix of almond-shaped and pea-sized grains. The maximum nominal size of the aggregate used is 31 millimeters, with a specific weight of 2.68 grams per cubic centimeter, the consumption sand complies with ASTM C136 standard [41].

2.1.2. Sand

Sand is one of the main components of concrete and is present in the composition of concrete as an effective element. Sand as a filler can increase the strength of concrete and also prevent the formation of cracks. With proper control and distribution of sand aggregates, the quality and efficiency of concrete can be improved. The sand used in this study originates from the river in the city of Mahallat.

2.1.3. Cement

The type of cement utilized in this research is Type 2 from the city of Delijan. Its specifications are tabulated in Table 1.

Table 1. Properties of Delijan type 2 portland cement

chemical properties	C_3A	5.1
	C_2S	22.7
	C_3S	51
	ALM	1.11
	SIM	2.56
	LSF	92.3
	F.CaO	1.12
	I.R	0.45
	L.O.I	2.22
	SO_3	2.78
	MgO	1.56
	CaO	63.43
	Fe_2O_3	3.88
	Al_2O_3	4.37
	SiO_2	21.1
Physical Characteristics	28-Day Compressive Strength (MPa)	45.5
	7-Day Compressive Strength (MPa)	34.4
	3-Day Compressive Strength (MPa)	21.2
	Final Setting Time (hours)	3.15
	Initial Setting Time (minutes)	140
	Expansion	0.03
	Blaine (gr/cm^2)	3141

2.1.4. Travertine Sludge

Travertine sludge (Fig. 6) is among the materials with widespread use in the construction industry and in the production of building materials [42]. These materials are usually obtained by the natural and industrial grinding and crushing of travertine gravel, resulting in the creation of very beautiful building materials.The county of Mahallat, due to the extensive range of stone mines it possesses, naturally produces a significant amount of stone powder as waste. This material can be extensively used in various ways, some of which are as follows: (i) utilization of this Travertine Sludge as mortar, (ii) use as a building facade, (iii) preparation of tile and ceramic adhesive, (iv)replacement for plastering in environments with moisture and dampness, (v) use in the production of paper and cardboard, and (vi) substitution as a part of the cement used in concrete construction. The chemical properties of Malahat travertine are presented in Table 2.

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Table 2. Chemical properties of travertine components of Mahalat city

Parameter	Constituent Percentage
CaO	53.45
MgO	0.432
SiO_2	0.155
SO_3	0.214
ZnO	0.054
Al_2O_3	0.045
CuO	0.012
SrO	0.025
LOI	45.62

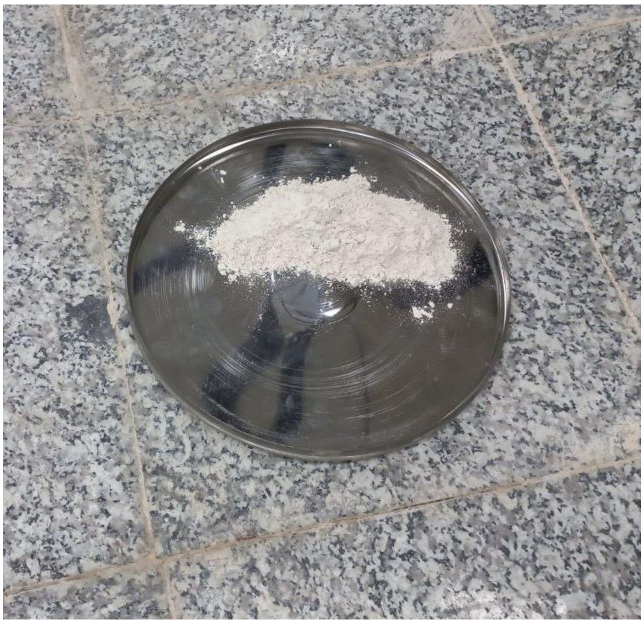

Figure 6. Travertine sludge

2.1.5. Water

The water used for the construction and maintenance of the samples was purified water from the city of Mahallat. The samples were cured in controlled temperature holding tanks.

2.1.6. Superplasticizer

To enhance efficiency and keep the water-to-cement ratio consistent, a superplasticizer of the ZHIKAVA brand with a pH of 4.4 has been used, which is shown in Fig. 7.

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Figure 7. ZHIKAVA brand superplasticizer

2.2. Mix Design

The mix designs have been obtained in accordance with the ACI-211 standards. To ensure that the test results are comparable, a water-to-cement ratio of 0.45 has been used in all designs. Therefore, with varying percentages of travertine sludge substitution for cement, the amount of cement used and consequently the amount of water used have changed. Samples have been evaluated for workability and compressive strength relative to a reference sample. The specifications and details of the mix designs are presented in Table 3 [43].

Table 3. Specifications and details of mix designs

Mix Design	Gravel (kg/m^3)	Sand (kg/m^3)	Travertine Sludge (kg/m^3)	Cement (kg/m^3)	Superplasticizer (kg/m^3)	Water-to-Cement Ratio
BaseMD	799.49	1040.73	-	395.59	5.93	0.45
MD10%	799.49	1040.73	39.55	356.03	5.93	0.45
MD15%	799.49	1040.73	59.33	336.25	5.93	0.45
MD20%	799.49	1040.73	79.11	316.47	5.93	0.45
MD25%	799.49	1040.73	98.89	296.69	5.93	0.45
MD30%	799.49	1040.73	118.67	276.91	5.93	0.45
MD35%	799.49	1040.73	138.32	257.27	5.93	0.45
MD40%	799.49	1040.73	158.23	237.35	5.93	0.45

*The percentage stated in MD represents the percentage of travertine sludge that has been substituted for cement.

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2.3 Sample Fabrication

In this research, to test compressive strength, cubic molds of 15×15×15 centimeters were used; for flexural strength testing, molds measuring 50×10×10 centimeters were utilized; and for permeability testing, molds sized 12×20×20 centimeters were employed. After the accurate weighing of the materials used, gravel and sand were poured into an electric mixer and mixed for 3 minutes until they reached a uniform appearance. In the next stage, travertine sludge along with cement was added to the mixer and mixed for another 3 minutes. Water and superplasticizer, previously dissolved together, were then added to the mixture and the mixing continued for another 3 minutes. Following the slump test, the internal surfaces of the related molds were oiled, and the molds were filled with the sample. The molds remained in the laboratory environment for 24 hours within the mold and were subsequently placed in concrete curing water bath (Fig. 8). They were tested at the ages of 7, 28, and 90 days under the related tests. The method of preparing samples with an electric mixer is shown in Fig. 9.

Figure 8. Concrete curing water bath

Figure 9. Sample preparation with electric mixer

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3. CONDUCTING EXPERIMENTS AND EXAMINING RESULTS

This section deals with the procedure of conducting tests according to relevant standards and also discusses their results. Concrete tests can be divided into two types: tests on fresh concrete (slump test) and tests on hardened concrete (compressive strength, flexural strength, and water permeability).

3.1. Fresh concrete tests

3.1.1. Slump test

To determine the workability of the concretes made from each mix design, a slump test is performed. This test is carried out in accordance with the ASTM C143/C143M-12 standard [44], where fresh concrete is filled in three layers into a truncated metal cone with a height of 300 millimeters, a large base diameter of 200 millimeters, and a smaller base diameter of 100 millimeters. Each layer is compacted with 20 strokes by a metal rod. Then, the surface is leveled, and the cone is slowly lifted vertically. After the cone is removed, the concrete settles; this drop in height is measured with a ruler and recorded. This amount of settlement is referred to as the concrete slump, which has an acceptable range of 5 to 7 centimeters for this test. It should be noted that the duration of this test is 3 minutes. The slump test is shown in Fig. 10.

Figure 10. Slump test cone

3.1.1.1. Slump test results

In this section, the results of this test are reported in Table 4.

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Table 4. The results of slump test

Mix Design	Travertine Sludge (kg/m^3)	Test Result (cm)	Permissible Range (cm)	Status
BaseMD	-	6.5	5-7	Ok
MD10%	39.55	4.8	5-7	Ok
MD15%	59.33	5.4	5-7	Ok
MD20%	79.11	5.1	5-7	Ok
MD25%	98.89	6	5-7	Ok
MD30%	118.67	5.8	5-7	Ok
MD35%	138.32	6.5	5-7	Ok
MD40%	158.23	6.7	5-7	Ok

3.2. Hardened concrete tests

3.2.1. Compressive strength test

In the study, the compressive strength of hardened concrete was evaluated based on cubic samples with standard dimensions of 150 millimeters. Accordingly, the samples were tested for compressive strength at ages of 7, 28, and 90 days post-curing. The standard procedure for this test was in accordance with ASTM C39 [45]. In Fig. 11, a 150 millimeter mold filled with concrete is shown.

Figure 11. A 150 millimeter mold filled with concrete

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3.2.1.1. Compressive Strength Test Results

The compressive strength test was conducted on seven mix designs where travertine sludge was used to replace cement at percentages of 10, 15, 20, 25, 30, 35, and 40. The results were as follows: at 7 days of age, an increase in the percentage of slurry used led to a decrease in strength; at 28 days, the concrete exhibited a different behavior in that the use of slurry up to 30% by weight of cement resulted in decreased strength, but beyond 30%, there was an increase in strength observed; at 90 days, an increase in the percentage of slurry used was associated with an increase in strength. It is essential to note that in this research, to minimize experimental error, five samples were made at each age of the concrete and the results were recorded as an average. The results of the compressive strength test are presented in a comparative manner in Table 5 and Fig. 12. Furthermore, the failure pattern of the 90-day sample with 40% travertine sludge is depicted in Fig. 13. It should also be mentioned that the stress-strain graph for samples with 20%, 35%, and 40% travertine sludge at 90 days of age is presented in Fig. 14.

Table 5. The results of the compressive strength tests

Mix Design	Travertine Sludge (kg/m^3)	Water-to-Cement Ratio	Compressive strength observed at 7 days (MPa)	Compressive strength observed at 28 days (MPa)	Compressive strength observed at 90 days (MPa)
BaseMD	-	0.45	38.48	46.76	55.05
MD10%	39.55	0.45	36.80	37.53	38.29
MD15%	59.33	0.45	33.54	34.04	34.55
MD20%	79.11	0.45	32.57	32.90	33.22
MD25%	98.89	0.45	28.35	28.69	29.04
MD30%	118.67	0.45	25.99	26.35	26.72
MD35%	138.32	0.45	28.13	28.72	29.32
MD40%	158.23	0.45	44.25	45.20	46.17

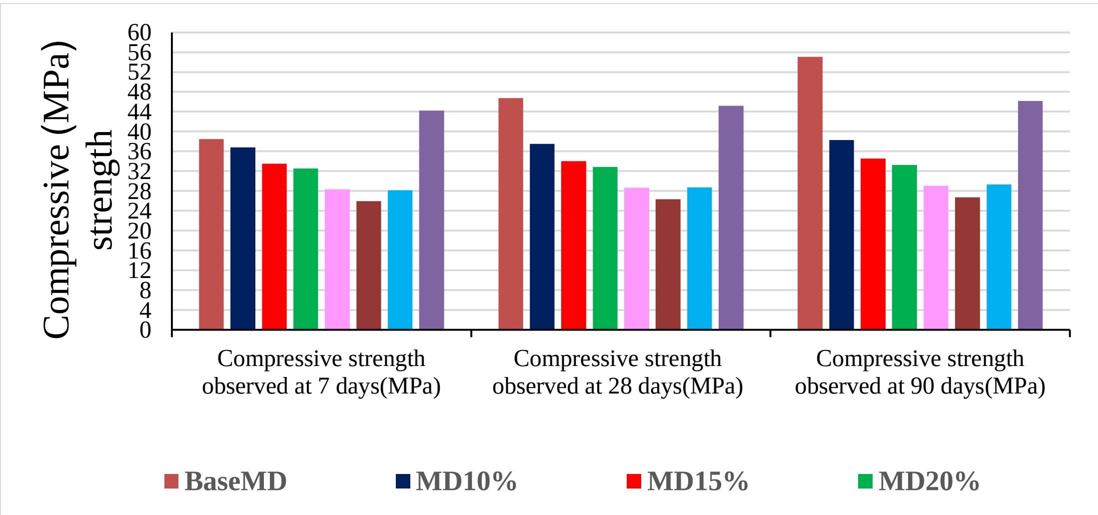

Figure 12. The results of the compressive strength tests

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Figure 13. The failure pattern of the 90-day sample with 40% travertine sludge

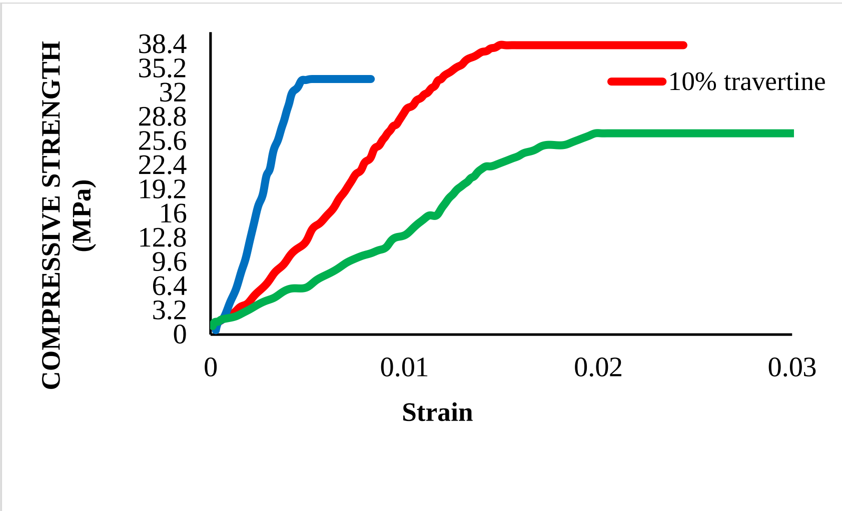

Figure 14. The stress-strain graph for samples with 20%, 35%, and 40% travertine sludge at 90 days

3.2.1.2. Analysis of compressive strength test results

In the study presented, an analysis of compressive strength test results is conducted, as shown in Fig. 12. It is observed that at different ages of the concrete – 7, 28, and 90 days – there is a variation in strength when stone powder is used to replace a portion of the cement. For example, it is noted that a 28-day-old sample with a 10% stone powder mix has a strength of 37.53 MPa. This strength, however, is reduced to 26.35 MPa in a sample of the same age with a 30% mix. Further observations reveal an intriguing pattern: beyond the 30% mix, there is a significant increase in strength. In a mix with 40% stone powder, the strength

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reaches 45.20 MPa, marking a 1.2-fold increase compared to the 10% mix. Additionally, from the stress-strain graph (Fig. 14), it is found that the ductility of the concrete improves with the increase in travertine sludge percentage. This finding sheds light on the impact of material composition on the concrete's properties and its potential application in various construction contexts.

3.2.2. Flexural Strength Test

To investigate the effect of travertine sludge on the tensile strength of concrete, three-point bending tests were conducted according to ASTM C78M standard on samples made with 5%, 10%, 15%, 20%, 25%, 30%, 35%, and 40% concentrations of travertine sludge, and aged 7, 28, and 90 days. The beams tested had cross-sectional dimensions of 100 millimeters in width, 100 millimeters in height, and 500 millimeters in length. Additionally, comparative diagrams of flexural strength are presented in Fig. 15. The mode of failure of a concrete beam under flexural stress is illustrated in Fig. 16 [46].

Table 6. The results of the flexural strength tests

Mix Design	Travertine Sludge (kg/m3)	Cement (kg/m3)	Tensile strength observed at 7 days (MPa)	Tensile strength observed at 28 days (MPa)	Tensile strength observed at 90 days (MPa)
BaseMD	-	395.59	0.64	0.78	0.92
MD10%	39.55	356.03	0.61	0.63	0.64
MD15%	59.33	336.25	0.57	0.58	0.59
MD20%	79.11	316.47	0.58	0.58	0.59
MD25%	98.89	296.69	0.52	0.53	0.53
MD30%	118.67	276.91	0.50	0.51	0.52
MD35%	138.32	257.27	0.61	0.62	0.63
MD40%	158.23	237.35	1.15	1.18	1.20

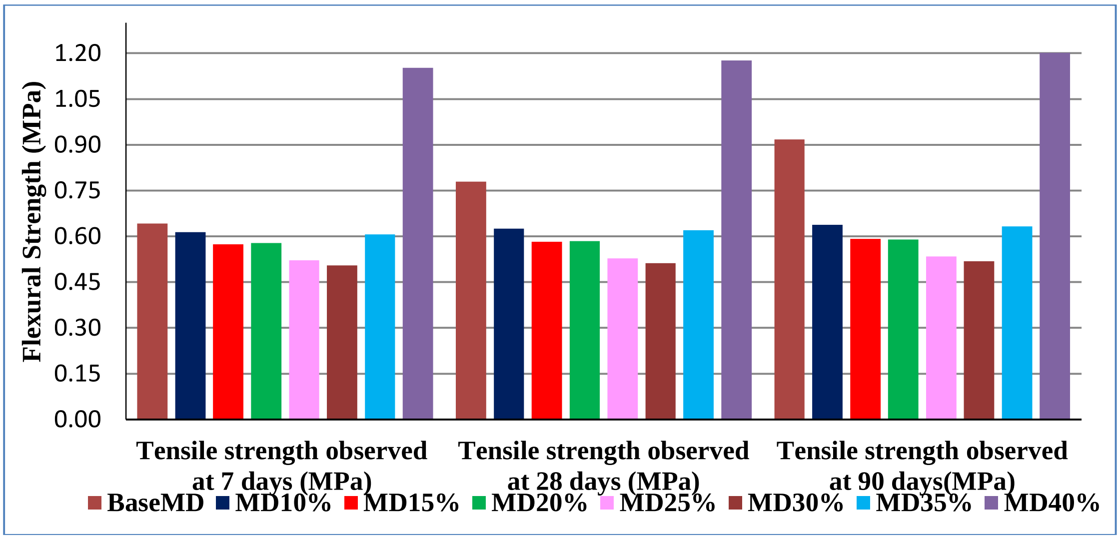

Figure 15 Comparative tensile strength chart of samples at ages of 7, 28, and 90 days

Figure 16 Comparative tensile strength chart of samples at ages of 7, 28, and 90 days

3.2.2.1. Analysis of bending strength test results

It is indicated in Table 6 that the results of the flexural strength test reveal a distinct pattern in the tensile strength of the samples, influenced by the behavior of pozzolanic materials. In mixtures containing 10 to 30 percent pozzolan, a noticeable decrease in strength is observed. However, it is noted that in mixtures with more than 30% pozzolan, there is an increasing trend in tensile strength. This trend becomes especially evident at a 90-day age with a 40% mixture plan, as shown in Fig. 15, where the strength reaches 1.2 megapascals (MPa), significantly contrasting other mixture plans. These results underscore the crucial role of pozzolan content in determining the flexural strength of the material and its implications for construction and material engineering.

3.2.3. Water permeability test

In the current study, the water permeability test for concrete was conducted based on the BS EN 12390-8 standard [47], aiming to determine the depth of water penetration in hardened concrete under specific time and pressure conditions. In this method, the samples, after curing until the age of 28 days, were allowed ample time to dry completely. Following this period, they were placed in a permeability apparatus under a pressure of 5 bars for 72 hours. After the duration of the test, the samples were split in half using a flexural jack, and the maximum extent of water penetration in the concrete was measured.

3.2.3.1. Results of the water permeability test

The results of the water permeability test are presented in Table 7. For recording the results of this test, the maximum water permeability in the sample was measured. An image of the permeability test apparatus is shown in Fig. 17. Additionally, an image of a permeability sample after being removed from the test is displayed in Fig. 18. The results of the water permeability test are reported in Table 7. Fig. 19 presents the method of reading the water permeability value after the sample is split.

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Table 7. The results of the water permeability test

Mix Design	Travertine Sludge (kg/m^3)	Test Result (mm)	Permissible Range (mm)
BaseMD	-	25	70
MD10%	39.55	27	70
MD15%	59.33	27	70
MD20%	79.11	25	70
MD25%	98.89	20	70
MD30%	118.67	17	70
MD35%	138.32	12	70
MD40%	158.23	9	70

Figure 17 An image of the permeability test apparatus

Figure 18 An image of a permeability sample after being removed from the test

(a) (b)

Figure 19 The method of reading the water permeability value after the sample is split

3.2.3.2. Interpretation of water permeability test results

The water permeability test results on concrete show a significant variability across different mixture designs, displaying a general trend of reduced water penetration with increased proportions of travertine sludge. Specifically, the permeability in the mixture with 40% travertine sludge is reduced by 18 millimeters compared to the 10% mixture. These findings suggest that waste products, particularly travertine sludge obtained from quarries and stone processing factories, can be effectively utilized in concrete production. This not only contributes to solving environmental issues by repurposing waste but also leads to the creation of concrete that is both strong and resistant to water penetration. Such concrete is especially suitable for structures requiring high durability and those exposed to direct contact with water and moisture.

4. CONCLUSIONS

The analysis of the test results on samples made by substituting travertine sludge as a percentage of the cement weight suggests that this material can be used as a substitute. The results indicate that with an increased use of stone powder, both compressive and flexural strengths show better outcomes compared to the reference sample.

The results from the compressive and flexural strength tests indicate that as the proportion of travertine sludge increases from 10% to 30% in place of cement, there is a decrease in strength. However, beyond 30%, an increase in strength is observed. Additionally, the water permeability test results show a consistent trend of reduced water penetration in the concrete as the percentage of travertine sludge increases right from the

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outset. This suggests a direct relationship between the amount of travertine sludge used and both the structural strength and permeability of the concrete.

This behavior is expected from pozzolanic materials. Additionally, travertine sludge, as a filler, not only enhances the bond between aggregates but also reduces water permeability in concrete. The reduced consumption of cement and water permeability in concrete allows for the use of concrete with travertine sludge substitution in areas where concrete is exposed to water. This research was conducted in the city of Mahallat using local materials: sand from Mahallat mines, type 2 cement from the Delijan cement factory, and travertine sludge from local travertine mines and factories. Therefore, the results are specific to the materials of this city. One of the most important achievements of this research is providing an efficient solution to the environmental issues of the region, considering the high production and processing of travertine in the Central Province, especially in Mahallat. The waste from this industry has created significant problems for this city and its surroundings. Finally, it is essential to note that this research lays the groundwork for using this material as a cement substitute, and researchers can further study other aspects of this field.

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