Concrete Mix Strength and Permeability with Various Supplementary Cementitious Materials

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Abstract. In order to reduce the amount of cement required, improve workability, mechanical properties, and durability, and have a positive environmental impact, supplementary cementitious materials are frequently utilized as a partial replacement for cement in concrete mixes. In this experimental investigation, the effects of employing waterproof and supplemental cementitious materials such as flyash, silica fume, and nano silica along with a water reduction agent were examined to increase the effectiveness and performance of concrete. The cement employed in this investigation, sulfate-resistant Portland cement, was partially substituted by the supplemental cementing components mentioned earlier to create concrete with a w/b ratio of (0.30-0.35) and C35 compressive strength. Thirteen various concrete mixtures were designed and tested at 28 days of age for compressive strength, splitting tensile strength, water sorptivity, absorption, and penetration depth under pressure. To enhance the dependability of the outcomes, three samples were evaluated, and their mean value was recorded. According to the research, mixing the chemicals with concrete resulted in a brand new substance that may meet the rising need for construction materials. All of the materials utilized in this study, with the exception of Water Proof, also showed good resistance to water absorption and strength improvement.

Keywords: Supplementary cementitious materials; sulfate-resisting cement; compression strength; and permeability.

1. INTRODUCTION

Nowadays, concrete often includes supplementary cementitious materials (SCMs) as a component, either separately or blended with other types of cement. One practical method for partially replacing Portland cement involves using SCMs like fly ash (FA) produced from coal combustion, blast furnace slag that results from iron manufacturing, or silica fume (SF) from silicon production. When these materials are used, there is no need for additional clinkering processes, which consume significant amounts of energy. As a result, incorporating SCMs into concrete can significantly reduce the CO_2 emissions associated with cement production. Additionally, this approach allows for the recycling of industrial waste products and promotes environmental sustainability. Finally, the process of grinding, mixing, and transporting concrete is much less energy-intensive than clinkering, which further contributes to reduced carbon emissions [1]. Concrete's performance can be improved by better understanding cementitious materials and integrating nanomaterials into them. Concrete's characteristics can be altered via nanoscale technologies to meet engineering needs [2]. Except for fine limestone, which is not elaborated upon in this context, the chemical composition of supplementary cementitious materials typically contains less calcium compared to Portland cement, as shown in Figure 1A [1]. As a result, the hydrates that are produced during hydration vary, and this affects their strength and toughness. The CaO-SiO_2-Al_2O_3 system's hydrate phases are schematically represented in Figure 1B [1].

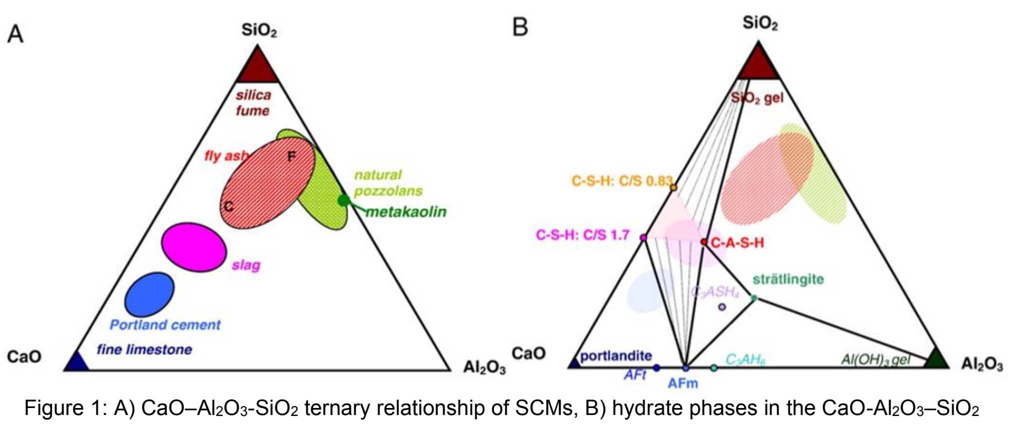

Figure 1: A) CaO–Al_2O_3-SiO_2 ternary relationship of SCMs, B) hydrate phases in the CaO-Al_2O_3–SiO_2 systems [1].

The C-S-H phase is one of the notable aspects of the wide range of compositions in the cement phase's diagram. Silica fume is composed of very fine particles with a specific surface area about six times greater than cement particles. This means that the pore space within the concrete is reduced when silica fume is added to the concrete. This effect has been observed because the fine particles of silica fume are much smaller than those of cement [3]. Incorporating silica fume into concrete mixtures enhances the concrete's compressive strength while having little to no impact on the concrete's splitting tensile strength. Additionally, the use of silica fume reduces the water absorption capacity of the concrete. Changing the ratio of water to binder can also significantly reduce the water absorption of the concrete [4].

There has been a growing interest in using fly ash in concrete in recent years due to the economic, environmental, and technical benefits associated with its use [5]. While the use of FA in concrete is known to produce positive results, such as enhanced concrete performance, there is one undesirable aspect to consider: the rate of strength development in FA concrete is low during its early stages, which could limit its use in constructing high-strength concrete structures. In a study conducted by Ehsani et al. [6], the influence of nano silica (NS) on the properties of cement paste and concrete, specifically those containing FA, was examined. The research involved fifteen samples of cement paste and concrete mixtures with 15% to 25% of the cement content being replaced by FA and four NS replacement ratios, which were 1.5%, 3%, 5%, and 7.5%. The study's results indicated that the inclusion of NS improved the strength development of cement paste and concrete compared to samples without NS, and it accelerated the early-age reactivity of FA-based concrete.

Attempts were made to evaluate the fly ash concrete development by Kosior-Kazberuk et al. [7]. The test findings reveal that all fly ash-containing mixtures were ultimately able to acquire higher flexural strengths than the control mixtures (FA/C = 0). The results obtained demonstrate that fly ash has a favorable impact on the compressive strength of all cements examined. Concrete incorporating fly ash can produce greater strength than Portland cement concrete and blast furnace cement concrete. However, the rate at which the strength of fly ash concrete increases may be slower, and the concrete may maintain its strength for longer periods of time. Esam et al. [8] examined the compressive strength, permeability, and sorptivity of concrete containing silica fume. Without silica fume, the sorptivity fell by up to 42.7%, while with 10% silica fume, the sorptivity reduced by 64.5% and 68.3% with 350 kg/m3 and 450 kg/m3 cement content, respectively, at 28 days. The specimens with lesser sorptivity displayed less permeability and greater compressive strength. Using samples made of the same concrete, Kubissa et al. [9] assessed sorptivity not only after 28 days but also after longer intervals of time (2, 3, 6, 9, 12, and 24 months). Research was done on four different types of concrete. Statistics were used to compare variations between the initial value of the sorptivity and subsequent measurements. Tests and measurements showed that the initial sorptivity value can be a fairly accurate approximation of subsequently recorded values for this parameter.

In an experimental study conducted by Kassim [10], the impact of adding silica fume on the water permeability characteristics of revibrated lightweight concrete was analyzed. The study found that even though the mixes were revibrated before the cement's final setting, the incorporation of silica fume resulted in increased compressive strength and reduced permeability for all of the mixtures. This research presents an experimental study on the partial replacement of cement with waterproof, fly ash, silica fume, and nano silica and the effect of these additives on concrete properties, compressive strength, and absorption, noting the improvement in strength and reducing the absorbency of the mixtures that have been prepared. This investigation is anticipated to provide valuable insights into the properties of hardened concrete resulting from hydraulic or pozzolanic activity.

2. MATERIALS

The following materials are utilized in this experimental study:

2.1 Waterproof WP

Sikalite® AE [11] is a powdered waterproofing admixture that blocks the capillaries and pores in Portland cement/sand mortars, preventing the movement of moisture. Table 1 summarizes the product information for the material [11].

Table 1: Basic material properties of utilized waterproof [11].

Form	Packaging (kg)	Shelf life	Density (kg/liter)
Powder	1.25-200	12 months in an original, unopened container	0.9

2.2 Fly Ash

It has low calcium with high silica content; the chemical composition of this substance is confirmed by ASTM C618 [12], as illustrated in Table 2 [13]. ASTM C618 outlines the chemical and physical criteria and standards for fly ash and natural pozzolans as a replacement for cement and incorporates the standard testing protocols of ASTM C311 [14]. This standard was introduced in 1968 to combine and supersede ASTM C350, which pertains to fly ash, and ASTM C402, which pertains to other pozzolans [15].

Table 2: Chemical compositions of fly ash [13].

Composition	SiO_2	Al_2O	Fe_2O	CaO	MgO	K_2O	Na_2O	TiO	P_2O_5	Mn_2O_3	SO_3	LOI
Fly ash	66.65	25.06	1.68	2.03	0.1	1.01	0.39	1.25	1.23	0.05	0.62	3.57
	$(SiO_2+Al_2O_3+Fe_2O_3)$= 93.39											
Chemical requirement According to ASTM C618 [12]	$SiO_2+Al_2O_3+Fe_2O_3$			/	/	/	/	/	/	/	Max%	Max%
	70										5	6

2.3 Silica Fume

This is a mineral additive that is finely ground and pozzolanic in nature. It is designed to be high-performing and can be added directly to concrete. When added, it has a dual effect on the concrete mixture. Firstly, it optimizes the packing of particles in the mixture, improving its physical properties. Secondly, it acts as a highly reactive pozzolan, enhancing its chemical properties. The chemical characteristics of silica fume are tabulated in Table 3 [16].

Table 3: Typical chemical characteristics of silica fume [16].

Properties	Silica Fume
Physical properties	
Specific gravity	2.2
Surface area, m^2/kg	20,000
Size, micron	0.1
Bulk density, kg/m	576
Chemical properties, Percentage	
SiO_2	20-25
Al_2O_3	4-8

2.4 Nano Silica

It is hydrophobic silica prepared by the chemical reaction of hydrophilic fumed silica reactive silanes. The basic material characteristics of nano silica are given in Table 4 [17].

Table 4: Basic material properties of nanosilica [17].

Form	Purity	Color	Melting point	Boiling point range	Density (g/cm^3)	Water
Powder	99.8%	White	1610-1728°C	2230	at 20 C^o 2.17-2.66	insoluble

2.5 Cement

The current study employed a sulfate-resistant Portland cement (SRPC) that meets the ASTM-Type (v) [18] standard. This SRPC was produced by Mass Cement Company and had a specific gravity of 3.08 and a Blaine fineness of 3.316 cm2/gm. The chemical and physical compositions of the SRC are listed in Table 5 [19].

Table 5: The chemical and physical compositions of used SRC [19].

Chemical analysis	SRC	Chemical analysis	SRC
Silicon dioxide (SiO2)	20.9	Free lime	1.00
Aluminum oxide (Al2O3)	4.22	Loss on ignition	1.5
Ferric oxide (Fe2O3)	4.94	Physical properties	
Calcium oxide (CaO)	62.77	Specific gravity	3.08
Magnesium oxide (MgO)	2.8	Compressive strength (MPa)	
Sulfur trioxide (SO3)	2.53	3 d	28.21
Total	99.7	7 d	39.17
C3S	54.00	Setting time (minutes)	
C2S	19.20	Initial	145
C3A	2.83	Final	235
C4AF	15.02	-	-

2.6 Fine Aggregate

The fine aggregate utilized was river sand. The sand was repeatedly washed and cleansed with water before being stretched out and allowed to dry in the open air. The fine aggregate was then packed in polypropylene bags and made suitable for use after being sieved at a sieve size of 4.75 mm to remove aggregate particles with a diameter larger than 4.75 mm. According to the sieve analysis results, the grading of fine aggregate shown in Table 6 was within the parameters of ASTM C33-99a [20].

Table 6: Grading of fine aggregate.

Sieve size (mm)	Passing (%)	ASTM C33-99a
9.5	100	100
4.75	98	95-100
2.36	83	80-100
1.18	64	50-85
0.6	42	25-60
0.3	20	5-30
0.15	5	0-10
Less than 75 microns	1.98	3% upper limit

2.7 Coarse Aggregate

This study used crushed gravel with a maximum particle size of 12.5 mm. It was repeatedly cleaned and rinsed with water before being allowed to air dry. According to Table 7, the coarse aggregate was graded in compliance with ASTM C33-99a [20] specifications.

Table 7: Grading of Coarse Aggregate.

Sieve size (mm)	Passing (%)	ASTM C33-99a
19	100	100
12.5	98.5	90-100
9.5	63.9	40-70
4.75	2.7	0-15
2.36	0.2	0-5
Less than 75 micron	0.66	1% upper limit

2.8 Superplasticizer

In order to create a concrete mix with a low water-cement ratio and high strength, a third-generation superplasticizer called Sika ViscoCrete-180 GS [21], which is composed of polycarboxylate polymers, was utilized. This particular superplasticizer is highly effective and functions through various mechanisms, such as surface adsorption, which enhances the concrete's flow, placement, and compaction properties [21]. The compositions of the admixtures utilized in this research are shown in Table 8.

Table 8: Properties of the Superplasticizer used in this study [21].

Color	Density (g/cm^3)	pH	Percentage of solid content (%)	Chloride (%)	Complying with
Light brown	1.07	4-6	28.5	Nil	ASTM C494 Type F and G

2.9 Water

Ordinary tap water was utilized to prepare, cast, and cure the concrete samples.

3. EXPERIMENTAL PROGRAM

The experimental investigations of this study are as follows:

3.1 Mix Proportion

All mixes in this study were prepared in accordance with ACI 211.1-91 [22]. All the mixes were prepared with a low water-to-binder ratio of 0.30 to minimize capillary voids. As the fineness of the additive was high, the water requirement for the mixes increased with an increase in the dosage of the additive. The objective was to achieve a compressive strength of 35 MPa at 28 days for the control mix. Table 9 provides a summary of the mixing design characteristics of the specimens that were tested.

Table 9: Mix proportions of tested specimens.

Mixture	Description*	Cement (kg)	Sand (kg)	Gravel (kg)	Water (kg)	w/b	WP	SF	FA	NS	HRWR %
CM	Control mix	460	750	875	216	0.47	/	/	/	/	/
M5	WP2	450.8	750	875	216	0.47	9.2	/	/	/	/
M1-1	FA15SF5	368	750	875	138	0.3	/	23	69	/	1
M1-2	FA15SF10	345	750	875	138	0.3	/	46	69	/	1
M1-3	FA15SF15	322	750	875	161	0.35	/	69	69	/	1
M2-1	FA20SF5	345	750	875	138	0.3	/	23	92	/	1
M2-2	FA20SF10	322	750	875	161	0.35	/	46	92	/	1
M2-3	FA20SF15	299	750	875	161	0.35	/	69	92	/	1
M3-1	FA25SF5	322	750	875	161	0.35	/	23	115	/	1
M3-2	FA25SF10	299	750	875	161	0.35	/	46	115	/	1
M3-3	FA25SF15	276	750	875	161	0.35	/	69	115	/	1
M4-1	FA15SF5NS0.2	367.08	750	875	138	0.3	/	23	69	0.92	1
M4-2	FA15SF5NS0.5	365.7	750	875	161	0.35	/	23	69	2.3	1
M4-3	FA15SF10NS0.2	344.08	750	875	161	0.35	/	46	69	0.92	1

*cm control mix, WP2- Mix containing 2% waterproof, FA15SF5- Mix containing 15%FA and 5%SF, FA15SF10- Mix containing 15%FA and10%SF, FA20SF5- Mix containing 20%FA and 5%SF, FA20SF10- Mix containing 20%FA and 10%SF, FA15SF5NS0.2- Mix containing 15%FA, 5%SF, and 0.2 NS and FA15SF5NS0.5- Mix containing 15%FA, 5%SF, and 0.5 NS.

3.2 Casting Procedure

The mixing and batching procedure used for the reference mixtures was followed consistently to ensure efficiency, uniformity, and homogeneity in the mixtures [10]. The materials were first weighed and prepared. Then, superplasticizer was added to the water and set aside. After that, the coarse aggregate and silica fume were mixed for 5 minutes (if SF exists in the concrete composition). The mixer was stopped, and then cement, sand, fly ash, and water with a superplasticizer were added. The mixer was run for 10 minutes in order to homogenize the materials. Moreover, the mixing procedure for the second group was initially weighing and preparing the materials when nano silica was added to the mixture. Then, add the superplasticizer. After that, coarse and fine aggregates and nano silica were mixed for five minutes. The mixer was stopped, and then a little mixing water was added. Then, the mixer was run for 10 minutes. The mixer was stopped, other materials with water were added, and the mixer was run for 5 minutes to homogenize the materials. Both groups were then poured into 10 cm cube molds and shaken on a vibrating table. The samples were left for 24 hours at room temperature, after which the molds were opened, and the samples were placed in a curing tank for 28 days.

3.3 Testing Procedure

The slump value and density of fresh concrete for each mix were immediately tested after mixing in accordance with ASTM C143 [23] and C138 [24]. At the age of 28 days, tests for compressive strength and splitting tensile strength were performed using 100×100×100 mm cubes in accordance with British Standards BS1881: Parts 116 and 117, respectively [25, 26]. Three samples were examined, and the average was taken to increase reliability. In accordance with the guidelines in TS EN 12390-8 [27], the water penetration depth under pressure test was conducted on 100 mm cube specimens. According to the protocol, the samples must be subjected to drinkable water for 72 hours while being pressurized to 500±50 kPa. Before testing, silicon paint was applied to the entire surface of the specimens except for a specific area to prevent water leaks. At the end of the testing period, the tested cubes were divided into two halves following the guidelines of BS 1881 Part-117B [26]. After marking the cubes, the maximum depth of water penetration was measured.

The sorptivity test was performed according to the guidelines of ASTM C 1585 [28]. Concrete cubes were placed in water to a depth of 2±1 mm, and the mass increase over time was measured to determine the rate of water absorption by the cubes. During contact, water enters the dry concrete and is absorbed by capillary suction. The cumulative water volume absorbed per specific unit area ($mm^3.mm^{-2}$) was calculated as a function of time. The permeable voids ratio and total water absorption percentage tests were carried out following ASTM C 642-13 [29]. In this test, the specimens' dry mass (100 mm cube) was determined, and the SSD weight was recorded after the specimens were submerged in water for 48 hours. Additionally, specimens were weighed while submerged in water. All permeability experiments were examined with ages that were equal and longer than 28 days. To strengthen the dependability of the findings, three specimens were used, and the average was reported. Finally, the absorption test per ASTM C642-13 was conducted [29].

4. RESULTS AND DISCUSSION

4.1 Slump Test

The slump value obtained from the actual slump test experiment is recorded for each mix design.

4.2 Density Results

Figure 2 shows the values of density for each mixture. The density values of concrete mixes change with the change in proportions of partially substituted additives by the weight of cement, which ranges between 2300 and 2500 kg/m^3.

4.3 Strength Properties

Table 10 and Figure 3 present the values of compressive strength and splitting tensile strength tests of all types of mixes at the age of 28 days. The difference in results between these tests and previous papers is attributed to the difference between the mixing ratios and the additives. For the control mix, the compressive strength test was conducted after seven days, and it was 33 MPa, and the compressive strength obtained at the age of 28 days was 41.5 MPa, but for other mixes, this test was conducted after 28 days. Concerning compressive strength, the use of additives led to a significant increase in compressive strength, as the mixture containing 25% fly ash and 15% silica fume achieved an increase in compressive strength of 93% relative to the control mixture, while the use of WP decreased the compressive strength to 25%. The increase in silica fume in addition to nano silica, increased the compressive strength of concrete and enhanced the pozzolanic reactivity of FA. As for the splitting tensile strength, there was no clear effect on the results obtained from this research, which ranged between 6 and 8 MPa, except for the mixture that contained WP (4.5 MPa).

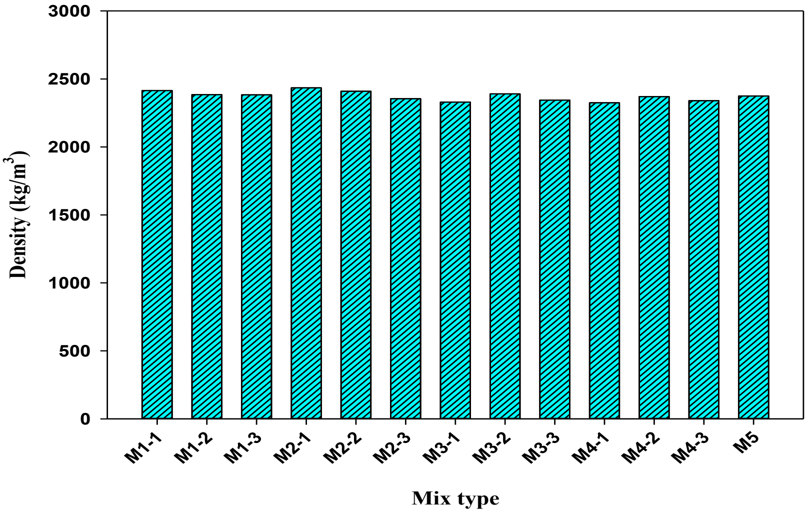

Figure 2: Density results for all specimens.

Table 10: Strength characteristics of the tested samples.

Mixture	Compressive strength (MPa)	Splitting tensile strength (MPa)	Dry density (kg/m^3)	Permeable voids ratio (%)
M5	31	4.5	2.3	4.5
M1-1	49.5	6.8	2.4	1.1
M1-2	57.4	6.5	2.4	1.05
M1-3	58	7	2.35	1.06
M2-1	54.4	7.5	2.4	1.24
M2-2	55.4	6.1	2.3	1.25
M2-3	62.5	6.55	2.3	2.13
M3-1	68.5	7.4	2.37	2.4
M3-2	76	8.05	2.3	2
M3-3	80	7.65	2.35	1.98
M4-1	60	6.1	2.36	2.42
M4-2	62	6.8	2.3	2.3
M4-3	70	6.88	2.3	2.5

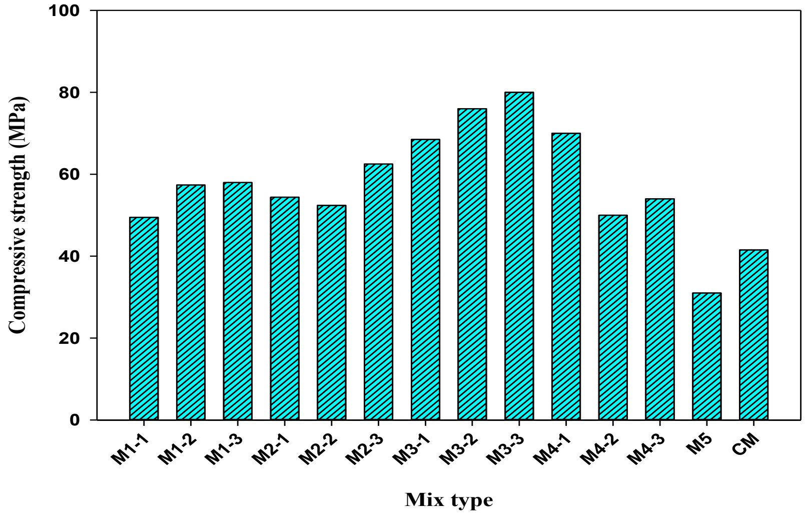

Figure 3: Compressive strength results for all mix types.

4.4 Sorptivity Results

The ability of a material to absorb and move water through capillary suction is known as sorptivity and is linked to various aspects of durability [30]. Immersing the material in water and measuring its water absorption can indirectly reveal the pore structure of the cement paste in the concrete. The sorptivity of the concrete with cement replaced with WP, SF, FA, and NS versus the square root of time for the mixes was determined and illustrated in Figure 4. All mixtures generally showed an absorption of less than 1mm, which is consistent with the results of other studies [31,32].

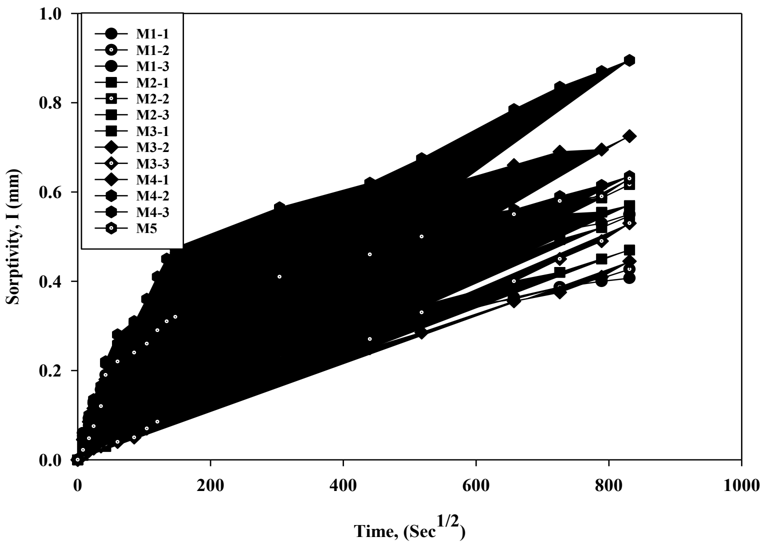

Figure 4: Sorptivity versus the square root of time for all mix types.

4.5 Water Absorption after Immersion

The water absorption values of concrete specimens with cement replaced with additives such as WP, SF, FA, and NS after immersion are presented in Figure 5. These results indicate that all mixes except M5 have a less than 2.5% water absorption rate. This is attributed to the fact that these additives play an important role in filling the pores, reducing the percentage of voids, and improving the microstructure of cement paste. Moreover, as shown in Figure 6, the findings reveal that the water penetration depth for all mixtures is less than 10 mm, except for the mixture that contains WP, which gives 16mm of water penetration depth under pressure.

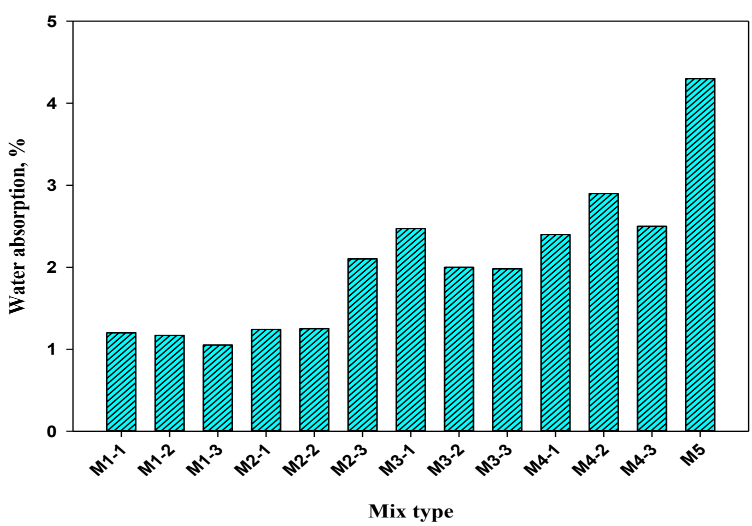

Figure 5: Absorption results for all mix types.

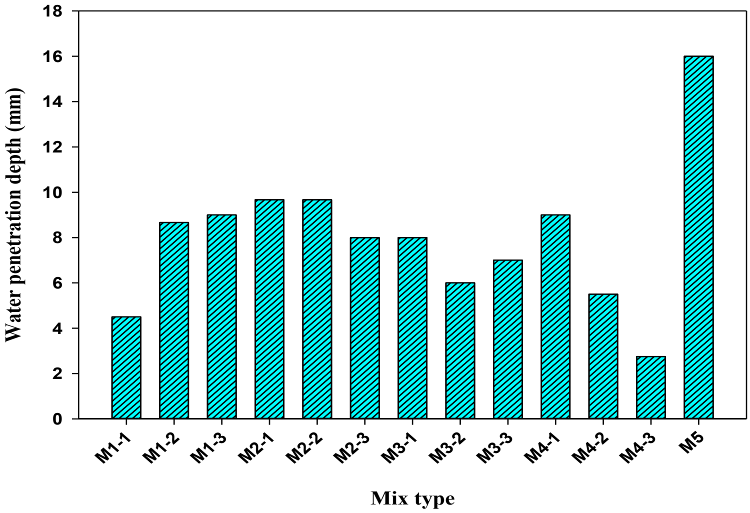

Figure 6: Water penetration depth results for all types of mixtures.

5. CONCLUSIONS

The conclusions of this experimental investigation are drawn as follows:

- The addition of NS, SF, and FA to cement concrete generates a new material form to address the ever-increasing demand for construction materials and economic and environmental benefits by minimizing waste pollution.
- All admixtures utilized in this study (except WP) demonstrated good resistance to water absorption as well as strength increases.
- The results showed that increasing the amount of fly ash in concrete reduces its water absorption.
- The findings revealed that, except for M5, all mixes have water absorption rates below 2.5%. This is explained by the fact that these additives play an important role in filling the pores, reducing the percentage of voids, and improving the microstructure of cement paste.
- The outcomes revealed that the compressive strength of specimen M3-3 increased by 93% as compared to the control mix, but the mix contains WP, and the compressive strength decreased to 25%.
- Based on the results, adding additives to the concrete mixes had no remarkable effect on the splitting tensile strength.
- Incorporating WP into the concrete had unsatisfactory results regarding compressive strength, splitting tensile strength, and water absorption.

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