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Original Article

Influence of Natural Biopolymers and Sodium Bentonite on the Performance of Anti-Washout Concrete

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Abstract *- The placement of concrete underwater can result in washout, a lack of cohesion between particles, and separation of concrete components; these conditions may compromise its mechanical properties and durability. To evaluate the effects of guar gum, gum arabic, sodium bentonite, and sodium alginate, we created a reference mixture with a design compressive strength (f'c) of 350 kg/cm² and a water-to-cement ratio of 0.35. The dosage ranges were 0.30% to 0.70% for both gums, 10% to 30% for bentonite, and 1% to 3% for alginate; all were based on cement weight. During testing, we measured slump, temperature, washout resistance, pH, and setting time in fresh concrete; compressive strength, indirect tensile strength, and electrical charge passed (ASTM C1202) were tested in hardened concrete. The reference mixture exhibited 13.6% washout loss and 3160 coulombs (moderate chloride ion penetrability). Guar gum at 0.60% produced the most favorable results; washout loss decreased to 0.8%, while compressive and indirect tensile strengths reached 424.68 and 37.62 kg/cm², respectively, at 28 days, with 497 coulombs (very low chloride ion penetrability). Sodium alginate at 2.50% showed 2.0% washout loss, strengths of 411.39 and 36.83 kg/cm², and 589 coulombs; gum arabic at 0.50% and bentonite at 15% reduced washout losses to 4.8% and 5.2%, respectively. Validation tests using alternative mix designs showed 1.02% washout loss and 223.5 kg/cm² under simulated rainfall; submerged casting resulted in 1.37% loss and 392.4 kg/cm². These findings support selected biopolymers for improving washout resistance and mechanical performance under the evaluated conditions.*

Keywords *- Anti-Washout Concrete, Chloride Penetration, Cohesion, Natural Biopolymers, Viscosity.*

1. Introduction

Globally, infrastructure development in aquatic and underwater environments has steadily intensified in response to the growing population density and economic dynamism characteristic of coastal and riverside areas [1,2]. It is estimated that about 40% of the world's population lives within 100 km of the ocean's edge, while more than 600 million people live in low-lying areas that are highly susceptible to flooding, erosion, and extreme hydrometeorological events [3, 4] This imposes highly complex technical requirements on the design and construction of civil infrastructure, due to continuous interaction with the aquatic environment, the combined effects of currents and waves, and the highly aggressive physical and chemical conditions of the environment [5, 6]. In the case of Peru, this scenario implies that a significant part of its port infrastructure, as well as bridges, coastal protection structures and related hydraulic works, must always be in contact with water, which will primarily lead to an increase in the structural safety performance requirements, durability and sustainability during their operational life [7,8]. From a construction standpoint, one of the most important technical considerations for this type of infrastructure involves placing concrete under submerged conditions, during which conventional fresh concrete undergoes partial leaching of the fine components of the mix, particularly the cement paste [9, 10]. This phenomenon reduces the initial cohesion and alters the effective composition of the material, resulting once hardened in a more porous and heterogeneous microstructure, which leads to significant variations in mechanical properties and a deterioration in the long-term performance of structural elements, particularly in terms of durability [11].

Figure 1 summarizes representative cases of premature deterioration in national port infrastructure, associated with various mechanisms of concrete degradation in marine and aquatic environments. In item (a), the Yacila Pier, located in the port of Paita (Piura), showed significant loss of cementitious material and surface disintegration of the concrete in elements subjected to immersion, which was attributed to the material's inadequate performance under highly chemically aggressive conditions, prompting technical studies and the planning of urgent repair measures [12]. In item (b), the ENAPU Ilo Port Terminal (Moquegua) showed

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localized deterioration in concrete piles in both the above-water and underwater areas, characterized by the exposure of reinforcing steel and the onset of corrosion processes, which led to the approval of work to chisel away and remove the affected concrete in order to restore the structural capacity of the load-bearing system [13]. In item (c), various port structures in the Áncash region showed widespread signs of premature aging of reinforced concrete, manifested as cracking and progressive loss of cover; this situation prompted technical assessments aimed at characterizing the progression of the damage and establishing medium-term maintenance and rehabilitation strategies [14]. Finally, regarding item (d), unsuitable structural performance of the reinforced concrete used in casting MU-1 liquid loading dock at Talara Refinery (Piura) due to prolonged exposure to marine environment was detected by surface deterioration and a noticed drop of the resistance of the concrete cover, which demanded significant corrective actions on site to guarantee adequate service conditions and safety operation [15]. To address this problem, several methods have been suggested and used to control the difficulties involved in pouring concrete with water. This consists mainly of construction methods that control the dispersion of contaminated material (watertight formwork, cofferdams, local containment systems or temporary pumping), which permit the work front to be partially isolated; this often comes at a higher cost, limited logistical options for land-based operations, longer time spans, and adverse effects from currents and waves or complex geometry [16, 17]. Secondly, controlled placement techniques like the tremie method and directed discharge pumping can be employed to reduce turbulence and disallow direct contact of fresh concrete with water; but because these methods are sensitive to personnel experience, on-site control quality, and flow stability, they may also lead to loss of fines under actual field conditions [9, 10]. The use of anti-washout concrete is especially important since it has been engineered to provide improved bonding and other properties that help prevent cement paste from being lost during placement; this also addresses the underlying problem [18]; A logical progression from here would be to develop formulations using these types of naturally occurring additives to improve underwater performance while reducing the use of synthetic additives; this approach may also help reduce maintenance requirements for marine structures. Despite these advances, previous studies have examined anti-washout admixtures in geopolymer concrete, rheological modifiers in cement-based materials, and biopolymers in underwater concrete [19-22]. However, direct comparative evidence on guar gum, gum arabic, sodium bentonite, and sodium alginate within the same concrete mix design remains limited, particularly when fresh-state washout resistance, mechanical performance, and resistance to chloride penetration are evaluated together. The objective of this research is to evaluate the performance of washout-resistant concrete containing additives including guar gum, gum arabic, sodium bentonite, and sodium alginate; this will be done through a rationalized approach to minimize the amount of cement paste lost during placement while maintaining the quality of the hardened concrete. This study is unique because it compares each additive under one common experimental setup, determines the most effective dosage for each additive, and evaluates the performance of the most effective formulation under simulated rainfall and submerged casting conditions. This research also has the goal of providing technical guidance regarding the selection and use of washout-resistant concrete as an alternative for marine works and river infrastructure; thus, minimizing the potential for early-stage deterioration and providing sustainable options within the national context.



Fig. 1 Representative Cases of Concrete Deterioration in Marine Infrastructure

2. Literature Review

This section describes research focused on improving the cohesiveness, water stability, and rheological properties of cement-based materials through the addition of polymers and minerals such as guar gum, gum arabic, sodium bentonite, and sodium alginate; these three aspects are important for producing washout-resistant concrete.

2.1. Guar Gum in Concrete

The literature that has been reviewed indicates that guar gum enhances the cohesive nature, stability in water, and flow characteristics (rheology) of cement-based materials; these are important characteristics for achieving washout-resistant concrete [10]. In addition, complementary studies were reviewed that explain, in terms of physicochemical

mechanisms, how this biopolymer increases viscosity and enhances the material's water stability and mechanical performance.

In Iran, researchers at Islamic Azad University conducted a comparative study between conventional concrete and three types of underwater concrete modified with biopolymers resistant to "scouring" (kathira, sodium alginate, and guar gum), evaluating their behavior in the fresh state, their resistance to scouring, and their mechanical and shrinkage performance. To do so, they used the same base mix consisting of 488 kg/m³ of Type II cement, 977 kg/m³ of coarse basalt aggregate, 675 kg/m³ of crushed sand, 205 kg/m³ of water (water-to-cement ratio = 0.42) and 6 kg/m³ of superplasticizer, along with three variants that incorporated 2.24 kg/m³ of each biopolymer (0.5% of the cement). The specimens were molded and cured in lime-saturated water at 20 °C and subjected to slump tests (with and without superplasticizer), washing according to the CRD-C61 method, pH, initial and final setting (Vicat), compression, indirect tensile, three-point bending, and shrinkage tests in accordance with ASTM C157. The very mixture of 2.24 kg/m³ was found to be the best in terms of this property within the scope of the study, considering guar gum separately. Slump without superplasticizer and with superplasticizer decreased drastically to 22 mm and 69 mm, proving the high cohesion. It registered a meager 3.15% material loss in the washout test, ranking it among the lowest values. The mixture also exhibited the lowest pH (9.35), indicating reduced cement dissolution. The setting times were significantly decreased (initial: 36 min; final: 90 min). With respect to mechanical performance, guar gum produced the highest compressive (46.1 MPa), indirect tensile (3.67 MPa) and flexural strengths (5.29 MPa). In conclusion, it demonstrated the least shrinkage during 180 days and established itself as the alternative biopolymer with optimal washout resistance, structural enhancement, and volumetric stability among all the alternatives evaluated [22].

In China, investigators from South China University of Technology and collaborators studied the enhancement in anti-washout properties, while using natural polysaccharides including Guar Gum (GG), konjac glucomannan (KGM), and KGM/GG blends to develop injectable Calcium Phosphate Cement (CPC). CPCs were prepared using KGM or GG solutions with concentrations ranging from 0.5 to 2.0 wt% and with different mixing ratios of KGM and GG (1:4 to 4:1), maintaining a total solids concentration of 1.0 wt%; the loss on ignition, rheological viscosity, setting time (ISO 9917-1), compressive strength, and cytocompatibility with mBMSCs were evaluated. The results indicated that the addition of KGM and GG significantly increased the washing resistance of CPCs; the KGM/GG blends had an even greater effect on improving the washing resistance of CPCs than the use of KGM or GG alone. In particular, the mixed ratio (5:5) of KGM/GG resulted in a significant decrease in mass loss to 6.88% (compared to 63.26% for untreated CPC), the highest viscosity, and the shortest post-setting time; this mixture also produced the highest compressive strength (14.48 MPa). Furthermore, the formulations containing guar gum maintained good adhesion and cell proliferation, confirming that its incorporation, either alone or in combination, improves the stability, mechanical properties, and biocompatibility of CPC for applications in bone defect repair [23].

In the United States, researchers at Purdue University's Lyles School of Civil Engineering evaluated the use of guar gum as a sustainable additive to partially replace cement, analyzing its effect on the mechanical and microstructural properties of concrete, as well as determining its optimal dosage using statistical methods. They prepared more than 200 specimens with water-to-cement ratios of 0.45, 0.50, and 0.55 and guar gum contents of up to 0.8% of the cement weight, evaluating workability (slump), moisture retention, compressive strength (ASTM C39), indirect tensile strength (ASTM C496), ultrasonic pulse velocity (ASTM C597), and microstructure via SEM, supplemented by Taguchi optimization and ANOVA. The results showed that low doses of guar gum increased cohesion, moisture retention, and microstructural densification all key properties for wash-resistant concrete; that the strengths reached optimal values around 0.2% for compressive strength and 0.4% for tensile strength, after which they decreased due to increased porosity; that the ultrasonic pulse velocity increased in line with the mechanical improvement at 0.2%; and that SEM revealed guar gum paste bridges and a more homogeneous microstructure at low concentrations, while high dosages generated more pores. The ANOVA confirmed that the percentage of guar gum had a greater influence than the water-to-cement ratio on the variation in strengths, highlighting its ability to improve cohesion, stability, density, and structural behavior, essential characteristics for enhancing the concrete's washout resistance [24].

In China, researchers from the School of Civil Engineering, Architecture, and Environment at Hubei University of Technology, in collaboration with the Hubei Ecological Road Research and Engineering Center, evaluated the use of guar gum as a modifier for vegetated concrete to improve its hydraulic properties, maintain the stability of revegetated slopes, and simultaneously reduce the cement content to less than 4%. They examined the intrinsic behavior of mixtures with various dosages of guar gum using direct shear, moisture stability, permeability tests and SEM microscopy and pH analyses. The results showed that guar gum significantly increased stability against water, reduced permeability, and increased shear strength, raising cohesion by up to 32.30% and the angle of friction by 6.63%; furthermore, the coefficient of stability against moisture reached its optimal value with 1.0% guar gum. SEM observations confirmed that guar gum bound soil particles together and filled the pores, resulting in a denser and more stable structure. This led to a reduction in alkalinity and

overall superior hydraulic and mechanical performance, with high potential for slope protection and stability [25].

In Mexico, researchers at the Autonomous University of Nuevo León evaluated polysaccharide biopolymers, including the commercially available guar gum, as viscosity modifiers in cement pastes to improve rheology, stability, and mechanical performance. They prepared pastes with a water-to-cement ratio of 0.45 and biopolymers ranging from 0.25 to 1.00% of the water content, comparing incorporation methods (dry addition and two pre-dissolution techniques) and analyzing rheological properties, stability via forced bleeding, hydration kinetics, setting, and compressive strength. The results showed that the pre-dissolution methods significantly improved viscoelastoplastic behavior and that higher dosages increased plastic viscosity, yield stress, and stiffness over time, in addition to reducing bleeding properties crucial for anti-washout performance. Among the additives, welan gum and guar gum produced the greatest relative increases up to 251.3% in storage modulus, 159.0% in yield stress, and 103.7% in plastic viscosity, demonstrating a strong ability to enhance the cohesion and stability of the pastes [21].

2.2. Gum Arabic in Concrete

The data gathered indicates that gum arabic plays an important role in the rheology, water stability, and microstructure of cementitious and geopolymer matrices, attributes that are consistent with its likely function as an anti-washout additive [20]. Here is a selection of the most relevant work on its application in cementitious systems.

In India, the physical and mechanical properties of geopolymer concretes containing natural anti-washout additives for underwater application were investigated by Aditya Engineering College that also probated workability, resistance to washout phenomenon, bleeding/segregation, compressive strength and study of microstructure through Micro-CT analysis. They have prepared nine geopolymer mixtures including fly ash (315kg/m³), GGBFS (135kg/m³) and an alkaline activator, introducing Gum Arabic (GA) or xanthan gum at 0.25% to 0.75% of the binder, as well as cement-based mixtures with 0.5% both additives. The following characterizations were performed: consistency by ASTM C143; washout resistance, CRD-C 61-89A; compressive strength in 100-mm cubes (ASTM C39) at the age of 28 days after underwater curing at a temperature of 15 °C; and microstructure X-ray diffraction (XRD), Scanning Electron Microscopy (SEM) and Energy-Dispersive Spectroscopy (EDS). The anti-washout additives reduced bleeding and material loss during immersion. For mixtures containing gum arabic, washout losses of 3.5% and 2.1% were reported, while the AG0.75 mixture showed a 10.2% increase in compressive strength compared with cement-only mixtures. The maximum compressive strength at 28 days was 54.73 MPa. Analyses conducted using XRD-SEM-EDS confirmed that the incorporation of gum arabic produced denser microstructures, higher levels of C-A-S-H gel formation, and a more complete development of geopolymerization products, thus confirming its function as the most effective additive in enhancing cohesion, hydraulic stability and washout resistance in underwater geopolymer concretes. [20].

Its use as a natural modifier in M25 concrete has been studied by researchers from the Department of Civil and Environmental Engineering at the University of Lagos, who reported that up to 1.2% biopolymer could dramatically improve workability (cfr: increased slump from 50 mm to 250 mm type "S") and low dosages such as 0.3% yielded optimal compressive strength of superior material upon control (32.2 N/mm² against 46.09 N/mm²), with XRD proving greater stability of microstructure leading to higher values quartz (55%), muscovite (10,9%), however the additive was described to have delayed setting time requiring three days for demolding as opposed to control which required only a period lasting over just between both days. [26]. For their part, researchers at Abubakar Tafawa Balewa University conducted a study in which they used gum arabic as a retarder in 1:2:2 concrete, finding that it increased slump by more than 20 mm compared to the control, delayed setting times by approximately 68%, progressively reduced water absorption at higher dosages, and, although it produced lower compressive strengths than the control (30 MPa at 28 days), the mixtures showed continuous strength gain up to 56 days, confirming that the additive improves water stability and hydration control under hot weather conditions [27].

In Sudan, researchers from the University of Khartoum and Red Sea University evaluated Sudanese gum arabic (Acacia senegal, or “Hashab”) as a Viscosity-Modifying Additive (VMA) in Self-Compacting Concrete (SCC) to reduce dust content and improve its stability in hot weather. They prepared a reference SCC and three mixtures containing 400-350 kg/m³ of cement, a water-to-cement ratio (w/c) of 0.45, a constant superplasticizer, and a single dose of 0.2% gum arabic, evaluating slump flow, T500, Segregation (SR), air content, and compressive strength at 28 days. The results showed that gum arabic increased the T500 time, indicating higher viscosity and cohesion; it also increased the air content (from 1% to 2.0%) and drastically reduced segregation, from 16% in the control to just 4% in the mix with 400 kg/m³ of cement, maintaining low values even with cement content reduced to 350 kg/m³. Furthermore, it allowed for a reduction in dust content without affecting self-compacting ability and only slightly reduced compressive strength (from 44 to 41 MPa). Overall, gum arabic met the regulatory criteria for VMAs and significantly improved cohesion, water stability, and resistance to segregation properties directly associated with better anti-washout performance [28].

Researchers from Universiti Teknologi Malaysia (UTM) and the partner universities in Malaysia assessed Arabic Gum Biopolymer (AGB) as a new additive material to enhance

workability, setting, durability and microstructure of mortars and concretes. In addition to XRF, XRD and SEM analyses, they prepared 0.1- 1.1% AGB mortars, pastes and concretes to determine flow, Vicat setting time, density and carbonation resistance. The results showed that AGB progressively increased flowability (up to a 73% increase in flow diameter at 1.1%), prolonged initial setting beyond 8 hours at 0.9%, slightly altered density, and reduced carbonation by 11%. Microstructural analyses revealed a denser C-S-H matrix, fewer voids, and greater homogeneity, reflecting an increase in cohesion and internal stability [29]. These improvements, particularly the increased cohesion, greater stability against CO_2 penetration, and microstructural densification, highlight gum arabic's potential to act as an additive that enhances stability and resistance to water, qualities that are directly compatible with anti-washout concrete applications.

2.3. Bentonite in Concrete

The evidence showed that bentonite increases the viscosity, cohesive properties, and water stability of cementitious mixtures, thus reducing segregation and bleeding during submersion in water [30]; therefore, bentonite is a mineral additive that improves the washout resistance of concrete.

In China, researchers at the University of Geosciences evaluated a Bentonite-Cement-Sodium Silicate (BCG) grout and confirmed that adding bentonite in amounts ranging from 0 to 50% resulted in significantly higher viscosities in Grout A (measured at 600 rpm), progressively increasing cohesion, stability in water, and resistance to washing, while markedly reducing bleeding after 120 minutes. The BCG exhibited short and adjustable setting times, controlled primarily by the water-to-solids ratio, with faster setting and higher early strengths observed when W/S = 1.5 compared to W/S = 2.0. Although higher bentonite contents decreased the compressive strength of the test cubes at 1 and 3 days, mixtures containing 10-20% bentonite showed the best balance between stability and strength. SEM analyses of samples containing 0, 10, and 20% bentonite revealed that bentonite promoted the formation of denser, more continuous, and less porous structures, reducing particle segregation and enhancing anti-washout capacity. In a real-world application as a pre-grout at the Wangfujing North station of the Beijing Metro, the BCG produced much more compact grout bodies, completely eliminated water seepage, which did occur with conventional Cement-Silicate Grout (CSG) and demonstrated superior performance in reducing permeability, validating its effectiveness as a grouting system with high stability and improved hydraulic performance [30].

In Spain, reviewed the use of bentonite as a supplementary cementitious material and concluded that incorporating it in proportions ranging from 3 to 21% when raw and up to 30 to 50% when calcined improves water retention, cohesion, mix stability, and impermeability, in addition to reducing absorption, sorptivity, and chloride penetration, with particularly favorable effects when combined with silica fume (22.5% bentonite + 10% silica), a mixture that also reduced CO_2 emissions by nearly 23%; likewise, increases in strength were observed in sulfated environments, and maximum mechanical strengths were achieved with 20% calcined bentonite [31]. Meanwhile, researchers at Tianjin University (China) demonstrated that various sodium bentonites produced high viscosities notable increases when mixed with cement (such as HB-B, which went from 38.44 s to 64.87 s in the Marsh funnel) and very low bleeding (4.64 to 6.6% compared to >14% in others), conditions associated with high hydraulic stability; furthermore, XRD, NMR, and FESEM analyses showed that bentonites with higher montmorillonite content formed denser laminar networks and continuous matrices with well-distributed hydration products, which promotes cohesion and viscosity recovery after shearing [32]. These properties are critical for wash-resistant concrete because they reduce segregation underwater, prevent the loss of fines and cement paste, stabilize the mixture against flow and hydraulic impact, and allow the concrete to maintain its integrity while being placed in submerged environments.

2.4. Sodium Alginate

Evidence was gathered showing that sodium alginate acts as a biopolymer capable of increasing cohesion, improving water stability, and promoting microstructural consolidation in various cementitious systems, attributes directly associated with better performance under underwater washing conditions [22]. Also, many other studies indicate that it contributes to controlling cement setting, reducing deformation of the material, and providing early-age mechanical stability; these characteristics support its potential as an additive for developing washout-resistant concrete, which will be discussed in greater detail below.

As stated previously, researchers from Islamic Azad University in Iran conducted a comparison between conventional concrete and underwater mixes that were modified by adding biopolymers resistant to scouring, such as kathira, sodium alginate, and guar gum. In the case of sodium alginate, the mixture containing 2.24 kg/m³ showed significant improvements in scour resistance: it reduced the slump to 26 mm without a superplasticizer and to 78 mm with one, increased the mixture's cohesion, and limited segregation; it exhibited a low scour loss of 3.3% (compared to 8.1% for the control) and reduced the water pH to 9.58, indicating less cement dissolution; it shortened setting times (2 min initial and 102 min final) and improved mechanical properties, reaching 44.16 MPa in compression, 3.61 MPa in indirect tensile strength, and 5.18 MPa in flexural strength. It also offered a reduction in shrinkage compared to the control, which related favorably to volumetric stability. In conclusion, sodium alginate displayed favorable combination of cohesive nature, hydraulic stability and low washout loss, which is

required to be used as an additive in washout-resistant concrete [22].

In China, researchers at the School of Materials Science and Engineering evaluated sodium alginate as an additive in Magnesium Potassium Phosphate Cement (MKPC), reporting improved water stability at dosages up to 1%, delayed setting, and greater early-age cohesion. At a 1% dosage, it extended the final setting time from 15 min to 35min, allowing for more uniform hydration and reducing the risk of disintegration under wet conditions. In addition, alginate was found to increase early-strength development at 3 hours, with an increase of 13.5% over the control group when using a w/c ratio of 0.15; this supports the initial stability of the mixture under washout-prone conditions. The results from XRD, pH, and SEM analyses showed that alginate decreased the dissolution of MgO while increasing the dissolution of KH2PO4; it did not affect the normal struvite-K formation process up to 1%, resulting in a more compact microstructure and less loss of cohesion in the pastes. However, higher levels of alginate (>1%) led to an increase in the number of pores and lower resistance at both time points. Therefore, it can be concluded that an alginate concentration of 1% is an adequate limit, as it delays setting, enhances cohesion, and provides water stability; these benefits are achieved without compromising other system properties required for applications exposed to underwater washout [33].

In China, the Key Laboratory of Deep Underground Science and Engineering staff at Sichuan University assessed sodium alginate as an additive that acts upon EPS lightweight concrete matrix with a twofold aim: increase its strength and reduce shrinkage; they found that calcium agitated for 72 h on the dosage of sodium alginate gave a much better mechanical response than that without it: compressive strength rose incrementally to maximum value at 2% (alginate) after which the trend reversed; whereas shrinks deformation by continuous measure at 28 days was curtailed up to 40%(average factitious, control mix) [34].

Overall, both studies reported improvements in mechanical stability following sodium alginate incorporation. These findings support its evaluation as an additive in washout-resistant concrete, particularly for enhancing cohesion, limiting particle separation, and maintaining mixture integrity during submerged placement.

At this moment, all marine infrastructure projects solicited in Peru, such as pier piles, breakwater foundations, port structures, outfall pipes and submerged elements subject to currents and waves, have a recurring issue: concrete's extreme vulnerability to washout of fine-grained material during underwater casting, which quenches initial aggregate cohesion, upsets the local pH, predisposes to early microstructure weakening and ultimately results in reduced durability through the marine environment. Despite the existence of traditional anti-washout additives, their performance does not always assure protection in regions prone to turbulence, hydraulic gradients and constant water movement. Therefore, in recent years, the use of natural biopolymers (such as guar gum, gum arabic and sodium alginate) and minerals (sodium bentonite) with a significant effect on cohesion, water stability, setting control, washout resistance and microstructure densification by cementitious systems have been investigated. Overall, the reviewed studies show that guar gum and sodium alginate can improve cohesion and water stability, gum arabic can reduce segregation, and sodium bentonite can enhance viscosity and particle retention. However, these findings were obtained using different binder systems, additive dosages, and testing conditions, which limits direct comparisons of washout resistance, mechanical strength, and chloride penetration resistance under a common experimental framework.

This study, therefore, is focused on a comparative evaluation of the effect of guar gum, arabic gum, sodium alginate and sodium bentonite on washout-resistant concrete designed for underwater applications to define its optimal dosage range, improving cohesion in favoring the control of disintegration upon submerged placing, initial pH evolution, as well as performance with respect to an established compacted/dense microstructure robust against chloride ingress. The aim is to devise strong engineering data underpinning the category of such additives as one of the viable options for marine construction, which will assist with enhancing reliability, durability and performance of infrastructures functioning within high-dynamic environments experienced in severe scouring conditions.

3. Materials and Methods

This section describes the mixtures and experimental conditions used to evaluate wash-resistant concrete incorporating guar gum, gum arabic, sodium bentonite, and sodium alginate; additive dosages were expressed as percentages by weight of cement based on a base mix design. Fresh concrete was evaluated through slump, temperature, washout resistance, and pH measurements; setting time was determined by penetration resistance on sieved mortar according to ASTM C403/C403M. Hardened concrete was assessed through compressive strength, indirect tensile strength, and electrical indication of resistance to chloride ion penetration; these tests enabled comparisons of mixture cohesion, water stability, mechanical performance, and durability.

3.1. Stabilizing additives for underwater concrete

This section describes stabilizing additives to enhance washing resistance and maintain the integrity of mixtures in underwater environments, which includes biopolymers as well as colloidal agents, for example: guar gum, gum arabic, bentonite, sodium alginate.

3.1.1. Guar Gum

Guar gum is a natural polysaccharide sourced from guar plant seeds; it is heterogeneous and branched, which gives this biopolymer a high thickening capacity in different industries [35][36]. Because of this, it shows fast hydration in cold water and has high gelling capacity, very good water solubility and stability at different pH levels [37].

Compact and granular microstructure in Figure 2 are typical for biopolymers with high water retainment potential and ability to form compact matrices. Additionally, their functional groups facilitate adsorption on metal surfaces and form stable protective films in alkaline environments or with chloride [38]. Such properties help to improve the binding capacity of wash-resistant concrete, reducing fine aggregate segregation, and improving mixture water stability during placement under water [10].

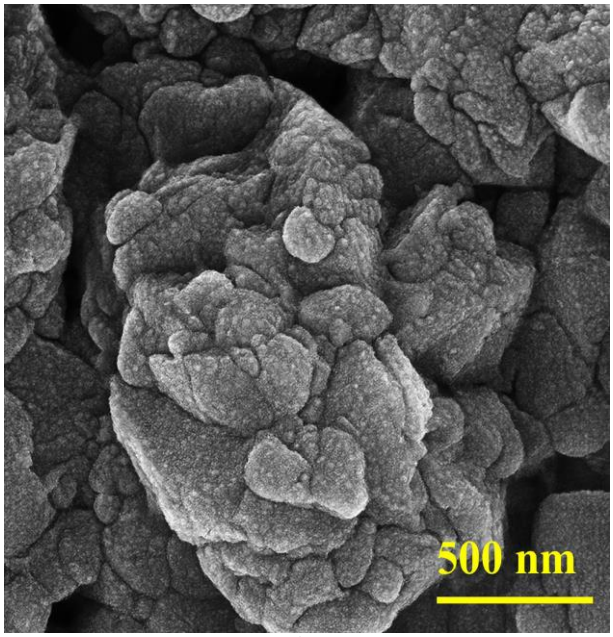


Fig. 2 SEM micrographs of the 500 ppm guar gum [38].

Extraction of Guar Gum

Guar gum preparation flowchart Figure 3: Flow chart representing the process behind the extraction of guar gum from seeds in order to use it as an additive in wash-out-resistant concrete, divided into four main steps. Initially, in step (a), commercial food-grade guar gum was purchased, powdered to be of fine particle size shape, and the physical form and storage were confirmed. During the second stage (b), a portion of uncooked guar gum was dried by air-calibrated oven to lessen the water substantiated in material, because which clumps tend to be produced across handling. Finally, in the third step (c), the dried material was sieved through a No. 200 mesh to yield equal particle sizes and disperse any agglomerations. In the last stage (d), the sieved guar gum was placed into clean and dry containers for later dosing and addition in the mix design of wash-resistant concrete.



Fig. 3 Extraction of Guar Gum

As stated in the literature review, guar gum is generally utilized in amounts of about 0.5% by weight of cement, a percentage sufficient to promote an increase in viscosity without hindering the workability of the system [22, 24].

Nevertheless, it was needed to experimentally confirm this range, so 0.3%, 0.4%, 0.5%, 0.6% and 0.7% of guar gum were sequentially used to provide a wider range of progressive concentrations, enabling a deeper study on the response of the cement towards well-controlled additions of the biopolymer to identify if any concentration will be preferable than others in terms such as concrete strength and workability decays respect to its untreated counterpart.

3.1.2. Gum Arabic

Gum arabic is a natural polysaccharide obtained from the dried exudate of species of genus Acacia; it has high solubility in water and is used as an industrial additive for its properties to modify rheological properties [26, 39].

Its branched polysaccharide structure is especially important since it has a large number of hydroxyl and carboxyl functional groups, which makes it capable of forming stable colloidal systems, adhesive behaviors, and shear-thinning capabilities depending upon concentration [40].

Figure 4 depicts a compact morphology containing dense grainy aggregates, a feature of biopolymers that build up strong interactions with aqueous substances. Gum arabic can be expected to behave as a hydration and microstructure modifier in the cementitious systems, covering the binder particles that increase cohesion and making the mixture more homogeneous [41]. These properties foster the stability and cohesion of concrete under underwater conditions.

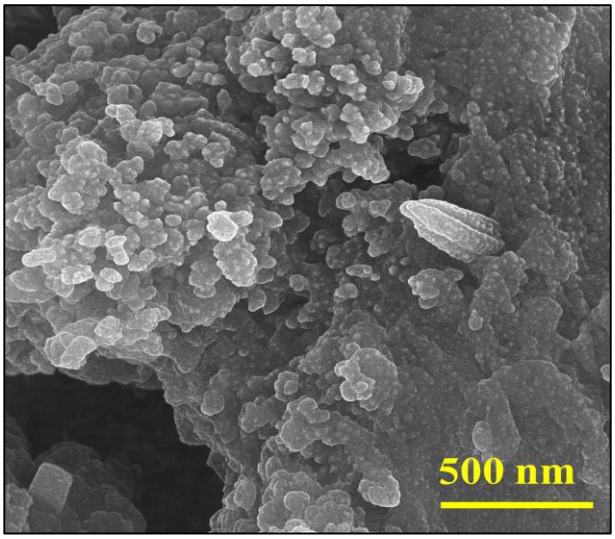


Fig. 4 SEM micrographs of the 500 ppm arabic gum [38]

Extraction of Gum Arabic

The process for preparing gum arabic to be mixed into the washout-resistant concrete is shown in Figure 5. Initially, in step (a), the edible gum arabic powder obtained commercially was received and examined by visual inspection for uniformity, color, and impurity. Then, in (b), to minimize excess moisture, the material was placed in an oven at a stable temperature rate of 55 °C for 6 hours. In the third stage (c), the dried gum arabic was passed through a No. 200 mesh in order to generate uniformity (this particle size was essential for well-distributed dispersion and good interaction with the cementitious matrix). Finally, (d) after sieved material was filled and stored in metal containers to be hermetically sealed and dry for preserving the physicochemical properties of the raw material until administration.

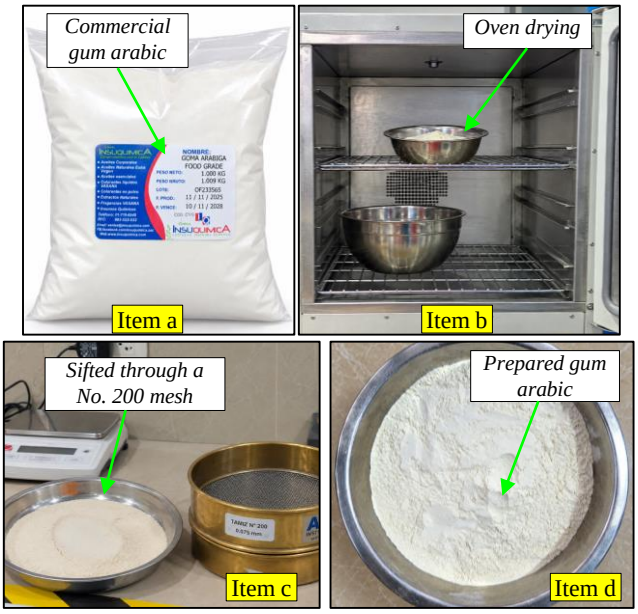


Fig. 5 Obtaining Gum Arabic

While some sources specify the amount of gum arabic as around 0.5% weight proportion relative to the solid cement fraction for referencing its effects in purely cementitious matrices [20, 26], based on previous studies, it was reported that the maximum stability and cohesion occurred with 0.3% weight % of biopolymer. In this study, this dosage range was extended by varying polymer amounts at concentrations of 0.3%, 0.4%, 0.5%, 0.6%, and 0.7% to evaluate more accurately its effect on stability and cohesive forces of aqueous system.

3.1.3. Sodium Bentonite:

Bentonite is a natural montmorillonite clay, identified by its high plasticity, ion-exchange capability and high water absorption connected to its layered structure, along with its expansive nature (Figure 6) [31, 42]. As well as this, due to the ball-bearing effect for a larger and much greater genesis of AFm phases and in calcined bentonite, which has more pozzolanic reactivity than conventional clays, promotes the growth of new cementitious compounds over time [43]; which means that all evidences are favourable due to its usage in cementitious matrices. These mechanisms generate a compact matrix which is more cohesive, thus contributing to the reduction of fine aggregate losses and disintegration in hydraulic action, with better performance as wash-resistant concrete [44].

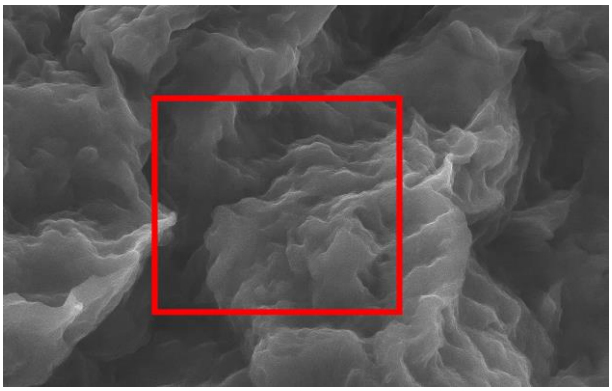


Fig. 6 SEM image of untreated bentonite specimen [42]

Production of Sodium Bentonite

The preparation and conditioning of the sodium bentonite prior to being mixed in with the cementitious portion of the wash-resistant concrete was comprised of four sequential stages, carried out under controlled laboratory conditions (as indicated on Figure 7). Step (a): Sodium bentonite in commercial form, supplied in 30 kg bags, was received and checked for the presence of dry lumps or contaminants; any surface moisture that could affect its interaction within the cementitious matrix was also examined. Step (b): Ground and mechanically homogenized sodium bentonite was then ball-milled to decrease its particle size, increase its specific surface area, and enhance its interaction with the cement hydration products. Step (c): Sieving of the ground sodium bentonite

through a No. 200 sieve was performed to obtain different particle size distributions; these were to be utilized in preparing the concrete mix for washout-resistant concrete.

Finally, Step (d): Calcination heat treatment at 750 °C for 2 h was applied to the sieved sodium bentonite to obtain an aluminosilicate material intended to exhibit pozzolanic reactivity upon contact with the cementitious matrix following hydration.

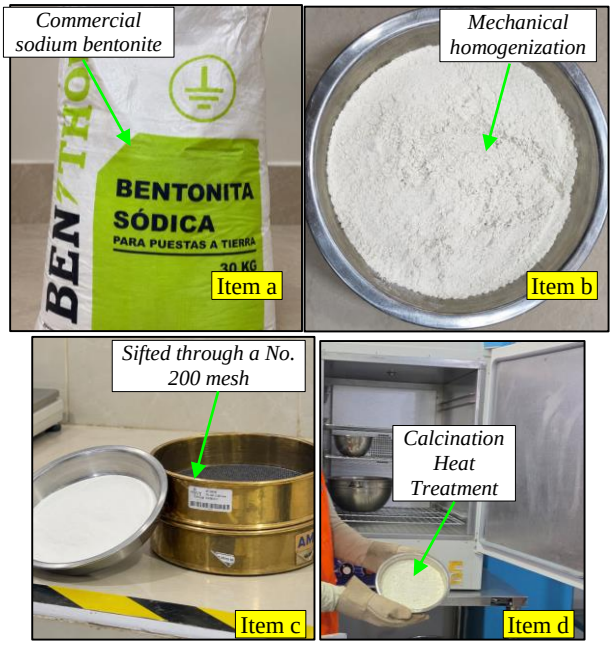


Fig. 7 Production of Sodium Bentonite

Considering that previous studies usually consider bentonite content in the vicinity of 20% of the mixture to characterize bentonite behaviour in cement-based samples [31][43]. A wider range of proportions were selected to allow the effect of bentonite on the cementitious matrix to be evaluated in detail throughout a range (10%, 15%, 20%, 25% and 30%) in this study.

3.1.4. Sodium Alginate

Is a white powdered biopolymer with highly absorbent properties which can also form viscous colloids when hydrated in water [34, 45]. It has a strong interaction with calcium ions and participates in the formation of a gel structure, which increases adhesion, cohesion and the ability to retain water from cementious systems [46], thus causing densification of the microstructure as well as increasing resistance to water penetration (Figure 8). Such a structure also allows for uniform incorporation and fixation of particles on the surfaces of minerals, with subsequent improvement in mechanical stability of the material and homogeneous distribution of all components [45]; these properties are vital, especially for wash-resisting concrete for retaining fine aggregates as well as mix stability during submersion.

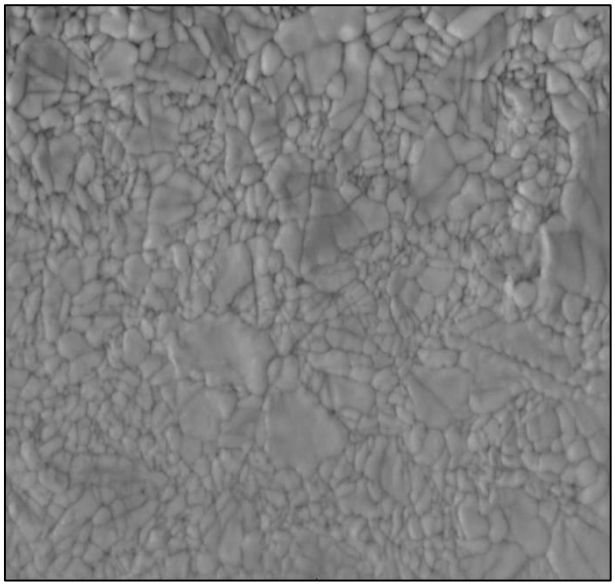


Fig. 8 SEM image of Sodium Alginate [47]

Obtaining Sodium Alginate

The preparation method of sodium alginate before adding the cementitious mixture for the wash-resistant concrete is shown in Figure 9. The biopolymer was first received in 600-gram airtight commercial containers, where it appeared as a very fine whitish yellow powder free of agglomeration (item a). An initial examination was carried out on its flowability and ensuring there is no moisture, which would affect the gelling behavior. Item (b) shows preparation of the material in the second phase, which was gently sieved through a No. 200 mesh sieve to break up some temporary micro-lumps from storage and provide a particle size distribution that would promote progressive hydration during mixing.

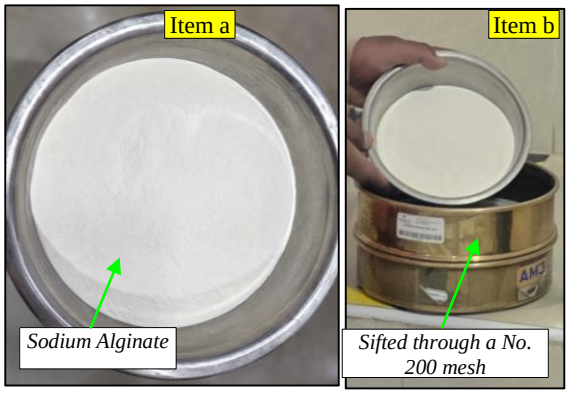


Fig. 9 Obtaining Sodium Alginate

Given that previous studies have generally focused on dosages close to 2% of the cement to characterize the behavior of sodium alginate [22, 33, 34]. In this study, concentrations of 1%, 1.5%, 2%, 2.5%, and 3% were used in order to broaden the range of analysis and allow for a more comprehensive evaluation of the effect of sodium alginate on the cementitious matrix.

3.2. Concrete

Concrete is a widely used construction material; technological advances have made it possible to develop modern mixes characterized by high workability, high fracture toughness, superior mechanical strength, and remarkable chemical durability attributes that expand its range of structural applications and ensure the construction of safe, stable, and sustainable buildings over time [46, 48, 49].

With regard to regulatory requirements, Peruvian Technical Standard E.060 [50] stipulates that, for elements exposed to chlorides such as marine structures, concrete must have a minimum compressive strength of 35 MPa and a water-to-cement ratio of no more than 0.40, in order to ensure adequate performance against reinforcement corrosion. In accordance with these requirements, this study developed a mix design using the specified proportions.

3.2.1. Concrete Mix Design

The aggregates used in the study were sourced from local quarries in the Huancayo region, selected for their quality and gradation stability. The fine aggregate consisted of coarse sand from the Mito quarry, located in Orcotuna, while the coarse aggregate consisted of ¾" crushed stone from the Ataura quarry in Jauja.

A theoretical mix ratio that corresponds to a compressive strength of f'c = 350 kg/cm² was adopted for the mix design with an a/c of 0.35 and a Nominal Maximum Size (NMS) of ¾" coarse aggregate.

According to this, the mix design per cubic meter comprised 594 kg of cement, 824 kg of fine aggregate, 683 kg coarse aggregate and 208 L of mixing water, as given in Table1.

Table 1. Concrete Mix Design F'c=350 kg/cm²

Property	Unit	Value
a/c	-	0.35
Coarse Aggregate Size	In	¾
Cement	Kg	594
Fine Aggregate	Kg	824
Coarse Aggregate	Kg	683
Water	L	208

3.2.2. Experimental Dosages of Additives Added to Concrete

Once the mix design was defined and the cement content set at 594 kg/m³, the experimental dosages for each of the four additives to be evaluated were determined based on cement weight percentage (given as %), converted to kg/m³.

These quantities, listed in Table 2, constituted the experimental base upon which both the fresh and hardened properties of wash-resistant concrete were evaluated.

Table 1. Additive dosages based on cement weight

Code	Input	% relative to the weight of the cement	Kg
Gg $_1$	Guar gum	0.3%	1.78
Gg $_2$	Guar gum	0.4%	2.38
Gg $_3$	Guar gum	0.5%	2.97
Gg $_4$	Guar gum	0.6%	3.56
Gg $_5$	Guar gum	0.7%	4.16
Ga $_1$	Gum arabic	0.3%	1.78
Ga $_2$	Gum arabic	0.4%	2.38
Ga $_3$	Gum arabic	0.5%	2.97
Ga $_4$	Gum arabic	0.6%	3.56
Ga $_5$	Gum arabic	0.7%	4.16
Bs $_1$	Sodium Bentonite	10%	59.40
Bs $_2$	Sodium Bentonite	15%	89.10
Bs $_3$	Sodium Bentonite	20%	118.80
Bs $_4$	Sodium Bentonite	25%	148.50
Bs $_5$	Sodium Bentonite	30%	178.20
As $_1$	Sodium Alginate	1.0%	5.94
As $_2$	Sodium Alginate	1.5%	8.91
As $_3$	Sodium Alginate	2.0%	11.88
As $_4$	Sodium Alginate	2.5%	14.85
As $_5$	Sodium Alginate	3.0%	17.82

3.3. Fresh Concrete Tests

The following subsections describe the testing that was conducted on freshly mixed concrete to evaluate its workability, water stability, and early-age behavior after the addition of the optimum admixtures.

This type of testing provided a controlled evaluation of the rheology and cohesiveness of the mixtures; this evaluation would ultimately help interpret their performance in the hardened state.

3.3.1. Slump Test ASTM C143

The slump test (ASTM C143M) is the standard method of measuring the consistency and workability of freshly mixed concrete by comparing the vertical deformation of a molded frustum-shaped mixture immediately after removal [51][52]. The settlement test that had performed before molding the test specimens is shown in Figure 10.

The Abrams cone was filled with concrete in three separate layers; each layer was compacted using a metal rod by applying 25 consistent blows. The top of the concrete was then made level, and the mold was carefully lifted vertically in a controlled manner to permit the concrete to settle on its own; the slump was determined by measuring the difference between the height of the mold and the height of the top surface of the settled concrete.

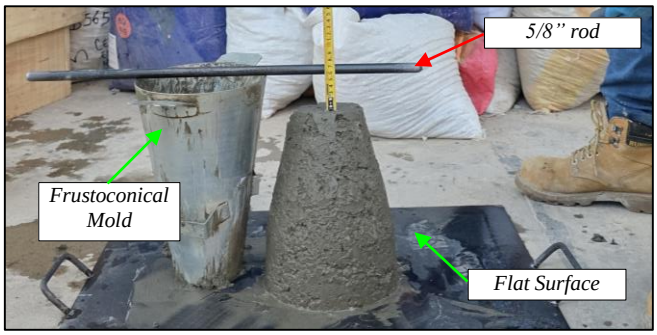


Fig. 10 Slump Test Procedure

3.3.2. Temperature Test ASTM C1064

The Fresh Concrete Temperature Test conforming to ASTM C1064 permits the accurate assessment of the thermal condition of freshly mixed concrete [53, 54]. It is used to ensure workability; set, and hydration of fresh concrete [55]. In the present study, a sample of concrete was placed in a wheelbarrow, and then a temperature probe was placed until the sensor head was completely immersed, ensuring that the sensor did not come into contact with either side (to ensure an accurate reading). Readings were taken immediately post-mixing, and the value obtained stabilized to provide initial reference for concrete temperature, shown in Figure 11.



Fig. 11 Procedure for Conducting the Temperature Test

3.3.3. Washout Resistance Test

Test ID Test Type Washout test (CRD-C61 washout test) A wall is formed using a plastic sheet to hold the fresh concrete, which is then vibrated out/placed in water, and assessed for washout effectiveness. Tests the ability of fresh concrete placed underwater to hold together and provide little disintegration of individual components [56, 57].

The process of conducting an immersion test using a metal basket that meets the requirements outlined by the standard is depicted in Figure 12.

As illustrated in detail in item (a), the test sample's initial mass (Mi) before testing was measured at 2.5 kg; representative and homogeneous sample conditions were maintained.

For this study, the sample was placed within a perforated metallic basket positioned at a height of 30 cm above the water surface; this arrangement was intended to represent the free fall of concrete into water, as illustrated in item (b).

Then, a mask containing the test sample was immersed for 60 s in step (c), where an egg timer measured time so that particles prone to washout were able to penetrate through the mesh.

Then, in step (d), the basket was removed from the container and drained until excess water was washed out while minimizing further losses due to handling.

Finally, as shown in item (e), the sample remained in the basket was re-weighed for a last mass (Mf), a value representing the losses of material due to washing and used to check the stability of the concrete at immersion conditions.

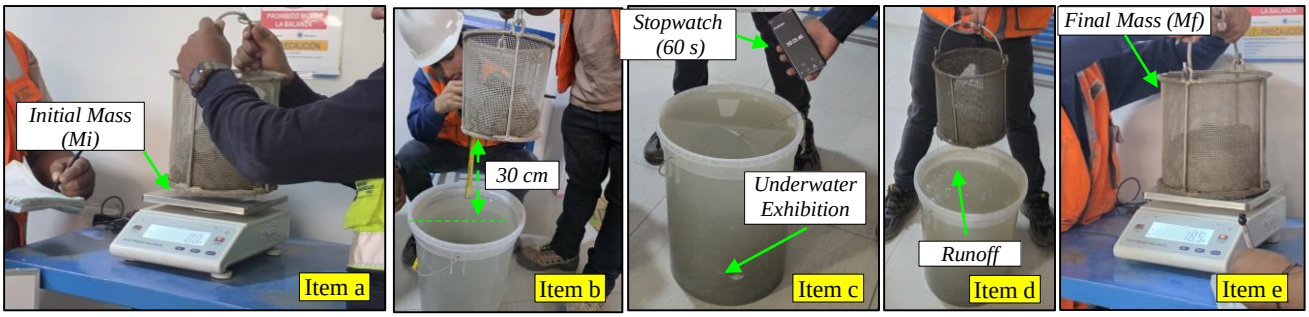


Fig. 12 CRD-C61 Washout Test Procedure

Based on this, the leaching percentage was determined using Equation 1:

$$D = \frac{Mi-Mf}{Mi} x100 \quad (1)$$

3.3.4. Measuring pH in Fresh Concrete

This pH measurement test on fresh concrete is useful for assessing the extent of cement leaching when in contact with water and can be a good indirect measurement of the deal with mixture water stability and leaching [22, 58]. The developed experimental procedure to measure the pH of fresh concrete is shown in Figure 13. First, as seen in (a), 500 ml of purified water was prepared in a glass container with transparency and the digital pH meter was tested to ascertain its proper functioning before starting the measurements. In the second step, 170 g of fresh concrete was weighed using a digital scale

(see b in Figure 13) and ensuring the representativeness of the sample by taking it directly from the fresh mixture that is being evaluated. In that case, and as indicated in step (c), the fresh concrete was poured into the water container so contact surface between cement paste and liquid medium is reached to promote the release of alkaline compounds. After a properly sorted resting time, the electrode of a pH meter was introduced in the obtained solution, and the correspondent pH value has been recorded, this result corresponding to one of the parameters employed for measuring concrete resistance against leaching under immersion conditions.

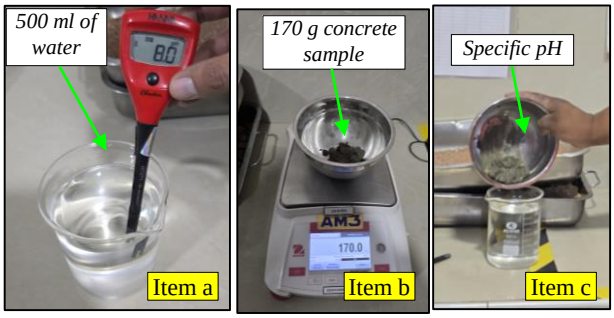


Fig. 13 Measuring pH in Fresh Concrete

3.3.5. Concrete Setting Time Test

The ASTM C403/C403M test determines the setting times of concrete based on the penetration resistance of the sieved mortar [59], allowing the evaluation of the transition of the mixture from a plastic state to a rigid state [60].

Figure 14 shows the procedure used to determine the setting time of the concrete. First, as shown in item (a), the concrete mix was prepared according to the proportions specified in Table 1 and Table 2, initially incorporating the dry materials and then adding water along with the anti-washout biopolymers, while continuing to mix until a homogeneous, cohesive mix free of segregation was obtained.

In the second stage, shown in item (b), the freshly mixed concrete had been passed through a No. 4 sieve in order to obtain the representative mortar for use in testing of penetration, whereby any coarse aggregate that could interfere with readings was removed.

Then the sieved mortar was put into firm cylindrical containers in step (c), making its surface flat, without any significant vibration so that density and real strength of the material were not modified. Step (d) in the procedure required to continue testing after the setting evaluation had begun, using the ASTM penetrometer with different diameter needles for ¼ penetration areas, repeatedly applying penetrations at equal intervals to various locations on the sample face and recording strength development with respect to elapsed time from initial mixing. The initial and the final settings were identified as the penetration resistance corresponding to 3.5 MPa and approximately 27.6 MPa, respectively, these values correspond to those set out by the standard for characterizing concrete hardening.

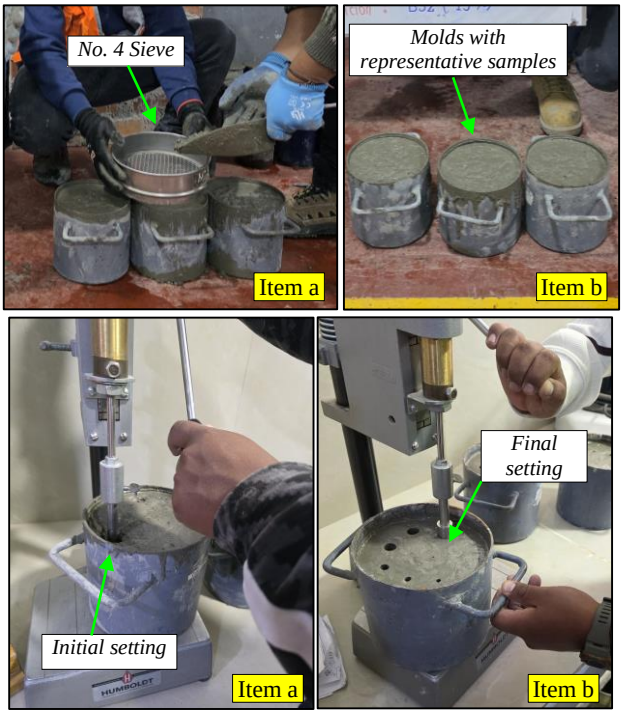


Fig. 14 ASTM C403/C403M Concrete Setting Time Test Procedure

3.4. Tests on Hardened Concrete

The tests performed on hardened concrete to assess its mechanical strength and internal stability, as well as durability after the alteration with selected additives, are described in this section. These procedures allowed the assessment of the structural capacity and ultimate behavior of the mixtures and provided defined criteria for comparing their performance against washout conditions.

3.4.1. Compressive Strength ASTM C39

The ASTM C39 method is used to determine the compressive strength of cured concrete [61, 62]. This method uses hardened concrete specimens at 7, 14, and 28 days of age. As shown in Figure 15, the cylindrical specimens (100 × 200 mm) were taken out of the curing tank and inspected visually to make sure they did not have any surface cracks that could affect the results; after the inspection, only surface water was removed. The specimens remained in a Saturated Surface-Dry (SSD) condition until testing; the time between removal from the curing tank and testing did not exceed 30 minutes. The loading surfaces were also inspected to make sure that they were immaculate, flat and free of loose particles before placing each cylinder on center in the plate of the hydraulic compression testing equipment. Lastly, a continuous axial load was provided to each specimen at a rate of 0.25 MPa/s until characteristic failure due to crushing occurred, and the maximum load resisted by each specimen was recorded for compressive strength tests.

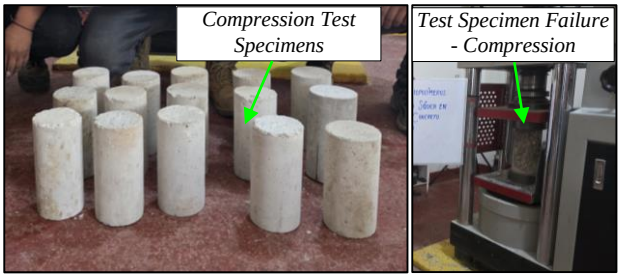


Fig. 15 Compressive Strength ASTM C39

3.4.2. Indirect Tensile Strength ASTM C496

The indirect tensile strength test which provides a measure of the tensile stress in concrete by applying a diametral compressive force to cylindrical specimens, described according to ASTM C496 [63, 64]. The specimens cured for 7-14-28 days (indicated in Figure 16) were subjected to a pre-conditioning performed in Superficially Dry (SSD) condition and positioned them horizontally between the platens of the test machine, in order to assure an uniform stress along the totality of the load bearing generatrices. After that, a static load was applied at the rate of 0.15 MPa/s until the characteristic longitudinal crack developed along the loaded diameter, and each specimen's maximum load was recorded.



Fig. 16 Indirect Tensile Strength ASTM C496

3.4.3. Rapid Chloride Penetration Test

ASTM C1202 test is used to establish a uniformized protocol for measuring chloride ion permeability in concrete, which serves as an informative parameter in assessing the ability of concrete to withstand penetration of chloride salts and hence corrosion susceptibility of embedded reinforcing steel [65, 66]. This classifies the resistance of the material to chloride penetration by means of placing it in an exposure category, which allows a comparison between the durability indices for all mixtures and evaluation of constructive design [67]. Such classification appears in Table 3.

Table 3. ASTM C1202 Test Classification [65]

Electric charge (Coulombs)	Chloride Permeability Classification
> 4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very Low
< 100	Negligible

The concept used for assessing chloride ion permeability by the electrical migration methodology designated in ASTM C1202, developed to determine concrete resistance to chloride penetration by means of a controlled electric potential gradient, is shown in Figure 17. The first was cylindrical concrete specimens 100 mm in diameter and 200 mm in height were cast with the additives under study for a mix design proportion and remained in molds for 24 hours, followed curing in water for 28 days to allow the correct evolution of the microstructural properties of the concrete (item (a)). So, as a second phase (figure (b)), they were use a diamond blade cutter for transversal cuts 50 mm thick discs and 100 mm diameter cylinders; dimensions and flatness of contact surfaces prior to testing are verified. Then, as described by (c), discs were left under vacuum at −90 kPa pressure, fully immersed in deionized water for 18 h, and samples were maintained during 1 h at atmospheric pressure to ensure complete saturation of internal porous network. For this, as shown in step (d), each disc was hermetically placed inside an ASTM C1202 cell; a solution of 0.3N NaCl in one compartment (anode) and a solution of 0.3 N NaOH in the other respectively connected at both ends via a direct current source. After that, a constant voltage of 60 V was applied to the cells for six hours; the electric current flowing through each cell was recorded at 30-minute intervals throughout this period. The recording of the electric current allowed for the calculation of the total amount of charge passed through each sample; this provided an indirect indication of the concrete's resistance to chloride ion penetration.

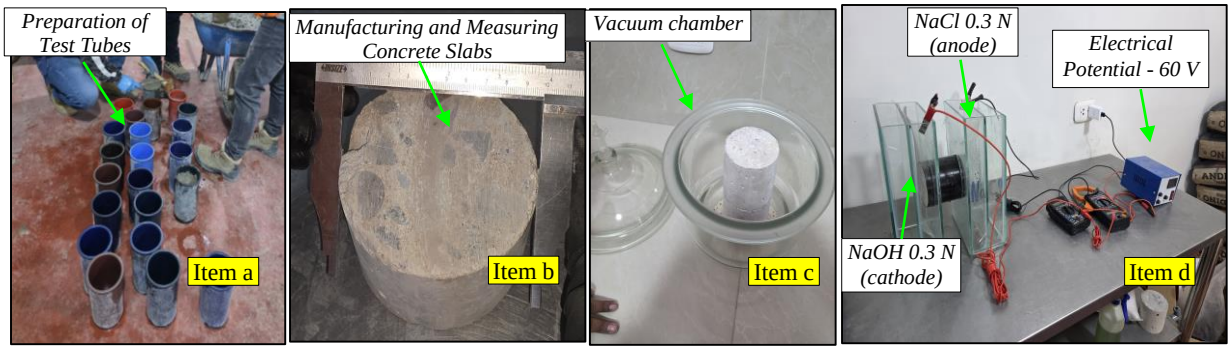


Fig. 17 ASTM C1202 Test Procedure

4. Results

4.1. Slump and Temperature Test

The investigation into workability was used to determine the effects of each additive on both the cohesion and mobility of fresh concrete; Table 4 presents the slump and temperature values obtained for each mixture design, which show differences in concrete behavior depending on the type of additive incorporated.

The control concrete also produced a 4 ¼" slump, characteristic of a mix with greater internal fluidity and less internal cohesion. The observed decrease of slump in these mixtures is a result of the formation of an extremely viscous colloidal network, as part of galactomannan, with increasing cohesiveness and consequently much less mobility in the mixture (the slump reducing slightly from 2 ¼" Gg_1 to 1 ¼" with Gg_5).

A direct comparison between the additions of gum arabic showed higher slump values, falling from 3 ½" to 2.5" between Ga_1 and Ga_5; this can be attributed to heavily branched polysaccharides causing lower-viscosity solutions with lower gelation capacity when comparing both types of gum used here with guar gum, respectively.

For instance, in sodium bentonite, the slump decreased from 3" Bs_1 to 1 ¾" that can be linked to montmorillonite's potential of dimming free water and raise the internal friction of cementitious set. Lastly, the sodium alginate was decreasing from 2 ½" As_1 to 1 ¼" As_5, a reduction explained by the production of gels with calcium-alginate that increased the surface cohesiveness and water retention capacity during alloying process. The temperature range of the concrete specimens was between 22.1 °C and 24.7 °C; there were no substantial alterations to the initial thermal equilibrium of the fresh concrete due to the addition of any of the materials.

Table 4. Slump and Temperature Test Results

Code	Slump (in)	Temperature (°C)
Standard	4 1/4"	24.2
Gg1	2 1/4"	22.4
Gg2	1 3/4"	22.9
Gg3	1 1/2"	22.7
Gg4	1 1/4"	23.3
Gg5	1 1/4"	22.8
Ga1	3 1/2"	22.1
Ga2	3 1/2"	22.5
Ga3	3 1/4"	22.3
Ga4	2 3/4"	22.7
Ga5	2 1/2"	22.4
Bs1	3"	23.5
Bs2	2 3/4"	23.9
Bs3	2 1/4"	24.4
Bs4	2"	24.1
Bs5	1 3/4"	24.7
As1	2 1/2"	22.6
As2	2 1/4"	22.9
As3	1 3/4"	23.4
As4	1 1/2"	23.1
As5	1 1/4"	23.7

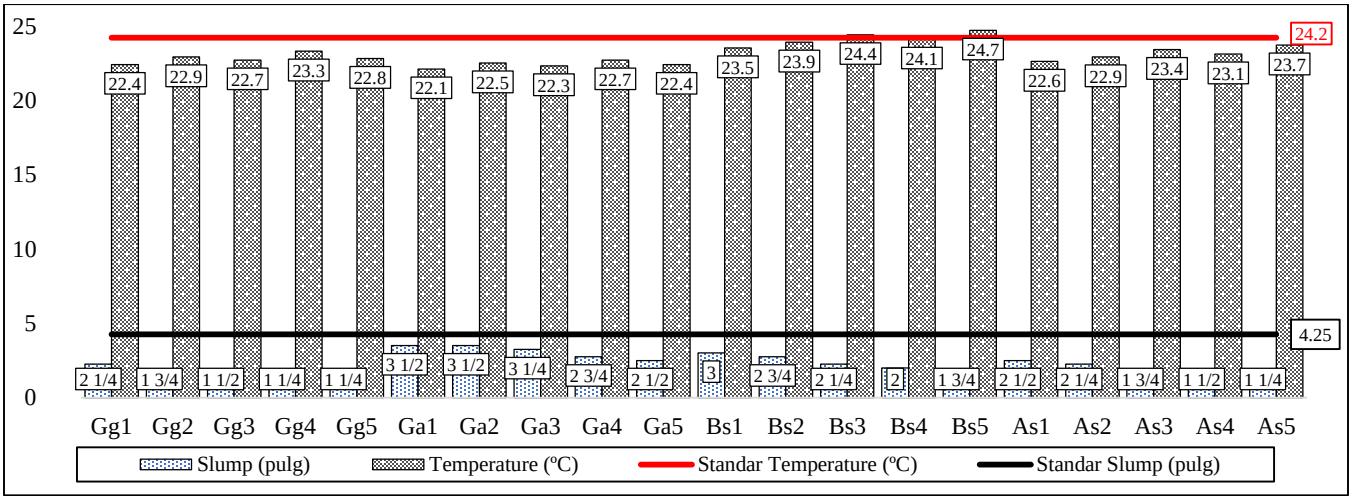


Fig. 18 Slump and Temperature Test Results

As seen in Figure 18, the percentage reductions in slump and variations in temperature were determined relative to the control mixture (0% additive) for each evaluated dosage. Guar gum produced a maximum slump reduction of 70.59% (Gg_4 and Gg_5), while the greatest temperature decrease was 7.44% (Gg_1). This behavior was consistent with the viscosity-enhancing properties of guar gum, which increased mixture cohesion and reduced mobility. In comparison to guar gum, gum arabic resulted in a smaller reduction in workability, which reflects the different rheological behaviors of the two

biopolymers; gum arabic reduced the slump by 41.18% (Ga5), and its maximum temperature drop was 8.68% (Ga1).

For sodium bentonite, the highest reduction in slump was 58.82% (Bs5), with temperature changes varying from a 2.89% decrease (Bs1) to a 2.07% increase (Bs5) relative to the control; the decrease in slump was related to the water uptake and swelling properties of montmorillonite particles.

Lastly, the maximum slump reduction of 70.59% (As5) was achieved with sodium alginate, and its maximum temperature reduction was 6.61% (As1); these results reflect its contribution to mixture cohesiveness through calcium-alginate interactions.

All four additives decreased the level of slump to different extents, but the temperature variations were smaller than the corresponding changes in workability.

4.2. Immersion Test

The test evaluated how well fresh concrete can resist washing out when immersed, providing an assessment of how effectively each additive can retain fine particles and limit cement disintegration. For each mix, as indicated in Table 5, the percentage of material lost was measured to assess the resistance of the mixtures to being washed out. The control concrete lost 13.6% of the material; this reflected its limited cohesion and susceptibility to hydraulic action during immersion, causing the cementitious particles and fine aggregates to separate from one another.

For guar gum, increasing dosages typically resulted in less material being lost due to improved cohesion resulting from the hydration of galactomannans. The Gg1 mixture lost 3.6%, representing a 73.53% decrease in material loss compared to the control mixture; material loss continued to decrease with Gg2 (2.4%) and Gg3 (1.6%) before reaching a minimum level of 0.8% with Gg4. With Gg5, which had the highest dosage, material loss increased slightly to 1.2%; this indicated that Gg4 had the highest level of washout resistance among all the guar gum mixtures evaluated.

With increasing doses of gum arabic, material loss decreased from 8.0% (Ga1) to 6.8% (Ga2) and 4.8% (Ga3); after reaching its lowest point, material loss increased to 5.2% and 5.6% for Ga4 and Ga5, respectively. Thus, Ga3 was identified as the most effective dosage of gum arabic for maintaining mixture stability during immersion.

The sodium bentonite mixture Bs1 showed a material loss of 7.2%; however, when the Bs2 dosage was used, material loss was reduced to 5.2%. This was the lowest material loss found in the sodium bentonite series. Material losses then began to increase with each subsequent dosage: 6.0% (Bs3), 6.8% (Bs4), and 7.6% (Bs5). Therefore, as the bentonite content increased from Bs2 to Bs5, the mixture became less resistant to washing out; the Bs2 formulation was the most effective among the sodium bentonite mixtures tested. Conversely, the Bs5 formulation had the greatest material loss, showing that adding more bentonite did not continuously improve mixture stability during immersion.

For sodium alginate, material loss was reduced from 4.4% (As1) to 4.0% (As2), 3.2% (As3), and 2.0% (As4); then, material loss increased to 2.8% (As5). The results indicate that As4 represents the most effective dosage among the sodium alginate mixtures tested; these findings reflect the favorable contribution of the biopolymer to mixture cohesion and resistance to material separation during immersion.

Table 5. Immersion Test Results

Code	Mi (Kg)	Mf (Kg)	D (%)
Standard	2.50	2.16	13.6
Gg_1	2.50	2.41	3.6
Gg_2	2.50	2.44	2.4
Gg_3	2.50	2.46	1.6
Gg_4	2.50	2.48	0.8
Gg5	2.50	2.47	1.2
Ga1	2.50	2.30	8.0
Ga2	2.50	2.33	6.8
Ga3	2.50	2.38	4.8
Ga4	2.50	2.37	5.2
Ga5	2.50	2.36	5.6
Bs_1	2.5	2.32	7.2
Bs_2	2.5	2.37	5.2
Bs_3	2.5	2.35	6
Bs_4	2.5	2.33	6.8
Bs_5	2.5	2.31	7.6
As1	2.50	2.39	4.4
As2	2.50	2.40	4.0
As3	2.50	2.42	3.2
As4	2.50	2.45	2.0
As5	2.50	2.43	2.8

The use of graphs allowed us to quantitatively compare the effects of different additives on the amount of washout loss in comparison to a standard concrete mix. As shown in Figure 19, the percentage washout loss was recorded for each of the formulations tested; this enabled us to determine how much each additive reduced washout loss compared to the control mix and to identify the most effective dosage for each additive.

The reductions in washout loss with the addition of guar gum were progressively greater as the amount added increased (up to Gg_4) and were especially evident: Gg_1 reduced the loss by 73.5%; Gg_2 by 82.4%; Gg_3 by 88.2%; Gg_4 by 94.1%; and Gg_5 by 91.2%. The formulation with the highest reduction was

Gg_4; this was consistent with the contribution of the polysaccharide to the overall cohesion and washout resistance of the mixture.

Fo For gum arabic, there was a moderate reduction in losses: Ga_1 decreased losses by 41.2%, Ga_2 by 50.0%, Ga_3 by 64.7%, Ga_4 by 61.8%, and Ga_5 by 58.8%; Ga_3 had the greatest effect on reducing losses, which was consistent with its balance between colloidal viscosity and hydraulic stability.

Sodium bentonite showed varying degrees of improvement, with reductions ranging from moderate to high: Bs_1 decreased the loss by 47.1%; Bs_2 decreased the loss by 61.8%; Bs_3 decreased the loss by 55.9%; Bs_4 decreased the loss by 50.0%; and Bs_5 decreased the loss by 44.1%. Among all evaluated bentonite mixtures, Bs_2 had the highest percentage of improvement, whereas Bs_5 had the lowest. The results showed that Bs_2 was the best-performing bentonite mixture for reducing washout loss; increasing the bentonite dosage beyond Bs_2 progressively reduced its effectiveness.

Finally, for the sodium alginate treatment, all formulations were able to produce pronounced decreases in the amount of washout loss as well. The percentage reduction in loss produced by As_1 was 67.6%; As_2 produced a 70.6% reduction in loss; As_3 produced a 76.5% reduction in loss; As_4 produced an 85.3% reduction in loss; and As_5 produced a 79.4% reduction in loss. Within the group of treatments using sodium alginate, the formulation that was found to be the most effective at reducing loss was As_4; this was consistent with the contribution of calcium alginate gel formation to the cohesion of the mixtures.

Overall, the study identified four formulations that provided the greatest level of resistance to washing when compared to other formulations within each of their respective additive groups. These formulations were Gg_4, As_4, Ga_3, and Bs_2. Of these four formulations, Gg_4 had the highest level of efficiency in terms of providing protection against washing; Gg_4 achieved a 94.1% decrease in the amount of lost material relative to the standard concrete control sample.

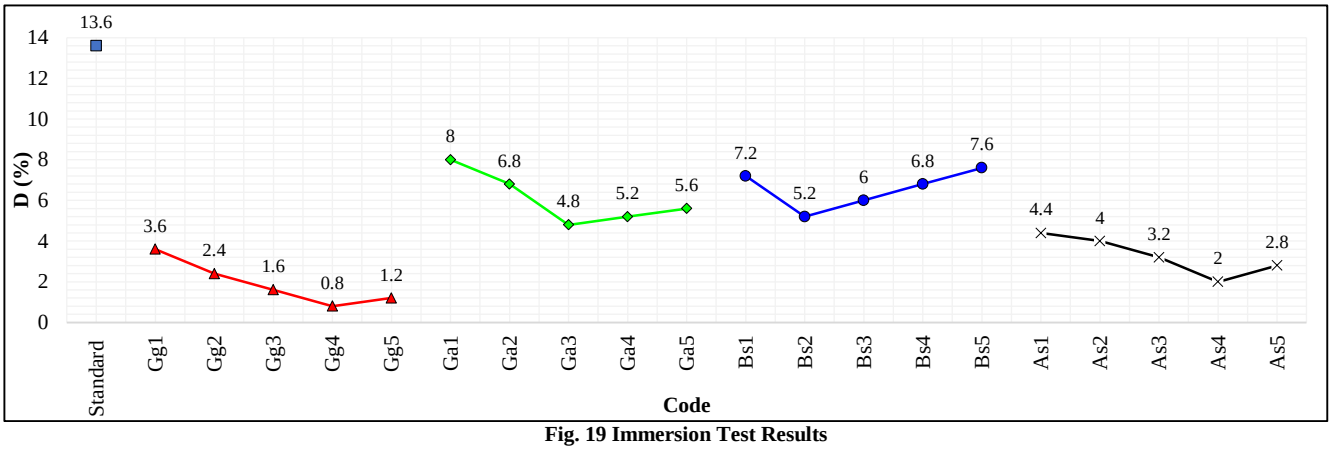


Fig. 19 Immersion Test Results

4.3. PH Measurement

A pH test was utilized to evaluate the release of alkaline substances into water when it came into contact with fresh concrete; this provided an indirect indication of cementitious material leaching and mixture stability. The measured pH values indicated differences in both the chemical nature and rheological behavior of each additive, as shown in Table 6.

The maximum alkalinity was obtained for the control concrete (pH = 12.71), due to the intensive liberation of hydroxyl ions (OH^-) caused by hydration process of Portland cement, showing a high level of disintegration and larger initial leaching of its components. The progressive decrease in values for the mixtures with guar gum was as follows: Gg_1 (8.93), Gg_2 (8.44), Gg_3 (7.88), Gg_4 (7.11) and Gg_5 (7.57). These decreases were as a result of galactomannan, which produced a gelled community that entrapped cementitious particles and reduced the leaching of hydroxides to restricting environments the discharge of alkalinity. The lowest Gg_4 value seen was due to the lower concentration of added polymer that is efficient at immobilizing SO_3 with initial products of hydration.

Thus, values of gum arabic were in between Ga_1 (10.91), Ga_2 (10.41), Ga_3 (9.13), Ga_4 (9.47) and Ga_5 (9.98), respectively. The reduction relative to the control standard was a result of the formation of a colloidal film surrounding the particles that reduced the release rate of $Ca(OH)_2$ partially, but not mainly establishing a structure as compacted as agar; since gum arabic has lower gelling power respect to guar gum.

As for sodium bentonite mixtures, values were obtained from Bs_1 (10.28), Bs_2 (9.94), Bs_3 (10.63), Bs_4 (10.87) and Bs_5 (11.42). Although bentonite reduced the pH relative to control (due to cation adsorption and its ion-exchange capacity), at high doses, for example, from Bs_4-Bs_5, a progressive increase in pH is observed because this expansive clay releases sodium (Na^+) into the medium, increasing the concentration of

alkaline species in solution. In sodium alginate, the pH linearly decreased from As_1 (9.57) to As_2 (9.18), As_3 (8.79), and As_4 (7.93), while a modest increase was observed at the last concentration (As_5; 8.31). This trend was explained by (i) the formation of calcium-alginate gel that caused immobilization of cementitious particles and thus reduction of hydroxide dissolution, which strongly decreased de alkalinity released into aqueous medium.

Table 6. PH Measurement Results

Code	PH
Standard	**12.71**
Gg_1	8.93
Gg_2	8.44
Gg_3	7.88
Gg_4	7.11
Gg_5	7.57
Ga_1	10.91
Ga_2	10.41
Ga_3	9.13
Ga_4	9.47
Ga_5	9.98
Bs_1	10.28
Bs_2	9.94
Bs_3	10.63
Bs_4	10.87
Bs_5	11.42
As_1	9.57
As_2	9.18
As_3	8.79
As_4	7.93
As_5	8.31

The graph (Figure 20) represents the effect of every additive in a percentage on standard concrete, as it is clearly seen that each individual additive has distinct dosage and type, which each influence the percentages differently. For Gg_1, the reduction was a minimum of 29.7% pH, and for Gg_4 it was a maximum of 44.1% pH, which meant that the polymer content in the system was sensitive to very moderate increases in the system (Gg_4). In terms of gum arabic, the reductions experienced were much more moderate and fluctuated between 14.2% in Ga_1 and 28.2% in Ga_3; therefore, gum arabic performed at a moderate level of effectiveness across the three grades tested, with limited variation in its performance among them. For sodium bentonite, the reduction percentages were confined within a smaller range of effects (from 10.1% in Bs_5 to 21.8% in Bs_2); this indicated a dispersion-related and concentration-dependent effect of the clay on the mixture. Lastly, the percentage reduction with sodium alginate increased from 24.7% at As_1 to 37.6% at As_4 as the dosage increased; thus, the results indicated a clear, gradual improvement in the effectiveness of the treatment.

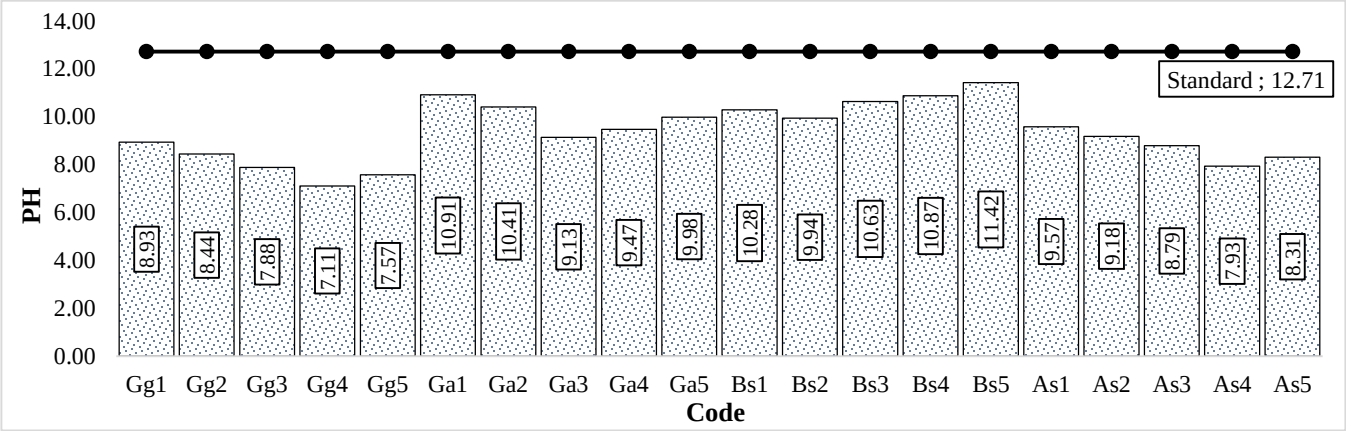


Fig. 20 PH Measurement Results

4.4. Setting Time Test - Concrete

Table 7 provides both the initial and final setting times for each of the concrete mixtures studied in this work; these values allow for a clearer assessment of the specific effects that each combination of agents has on the cement hydration process. The control concrete had an initial setting time of 156 minutes; during normal hydration, calcium ions (Ca^{2+}) are gradually released, eventually leading to the formation of calcium silicate hydrate (C-S-H) gel. The final setting time for the control concrete was 187 minutes; this indicates continued development of the cement paste without external rheological modification.

Under the influence of guar gum (Gg4), the initial setting time was 38 min, substantially shorter than that of control due to the polysaccharide absorption of some mixing water and creation of a viscous colloidal matrix enhancing early nucleation of hydrated products its final setting time was 97 min, demonstrating that this gelled structure also caused the paste to accelerate in final consolidation.

For gum arabic, the Ga3 dosage reported an initial setting time of 101 min, a moderately significant variation substantiated by the formation of hydrocolloid films around cement particles regulating water availability but not interfering with hydration; for final setting times, Ga3 recorded 147 min, corroborating how this additive shortened hardening time while maintaining very similar kinetics compared to the control.

Regarding sodium bentonite, there were very small differences between the setting times of the Bs_2 mixture (149 minutes for initial setting time and 184 minutes for final setting time) and those of the control concrete (156 minutes for initial setting time and 187 minutes for final setting time); this indicated only minor changes in setting behavior.

Regarding sodium alginate, the As_4 mixture had a lower initial setting time (63 minutes) and final setting time (113 minutes); this reduction was consistent with the formation of calcium-alginate gels.

These gels developed through the interaction of the carboxylate groups on the biopolymer with Ca^{2+} ions released during cement hydration; this promoted earlier development of cohesion within the cementitious matrix.

Table 7. Initial and Final Setting Time Results (ASTM C403/C403M)

Code	Initial Setting (min)	Final Setting (min)
Standard	156	187
Gg_1	78	142
Gg_2	61	128
Gg_3	49	112
Gg_4	38	97
Gg_5	41	101
Ga_1	132	175
Ga_2	124	168
Ga_3	101	147
Ga_4	109	152
Ga_5	117	159
Bs_1	155	193
Bs_2	149	184
Bs_3	153	186
Bs_4	157	191
Bs_5	161	195
As_1	96	152
As_2	84	132
As_3	72	125
As_4	63	113
As_5	67	118

Individual trends demonstrated that setting times decreased as the dosage approached its most effective level, after which they began to rise again; the decrease in setting time was less pronounced with the use of sodium bentonite.

The results for guar gum demonstrated that it reduced the initial setting time by 50.0% for Gg_1, 60.9% for Gg_2, and 68.6% for Gg_3; the greatest reduction was 75.6% for Gg_4, followed by a slightly lower reduction of 73.7% for Gg_5. This latter finding further supports the trend of decreasing setting times to a minimum before increasing again, as observed in the data.

The reduction sequences were comparable for gum arabic: 15.4% for Ga_1, 20.5% for Ga_2, and 35.3% for Ga_3; Ga_3 had the shortest setting time. As dosage increased further, the reductions decreased to 30.1% for Ga_4 and 25.0% for Ga_5; these followed a similar trend after reaching the most effective dosage.

Regarding sodium bentonite, the highest reduction was observed in Bs_2 (4.5%), with a smaller reduction of 0.6% for Bs_1; subsequently, the reduction decreased to 1.9% for Bs_3, while Bs_4 and Bs_5 increased the initial setting time by 0.6% and 3.2%, respectively. These results showed that this additive had very little effect on setting times when compared to the other materials.

With sodium alginate, the reductions were 38.5% (As_1), 46.2% (As_2), and 53.8% (As_3), reaching the greatest reduction at As_4 (59.6%), while As_5 showed a slightly lower reduction of 57.1%, repeating the same trend after the optimal dose was reached.

For final setting, a similar pattern was also seen. The setting times were decreased by 24.1%, 31.6%, and 40.1% for Gg_1, Gg_2, and Gg_3, respectively, reaching the lowest setting time at Gg_4 (48.1% reduction), followed by a smaller reduction at Gg_5 (46.0%).

Gum arabic's highest reduction was observed in Ga_3 with 21.4%; however, Ga_4 and Ga_5 had lower reductions of 18.7% and 15.0%, respectively. Bentonite's largest reduction was found in Bs_2 (1.6%), followed by Bs_3 (0.5%); in contrast, Bs_1, Bs_4, and Bs_5 caused increases in the final setting time of 3.2%, 2.1%, and 4.3%, respectively.

The findings of this study showed that sodium bentonite caused only minor changes in setting times when compared to the other additives tested.

The reduction values for sodium alginate were greatest at As_4 (39.6%), followed by a lower reduction at As_5 (36.9%); this was similar to the pattern observed in the initial setting time tests.

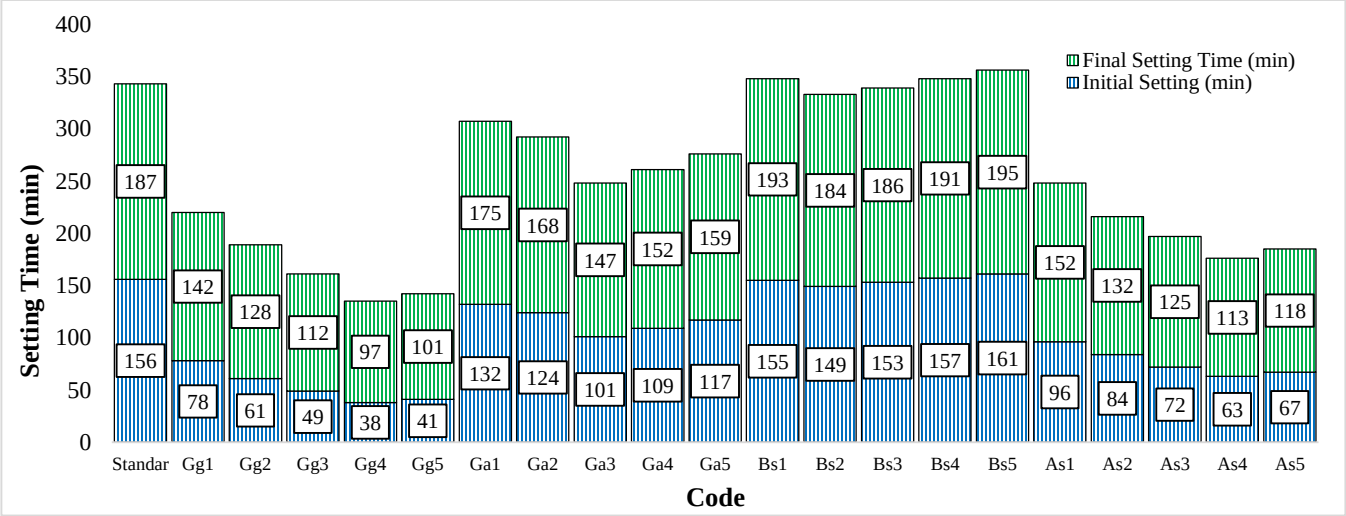


Fig. 21 Initial and Final Setting Time Results (ASTM C403/C403M)

4.5. Compressive Strength ASTM C39

The compressive strength results for 7, 14, and 28 days are shown in Table 8; these results indicate that the mechanical performance varies depending upon the type of additive used as well as its concentration in the concrete mixture. At 7, 14, and 28 days, the control mixture achieved compressive strengths of 232.47 kg/cm², 338.72 kg/cm², and 364.56 kg/cm², respectively; these values served as a basis for assessing how each additive affects compressive strength.

All of the mixtures that included guar gum at seven days had higher strength than the control, and their strengths ranged from 244.83 to 287.53 kg/cm², with Gg_4 having the greatest amount of strength (287.53 kg/cm²). The use of sodium alginate was also effective in increasing the strength of the samples. Sodium alginate resulted in strength ranges from 218.23 to 276.17 kg/cm²; however, As_1 did not exceed the control, and As_4 was able to reach the maximum strength of 276.17 kg/cm².

When using gum arabic, both Ga_1 and Ga_2 produced lower strengths than the control (202.60 and 214.92 kg/cm²), while Ga_3 and Ga_4 both produced greater strengths than the control (256.48 and 246.77 kg/cm², respectively). On the other hand, the addition of sodium bentonite produced very little improvement in strength. The only mixture containing sodium bentonite that produced greater strength than the control was Bs_2 (241.72 kg/cm²).

The compressive strength of each mixture at 14 days was greater than its compressive strength at 7 days. Compressive strength of concrete mixed with guar gum varied from 351.19 kg/cm² to 395.86 kg/cm²; Gg_4 reached the highest compressive strength of 395.86 kg/cm². Sodium alginate mixtures had compressive strengths varying from 328.47 kg/cm² to 369.78 kg/cm²; once again, As_4 reached the highest compressive strength of 369.78 kg/cm². However, As_1 did not exceed the control compressive strength. Gum arabic mixtures only exceeded the control compressive strength of 338.72 kg/cm² with Ga_3 (352.28 kg/cm²) and Ga_4 (345.93 kg/cm²); this indicated that intermediate levels of dosage produced the most favorable results regarding mechanical properties. Similarly, Bs_2 was the only sodium bentonite mixture to exceed the control compressive strength of 338.72 kg/cm², obtaining a compressive strength of 345.54 kg/cm²; all other sodium bentonite mixtures produced compressive strengths lower than the control.

At 28 days, every mixture continued to experience an increase in compressive strength. Guar gum had a range of compressive strengths from 381.37 to 424.68 kg/cm²; the Gg_4 mixture had the highest compressive strength at 424.68 kg/cm². Sodium alginate also showed notable improvements in compressive strength, with values ranging from 354.18 to 411.39 kg/cm²; the As_4 mixture had the highest compressive strength at 411.39 kg/cm².

However, the As_1 mixture had a lower compressive strength than the control mixture. Only the Ga_3 (378.57 kg/cm²) and Ga_4 (372.13 kg/cm²) gum arabic mixtures were able to exceed the control mixture's compressive strength of 364.56 kg/cm²; all other gum arabic mixtures (Ga_1, Ga_2, and Ga_5) had lower compressive strengths than the control mixture. Only the Bs_2 (372.18 kg/cm²) sodium bentonite mixture exceeded the compressive strength of the control mixture; all other sodium bentonite mixtures had lower compressive strengths than the control.

Overall, the results showed that guar gum at 0.60% (Gg_4) had the highest compressive strength of all the mixtures tested; the next highest was sodium alginate at 2.50% (As_4). Gum arabic and sodium bentonite produced smaller increases in compressive strength than either guar gum or sodium alginate; the most effective concentrations were 0.50% (Ga_3) for gum arabic and 15% (Bs_2) for sodium bentonite.

Table 8. Compressive Strength Results

Code	F'c (kg/cm^2) - 7 days	F'c (kg/cm^2) - 14 days	F'c (kg/cm^2) - 28 days
Standard	232.47	338.72	364.56
Gg_1	244.83	351.19	381.37
Gg_2	262.58	363.86	396.74
Gg_3	265.37	378.18	407.62
Gg_4	287.53	395.86	424.68
Gg_5	276.92	387.41	412.23
Ga_1	202.60	304.17	345.34
Ga_2	214.92	312.63	353.42
Ga_3	256.48	352.28	378.57
Ga_4	246.77	345.93	372.13
Ga_5	223.38	326.47	359.89
Bs_1	216.37	319.81	351.26
Bs_2	241.72	345.54	372.18
Bs_3	221.74	328.97	359.93
Bs_4	208.46	309.71	341.78
Bs_5	198.91	301.13	334.37
As_1	218.23	328.47	354.18
As_2	239.68	345.39	374.47
As_3	251.83	352.82	384.74
As_4	276.17	369.78	411.39
As_5	266.41	359.59	398.83

In order to evaluate the effects of the different additives on mechanical strength development, the percentage change in 28-day strength relative to the reference mixture is plotted in Figure 22; this provides an opportunity to compare how well each additive performed at the age when the highest measured strengths were obtained.

The guar gum series shows that there were increases in strength for the mixtures Gg_1, Gg_2, Gg_3, Gg_4, and Gg_5 (4.61%, 8.83%, 11.81%, 16.49%, and 13.08%, respectively); these increases were progressive up to Gg_4, after which a lower relative increase was observed in Gg_5.

For gum arabic, Ga1 and Ga2 decreased by 5.27% and 3.06%, while Ga3 and Ga4 increased by 3.84% and 2.08%; the Ga5 mixture also decreased by 1.28%, indicating that only the intermediate dosages outperformed the control. For sodium bentonite, Bs1, Bs3, Bs4, and Bs5 decreased by 3.65%, 1.27%, 6.25%, and 8.28%, respectively, while Bs2 increased its strength by 2.09%, making it the only mixture to outperform the control.

For sodium alginate, As_1 showed a decrease of 2.85%; whereas As_2, As_3, As_4, and As_5 showed increases of 2.72%, 5.54%, 12.85%, and 9.40%, respectively. These results show that the effect of sodium alginate improved progressively until As_4 was reached and then diminished at As_5. Therefore, as shown in the figure, the additives exhibited increasing improvements up to their most effective dosages; however, once the amount of additive used exceeded these levels, there was a decline in their effectiveness.

The highest percentages of increase observed were for Gg_4 (16.49%), Ga_3 (3.84%), Bs_2 (2.09%), and As_4 (12.85%); these dosages were considered the most effective for each additive at 28 days.

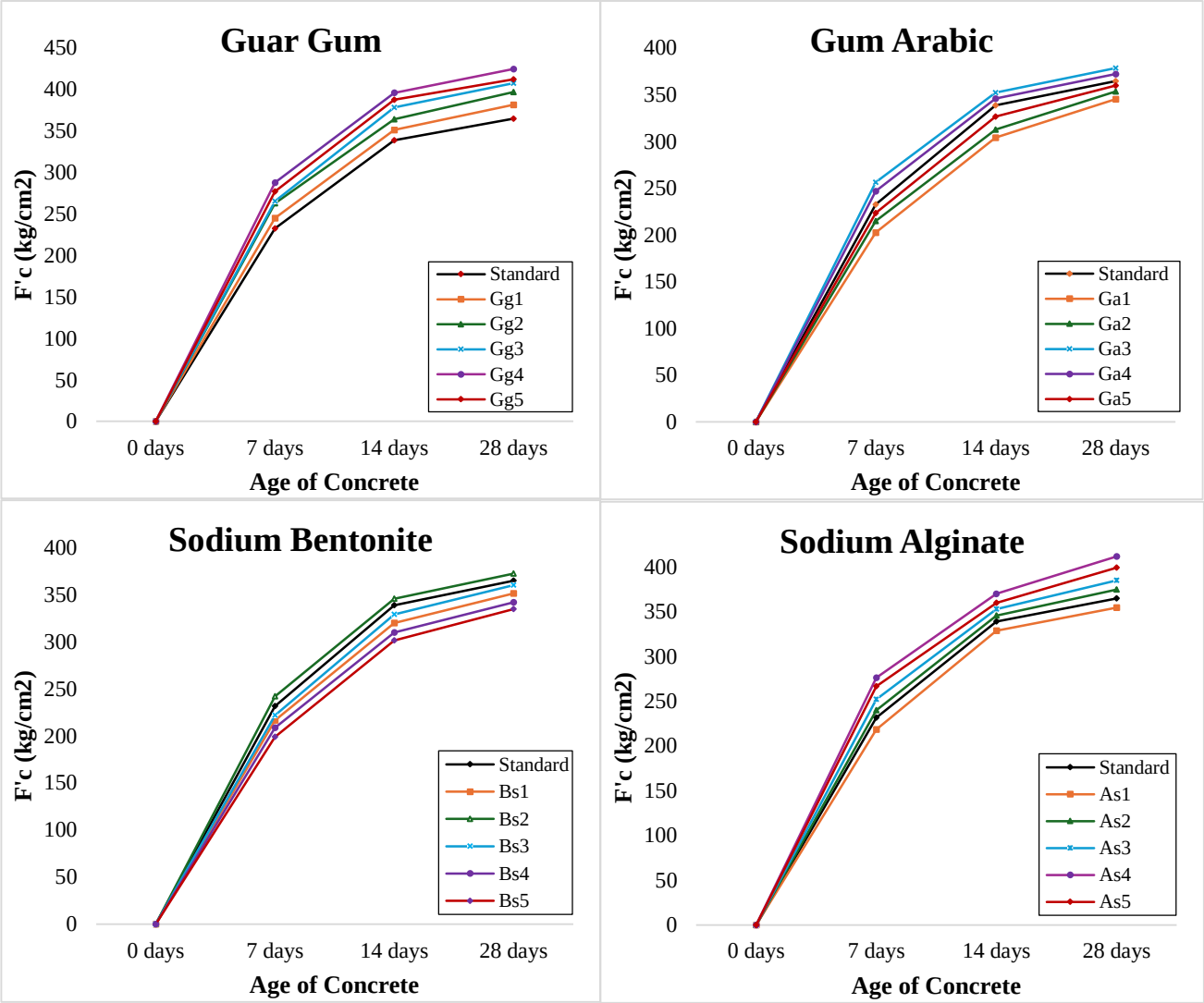


Fig. 22 Development of compressive strength with concrete age

4.6. Indirect Tensile Strength ASTM C496

The development of indirect tensile strength (Fct) is shown in Table 9 for 7, 14, and 28 days; the variation in results reflects the different additives used in the concrete mixtures as well as their dosages. On the seventh day, the control concrete had an indirect tensile strength of 26.27 kg/cm². The concrete mixtures that included guar gum showed higher indirect tensile strength values than the control, ranging between 27.47 and 31.07 kg/cm²; Gg_4 had the highest indirect tensile strength. For gum arabic, Ga_1, Ga_2, and Ga_5 had lower values than the control; however, Ga_3 and Ga_4 reached 28.35 and 27.21 kg/cm², respectively.

On the other hand, Bs_2 was the only sodium bentonite mixture that exceeded the control, reaching 27.12 kg/cm²; the other four dosages exhibited lower strengths, varying between 23.79 and 25.72 kg/cm². Sodium alginate also increased the strength of every mixture except As_1 (26.15 kg/cm²); the remaining mixtures had strengths between 27.79 and 30.37 kg/cm², with the greatest strength exhibited by As_4.

The control reached 31.91 kg/cm² at 14 days, with guar gum mixtures showing higher strengths between 32.83 and 36.41 kg/cm²; Gg_4 remained the best-performing dosage. The gum arabic mixtures Ga_3 and Ga_4 both exceeded the control, reaching 33.94 and 32.85 kg/cm², respectively; the other mixtures, Ga_1, Ga_2, and Ga_5, had lower strengths. Out of all the sodium bentonite mixtures, only Bs_2 exceeded the control, achieving a strength of 32.45 kg/cm²; the other mixtures produced lower strengths. All sodium alginate mixtures exceeded the control, with strengths ranging from 32.06 to 35.28 kg/cm²; As_4 achieved the maximum value.

At 28 days, the indirect tensile strength of the control concrete was 33.14 kg/cm²; however, the mixtures containing guar gum had higher strengths ranging from 34.38 to 37.62

kg/cm², with Gg_4 producing the greatest indirect tensile strength. Gum arabic mixtures had strengths ranging from 31.19 to 34.89 kg/cm²; Ga_3 and Ga_4 both exceeded the control concrete, and Ga_3 provided the highest level of performance within this group. Among sodium bentonite mixtures, only Bs_2 exceeded the control concrete, reaching 33.92 kg/cm²; all other dosages produced lower indirect tensile strengths than the control, with Bs_3 reaching 32.81 kg/cm² and Bs_5 producing the lowest strength at 30.35 kg/cm². All sodium alginate mixtures produced indirect tensile strengths higher than the control concrete; the strengths ranged from 33.35 to 36.83 kg/cm², and As_4 produced the greatest value.

Table 9. Indirect Tensile Strength Results (Fct)

Code	Fct (kg/cm²) - 7 days	Fct (kg/cm²) - 14 days	Fct (kg/cm²) - 28 days
Standard	26.27	31.91	33.14
Gg_1	27.47	32.83	34.38
Gg_2	28.46	33.79	35.27
Gg_3	29.31	34.59	35.82
Gg_4	31.07	36.41	37.62
Gg_5	29.97	35.26	36.76
Ga_1	24.25	30.11	31.19
Ga_2	25.21	30.67	31.83
Ga_3	28.35	33.94	34.89
Ga_4	27.21	32.85	33.92
Ga5	25.69	31.32	32.41
Bs1	25.02	30.81	32.22
Bs2	27.12	32.45	33.92
Bs3	25.72	31.33	32.81
Bs4	24.51	29.97	31.34
Bs5	23.79	28.82	30.35
As_1	26.15	32.06	33.35
As_2	27.79	33.55	35.03
As_3	28.79	34.07	35.72
As_4	30.37	35.28	36.83
As_5	29.56	34.67	36.22

Figure 23 shows the percentage change in indirect tensile strength at 28 days compared to the control concrete mix; this allows a quantitative comparison of the improvements in mechanical performance achieved with different additives.

The guar gum series (mixtures Gg_1–Gg_5) improved indirect tensile strength by 3.74%, 6.43%, 8.09%, 13.52%, and 10.92%, respectively. The improvement in indirect tensile strength was progressively greater with each mixture from Gg_1 through Gg_4; however, there was a slight decrease in indirect tensile strength with mixture Gg_5 compared to Gg_4. This indicates that adding more guar gum beyond the most effective dosage did not further increase indirect tensile strength.

With respect to gum arabic, mixtures Ga_1 and Ga_2 demonstrated reductions in indirect tensile strength of 5.88% and 3.95%, respectively; however, mixtures Ga_3 and Ga_4 demonstrated increases in indirect tensile strength of 5.28% and 2.35%. On the other hand, mixture Ga_5 demonstrated a reduction in indirect tensile strength of 2.20%. Therefore, the results indicate that the most favorable mechanical performance with respect to indirect tensile strength for this particular group occurred at an intermediate dosage level.

With regard to sodium bentonite, Bs_1 had a decrease of 2.78%; in contrast, Bs_2 increased the indirect tensile strength by 2.35%. At higher dosages, Bs_3, Bs_4, and Bs_5 showed reductions of 1.00%, 5.43%, and 8.42%, respectively. This showed that the improvement found with Bs_2 was not maintained at higher bentonite concentrations; instead, the mixtures exhibited progressively greater reductions in indirect tensile strength.

For sodium alginate, As_1 increased strength by 0.63%, while As_2, As_3, As_4, and As_5 produced improvements of 5.70%, 7.79%, 11.13%, and 9.29%, respectively. The progressive increase up to As_4, followed by a reduction at As_5, demonstrated that the beneficial effect of sodium alginate depended on the incorporated dosage.

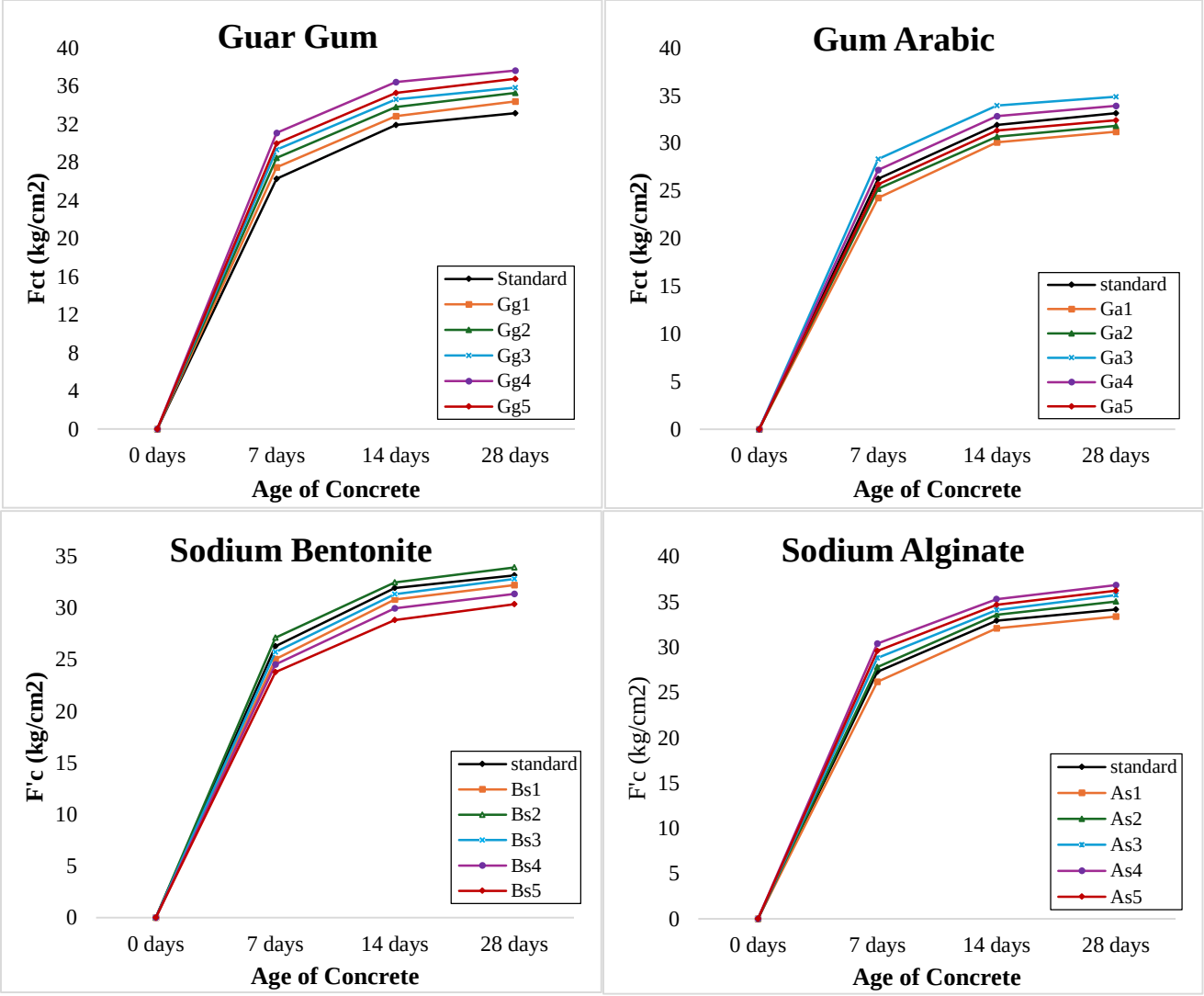


Fig. 23 Indirect tensile strength test results (ASTM C496)

4.7. Rapid Chloride Penetration Test

The data for the amount of charge transferred as per ASTM C1202, along with the resulting classification of chloride ion penetrability, are provided in Table 10. The control concrete had a charge of 3160 coulombs; this was in the "moderate" category for chloride ion penetrability and represented a higher electrical reading than those of the modified concrete mixtures.

The mixtures containing guar gum (Gg_1–Gg_5) showed substantially lower electrical charges; the charge decreased from 885 coulombs with Gg_1 to 497 coulombs with Gg_4, then increased slightly to 553 coulombs with Gg_5. All of the mixtures were in the "very low" chloride ion penetrability category, which indicates that the use of guar gum was effective at decreasing the electrical charge that passed through the concrete. Gg_4 had the lowest electrical charge out of all the mixtures tested; because of this, it was considered the most effective formulation within the evaluated range.

The charges for gum arabic (Ga_1–Ga_5) were recorded as being in the range of 1043–1485 coulombs; these values were classified as having "low" chloride ion penetrability. While all five charges were lower than the charge of the control, they did not show the same level of reduction as the charges of the guar gum mixtures. Ga_3 had the lowest charge of 1043 coulombs; higher charges were observed in Ga_4 at 1158 coulombs and Ga_5 at 1226 coulombs. These findings indicate that intermediate doses provided the greatest improvement in terms of reducing the electrical charge transferred through the concrete.

The amount of charge transferred through sodium bentonite mixtures (Bs_1–Bs_5) was recorded as 1942 and 1876 coulombs for Bs_1 and Bs_2, respectively; these values fell under the "low" chloride ion penetrability category. On the other hand, the charges recorded for Bs_3, Bs_4, and Bs_5 increased progressively to 2274, 2531, and 2698 coulombs, respectively; these values fell into the "moderate" chloride ion

penetrability category. This indicates that Bs_2 produced the lowest amount of transferred charge in comparison to all other sodium bentonite mixtures tested; increasing the bentonite dosage beyond Bs_2 progressively decreased its effectiveness.

Finally, the sodium alginate formulations (As_1–As_5) exhibited a decrease in charge from 975 coulombs in As_1 to 589 coulombs in As_4, followed by a slight increase to 645 coulombs in As_5; all formulations were classified as having very low chloride ion penetrability, confirming the substantial reduction in electrical charge achieved with the addition of sodium alginate.

Table 10. ASTM C1202 Transferred Load Results

Code	Load (Coulombs)	ASTM C1202 Classification
Standard	3160	Moderate
Gg_1	885	Very Low
Gg_2	742	Very Low
Gg_3	611	Very Low
Gg_4	497	Very Low
Gg_5	553	Very Low
Ga_1	1485	Low
Ga_2	1342	Low
Ga_3	1043	Low
Ga_4	1158	Low
Ga_5	1226	Low
Bs_1	1942	Low
Bs_2	1876	Low
Bs_3	2274	Moderate
Bs_4	2531	Moderate
Bs_5	2698	Moderate
As_1	975	Very Low
As_2	832	Very Low
As_3	703	Very Low
As_4	589	Very Low
As_5	645	Very Low

Figure 24 shows the transferred charge values of each mixture, from which the percentage reduction compared to the reference concrete was determined; in addition, these values allowed the relative effectiveness of the studied admixtures to be assessed.

The guar gum series contained five different mixtures (Gg_1, Gg_2, Gg_3, Gg_4, and Gg_5), which lowered the transferred charge by 71.99%, 76.52%, 80.66%, 84.27%, and 82.50%, respectively. The percentage reduction in transferred charge increased progressively up to Gg_4 and then decreased slightly with Gg_5; therefore, it was evident that adding more guar gum beyond the most effective dosage did not provide any additional benefit in reducing the transferred charge.

For gum arabic, the reductions in transferred charge for Ga_1, Ga_2, Ga_3, Ga_4, and Ga_5 were 53.01%, 57.53%, 66.99%, 63.35%, and 61.20%, respectively. Ga_3 had the highest reduction in transferred charge, while Ga_4 and Ga_5 had lower reductions; these findings showed that increasing the additive content beyond the intermediate dosage reduced its effectiveness.

The mixtures containing sodium bentonite (Bs_1, Bs_2, Bs_3, Bs_4, and Bs_5) lowered the amount of charge transferred through the concrete by 38.54%, 40.63%, 28.04%, 19.91%, and 14.62%, respectively.

Out of all these mixtures, Bs_2 had the highest percentage reduction; however, increasing the sodium bentonite dosage beyond Bs_2 resulted in progressively smaller reductions in transferred charge. This showed that higher bentonite concentrations reduced its effectiveness in limiting electrical charge passage through the concrete.

For sodium alginate, the mixtures As_1, As_2, As_3, As_4, and As_5 showed reductions in transferred charge of 69.15%, 73.67%, 77.75%, 81.36%, and 79.59%, respectively. These percentages represent the gradual increase in reduction up to As_4, after which the percentage dropped slightly for As_5; this decrease in effectiveness reflects the influence of additive dosage on the electrical indication of resistance to chloride ion penetration.

The best-performing formulations were then compared, and the greatest decrease in transferred charge was achieved by Gg_4 (84.27%), followed by As_4 (81.36%), Ga_3 (66.99%), and Bs_2 (40.63%). Gg_4 achieved greater reductions in transferred charge than these other formulations; the differences were 2.91, 17.28, and 43.64 percentage points, respectively.

Guar gum was found to be the most effective additive tested, followed by sodium alginate; gum arabic and sodium bentonite were comparatively less effective in reducing the electrical charge transferred through the concrete.

All additives showed some level of reduction in transferred charge, demonstrating that it is important to select an appropriate dosage to obtain the greatest possible improvement in the electrical indication of resistance to chloride ion penetration.

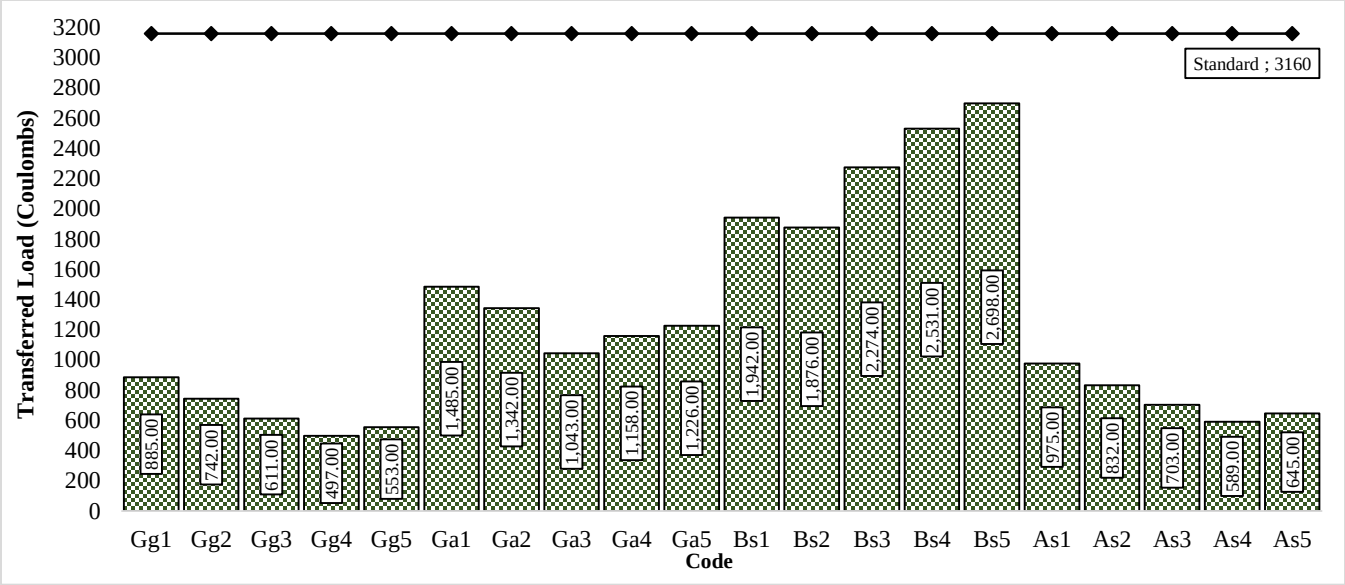


Fig. 24 Variation in Transferred Load According to ASTM C1202

4.8. Optimal Doses of Additives

The results of the underwater cohesion tests, mechanical behavior tests, and durability tests were used to determine the most effective dosage of each additive. Table 11 lists the additive formulations that provided the best combination of washout resistance, mechanical strength, and resistance to chloride ion penetration; the data showed that each additive reached its greatest overall effectiveness at a particular concentration within the evaluated range. The best-performing guar gum mixture contained 0.60% (Gg_4), which exhibited high washout resistance, the highest compressive and indirect tensile strengths, and very low chloride ion penetrability; for gum arabic, the most effective concentration was 0.50% (Ga_3), providing a favorable balance among mixture stability, mechanical strength, pH, and durability. Sodium bentonite performed best at 15% (Bs_2), as it had the lowest washout loss and the highest compressive and indirect tensile strengths among the sodium bentonite mixtures tested; both mechanical strengths of Bs_2 exceeded those of the reference concrete.

Finally, sodium alginate achieved its optimal performance at 2.50% (As_4), effectively combining washout resistance, shorter setting times, notable improvements in mechanical strength, and very low chloride ion penetrability.

Table 11. Optimal doses of additives

Additive	Optimal dose	Code	Criteria Justifying the Selection
Guar Gum	0.60%	Gg4	Minimal washout loss (0.8%), highest compressive strength (424.68 kg/cm²) and tensile strength (37.62 kg/cm²), shorter setting times, and very low chloride ion penetrability (497 coulombs).
Gum Arabic	0.50%	Ga3	Lowest washout loss within the group (4.8%), highest compressive strength (378.57 kg/cm²) and tensile strength (34.89 kg/cm²) within the group, and low chloride ion penetrability (1043 coulombs).
Sodium Bentonite	15%	Bs2	Lowest washout loss within the group (5.2%), lowest pH (9.94), highest compressive strength (372.18 kg/cm²) and tensile strength (33.92 kg/cm²) within the group, and low chloride ion penetrability (1876 coulombs).
Sodium Alginate	2.50%	As4	Low washout loss (2.0%), lower pH (7.93), higher compressive strength (411.39 kg/cm²) and tensile strength (36.83 kg/cm²), shorter setting times, and very low chloride ion penetrability (589 coulombs).

4.9. Evaluation of the Selected Guar Gum Dosage under Simulated Conditions

From the evaluation of the optimal dosage (Gg_4) shown in Table 11, a small-scale experimental test was carried out to assess its performance under simulated construction site conditions. Thus, two test series were performed, simulating critical situations for placing fresh concrete: rainfall on horizontal elements and pouring in contact with water.

The submerged casting test retained the original mix design (Table 1: w/c = 0.35; target f'c = 350 kg/cm²), whereas the simulated rainfall test used a different mix design (Table

12: w/c = 0.45; target f'c = 210 kg/cm²). Consequently, the rainfall test was considered a supplementary assessment of the selected 0.60% guar gum dosage rather than confirmation of its optimality in a different concrete matrix.

4.9.1. Test of a Slab Subjected to Simulated Rain

The study examined the performance (in the fresh state) of the cast concrete slabs, which were prepared with dimensions of 0.50 m × 0.50 m × 0.20 m, including control slabs and slabs containing Gg_4 at the dosage selected from the main experimental program (0.60%), using the mix design described in Table 12. These slabs were exposed to simulated rainfall while the concrete was still fresh. This thickness of 0.20 m was selected to enable further core sampling by diamond drilling in order to obtain an appropriate height-to-diameter ratio. Simulated rain was applied for 30 minutes after pouring and leveling, as illustrated in Figure. 25.

Table 2. Concrete Mix Design for Slab F'c=210 kg/cm²

Property	Unit	Value
a/c	-	0.45
Coarse Aggregate Size	In	¾
Cement	Kg	413
Fine Aggregate	Kg	935
Coarse Aggregate	Kg	779
Water	L	186
Guar Gum - Gg4	%	0.60

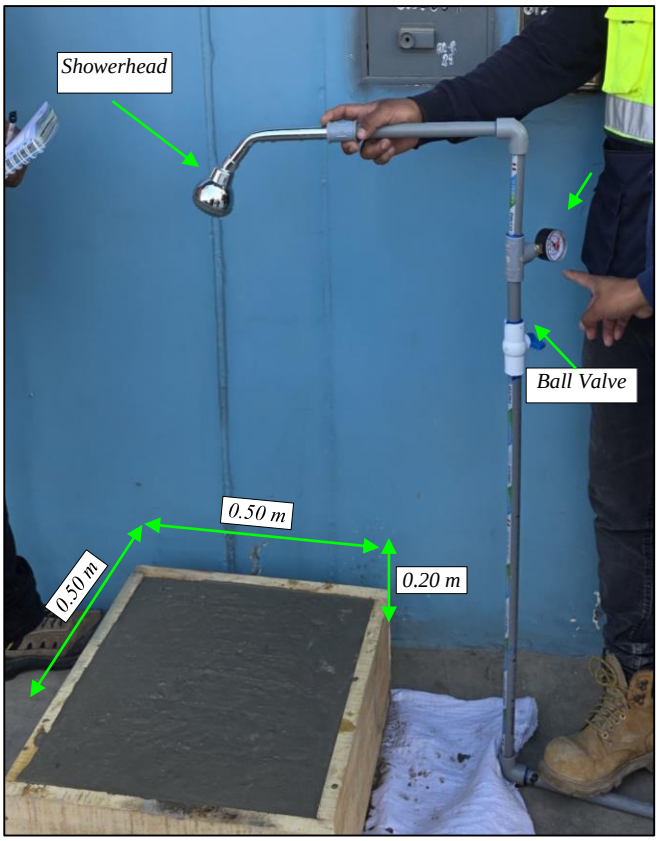


Fig. 25 Experimental Rain Simulation System

In this case, the applied rainfall intensity was calculated using the modified IILA-SENAMHI-UNI formula, which gave a value of 23.55 mm/h for a return period of 10 years. This corresponded to a rainfall depth of approximately 11.78 mm during the 30-minute interval (since 1 mm of rainfall is equivalent to 1 L/m²). Based on the slab dimensions, an effective rainfall volume of 2.95 L was considered for the test surface.

The simulation of rain was achieved through the use of a Showerhead (SH) fixed to a vertical supply pipe positioned 1.50 m above the slab surface; this arrangement ensured adequate dispersion and uniform coverage of the test area. A ball valve was installed on the supply line for flow control purposes, while a pressure gauge was utilized to measure the operating pressure.

The mass loss from the slabs after being exposed to simulated rainfall was used as a measure for comparing the surface washout resistance of the standard concrete and the Gg_4 mix, following an adaptation of the CRD-C61 test. The slabs were weighed before and after exposure to the simulated rainfall; compressive strength at 28 days was determined using the ASTM C39 method. Table 13 shows that the standard concrete lost 5.40% of its material during the simulated rainfall and had a compressive strength of 179.8 kg/cm², which was below the target compressive strength of 210 kg/cm². On the other hand, the Gg_4 mix with 0.60% guar gum had a reduced material loss of 1.02% and a higher compressive strength of 223.5 kg/cm²; this exceeded the target compressive strength. It is possible that the lower compressive strength of the control mixture was associated with its greater loss of cementitious material during the simulated r[illegible] suggests that improved washout resistance [illegible] contributed to better mechanical performance under the evaluated conditions.

Table 13. Results of the Washout Test under Simulated Rainfall Conditions

Code	CRD-C61			ASTM C39
	Mi (Kg)	Mf (Kg)	D (%)	F'c (kg/cm2)
Standard	115.45	109.22	5.4	179.8
Gg_4	115.63	114.45	1.02	223.5

4.9.2. Submerged Drainage Test

In order to observe the performance of 100 mm × 200 mm cylindrical specimens that were created by casting under conditions simulating underwater placement, an experimental test was conducted. The experimental test utilized the standard concrete mix listed in Table 1, as well as a modified mix with the most effective Gg_4 dosage (0.60% guar gum). To accomplish this, the cylindrical molds were positioned within a vessel that contained clean water; care was taken to ensure that there was sufficient water to completely submerge the molds during casting. This arrangement was intended to simulate conditions commonly encountered when concrete is placed underwater (see Figure 26).

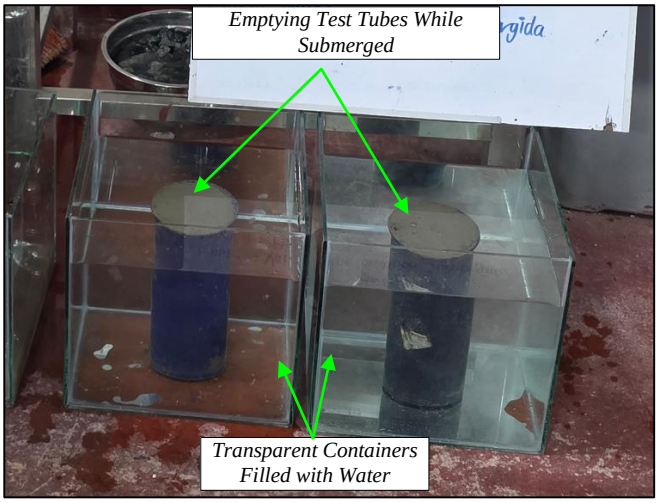


Fig. 26 Experimental simulation system under submerged conditions

The mass of the fresh concrete (Mi) was recorded from a representative portion of the mixture, ensuring that it was homogeneous after mixing and before pouring. The concrete was then placed directly into the molds while submerged, avoiding excessive vibration to prevent the paste from breaking up. After pouring, the molds were removed from the water and drained for 60 seconds in a controlled manner (i.e., excess water adhering to the mold walls was eliminated without introducing additional losses during handling).

The final mass of the retained concrete (Mf) was determined by subtracting the weight of the mold; material loss was then calculated based on the criteria used in the CRD-C61 immersion test, adapted to the submerged casting procedure. For the initial 24 hours, the test samples were immersed in water; after that period, the samples were removed from the molds and allowed to cure for 28 days. Finally, compressive strength testing was performed according to ASTM C39 to assess the mechanical performance of the two types of concrete, i.e., standard concrete and the Gg_4 mixture, under submerged casting conditions. Table 14 demonstrates that the modified concrete had less material loss than the standard concrete (1.37% vs. 8.82%) and had a higher compressive strength (392.4 kg/cm² vs. 327.5 kg/cm²); these results indicate better cohesion in the fresh state and greater resistance to the direct action of water under the evaluated conditions.

Table 14. Results of the submerged discharge test

Code	CRD-C61			ASTM C39
	Mi (Kg)	Mf (Kg)	D (%)	F'c (kg/cm2)
Standard	3.63	3.31	8.82	327.5
Gg_4	3.64	3.59	1.37	392.4

5. Discussion

Researchers at Islamic Azad University in Iran tested the effects of adding biopolymers like guar gum and sodium alginate to underwater concrete. The researchers evaluated the effects of adding these biopolymers on cohesion, water stability, setting time, mechanical strength, and shrinkage; based upon their findings, they concluded that the addition of biopolymers improved the overall performance of the concrete compared to traditional mixes. Guar gum had a washout loss of 3.15%, a water pH of 9.35, and initial and final setting times of 36 and 90 minutes, respectively. Guar gum had a compressive strength of 46.1 MPa and an indirect tensile strength of 3.67 MPa. Sodium alginate had a washout loss of 3.3%, a water pH of 9.58, and initial and final setting times of 2 and 102 minutes, respectively. Sodium alginate had a compressive strength of 44.16 MPa and an indirect tensile strength of 3.61 MPa. Both additives produced a more cohesive mix with less disintegration in water; therefore, they contributed to greater stability of the concrete mixture [22]. Similar results were found in the current study. Guar gum (Gg_4, 0.60%) and sodium alginate (As_4, 2.50%) produced lower washout losses of 0.8% and 2.0%, respectively; these results indicate better resistance to material loss under the conditions evaluated in the present study. Also, both mixtures produced compressive strengths of 424.68 and 411.39 kg/cm² after 28 days. Both mixtures also showed reduced total transferred charges of 497 and 589 coulombs, respectively. It is possible that the improved properties of the mixtures were associated with the formation of viscous polymer networks and calcium-alginate gels; these structures may have helped to retain cement particles and reduce their separation during immersion. Additionally, differences between the two studies could have been due to differences in the materials used, quantities added, and mix proportions. For example, in Iran, the water-to-cement ratio was 0.42, while in the current study it was 0.35; this difference may have contributed to greater cohesion and lower material loss in the present study, although the influence of each factor could not be determined independently.

Researchers from China studied how to enhance the water stability of calcium phosphate cement (CPC) using konjac glucomannan (KGM) and guar gum (GG). The study showed that when no additives were used with CPC, the mass loss was 63.26%; however, when KGM and GG were blended together at a ratio of 5:5, the mass loss decreased to 6.88%. Additionally, the KGM/GG mixture had increased viscosity and showed favorable setting behavior; after setting, the mixture exhibited a compressive strength of 14.48 MPa. Also, the formulations containing guar gum maintained good cell adhesion and proliferation; thus, they showed potential for repairing bone defects [23]. Guar gum also performed well in the underwater concrete evaluated in the present study, where Gg_4 achieved a lower numerical washout loss of 0.8% and increased compressive strength from 364.56 to 424.68 kg/cm². In both investigations, the improvement in water stability could be associated with the formation of viscous networks that helped retain particles and limit their dispersion during contact with water. However, the mechanical results cannot be

directly compared because the Chinese study used injectable CPC for bone repair, whereas the present research employed Portland cement concrete for underwater construction. These differences in composition and hardening mechanisms could explain the variations in mechanical performance, despite the favorable effects on washout resistance observed in both cases.

In India, researchers at Aditya Engineering College investigated underwater geopolymer concrete containing fly ash, ground granulated blast furnace slag, and natural anti-washout additives such as gum arabic and xanthan gum. Mixtures containing 0.25-0.75% of these additives were evaluated through workability, washout resistance, compressive strength, and microstructural analyses. The results showed that gum arabic reduced material loss, with washout losses of 3.5% and a minimum of 2.1%, while the maximum compressive strength reached 54.73 MPa at 28 days. Microstructural analyses using XRD, SEM, and EDS indicated denser matrices and greater development of geopolymerization products [20]. In addition, gum arabic improved the performance of the cementitious material in a water environment. At a dosage of 0.50% (Ga_3), the washout loss dropped from 13.6% to 4.8%, and compressive strength increased from 364.56 to 378.57 kg/cm². The amount of transferred charge also decreased from 3160 to 1043 coulombs; this indicated improved resistance to chloride ion penetration in the concrete. However, the Indian study reported a washout loss of 2.1%; although this was a more favorable numerical result than in the present study, the tests were performed under different conditions. There are several possible reasons for the differences between the two studies. For example, the chemistry of the binder and the proportions of the ingredients used in the mixtures may account for some of these differences. Additionally, the Indian study used gum arabic within an alkali-activated geopolymer system; however, the present study used gum arabic within a Portland cement concrete mixture. Therefore, the differences between these systems may have influenced how gum arabic interacted with cementitious particles, affecting the viscosity, cohesion, and workability of each mixture. Nevertheless, both studies showed that controlled additions of gum arabic could improve water stability while maintaining favorable mechanical performance.

A BCG (bentonite-cement-sodium silicate) grout, designed for injection into areas with high water content, was evaluated by Chinese investigators. Their findings revealed that as bentonite content increased from 0 to 50%, viscosity increased and bleeding decreased; this provided improved water stability for the grout. Additionally, the investigators determined that both the setting time and early mechanical strength of the grout were affected by the water-to-solids (W/S) ratio. They found that a W/S ratio of 1.5 resulted in faster setting and higher early strength than a W/S ratio of 2.0. However, the researchers also found that although higher bentonite contents resulted in lower compressive strength, mixtures containing between 10% and 20% bentonite demonstrated the most effective compromise between stability and mechanical performance. Results of microstructural analysis showed that the grout matrices were denser and more continuous; field applications at the Beijing Metro also demonstrated improved water-sealing performance [30]. Results from the current investigation indicated a similar trend. Specifically, sodium bentonite at 15% (Bs_2) resulted in a decrease in washout loss to 5.2% and an increase in compressive strength from 364.56 to 372.18 kg/cm². Additionally, the indirect tensile strength of the Bs_2 formulation exceeded that of the control, reaching 33.92 kg/cm² compared to 33.14 kg/cm²; lastly, the total transferred charge was reduced from 3160 to 1876 coulombs. The improvement could be associated with the water absorption capacity and layered structure of montmorillonite, which may help retain fine particles and reduce material loss during immersion. At higher dosages, greater water demand and compaction difficulties could explain the lower mechanical performance. Although the Chinese study focused on injection grout and the present research evaluated concrete with coarse aggregate, both indicated that moderate bentonite contents provided a better balance between water stability and mechanical performance than higher dosages.

6. Conclusion

First, the results obtained lead to the conclusion that the incorporation of biopolymers and sodium bentonite into concrete designed for underwater applications is a highly effective strategy for increasing cohesion, minimizing fine-grained material washout, and enhancing mechanical and durability performance against chloride penetration, critical factors in marine environments where currents, waves, and turbulence intensify the early disintegration of the material. The experimental methodology, based on a mix design compliant with the criteria of Standard E.060 and the systematic application of standardized tests on fresh and hardened concrete, allowed for the precise characterization of the effect of each additive on water stability, pH evolution, setting, and microstructural consolidation of the concrete subjected to submerged placement. In summary, the findings confirm the hypothesis whereby high-performance wash-resistant concrete can be developed from conventional concrete through specific rheological and microstructural modifications leading to resistance against hydraulic scouring, being less susceptible to chloride attack, thus enabling more stable foundations, piles, piers and structures for marine environment applications. Second, the analysis of guar gum demonstrated it is the most significant additive for the enhancement of underwater concrete performance, and 0.60% of cement weight is an ideal dosage for achieving optimal performance. It noticeably enhances the mixture stability against turbulence in its fresh state by increasing cohesion, as well as reduction of settlement and washout, alkalinity release, and setting time. In other words, when the cement paste has

hardened, it exhibits higher strength and lower chloride diffusivity than the unmodified control cement paste; this suggests that the use of guar gum, in addition to acting as a thickener, may also improve the internal packing structure of the cement paste. At certain dosages, guar gum can result in over-thickening, micro-agglomeration, and non-uniform behavior of the cement paste; these effects can negatively affect workability and lead to reduced strength and sealing efficiency. These results indicate that there is a limited range of effective dosages (i.e., a "narrow functional window") where the use of an intermediate dosage can provide the highest degree of cohesiveness while maintaining the integrity of the cementitious system. Third, gum arabic can improve the performance of concrete by helping to modify its cohesiveness and durability, although its effects are more modest than those of the other additives. At a dosage level of approximately 0.50% by weight of cement, gum arabic provides an intermediate level of modification; this helps to limit particle settling and improve leakage resistance without creating excessive stiffness or alkalinity through the formation of colloidal films that coat cement particles. Once the concrete hardens, these colloidal films may contribute to improved packing of the particles within the matrix; they may also provide modest improvements in compressive and tensile strength, as well as a noticeable reduction in the electrical indication of chloride ion penetrability.

If the most effective dosage of gum arabic is exceeded, the colloidal system may become saturated, and the adhesive film may lose its continuity; therefore, any further improvements in cohesion, durability, or workability could become marginal. Fourth, sodium bentonite acts as a mineral modifier that increases viscosity and water stability; the degree of improvement depends upon the amount of bentonite used. When the amount of bentonite is at or near 15% of the total weight of cement, it can enhance cohesion, minimize bleeding, and allow for more stable placement of the mix under submerged conditions. Once the mix has hardened, the layered structure of montmorillonite helps refine the pore network, resulting in slight gains in compressive strength and a moderate reduction in the electrical indication of chloride ion penetrability. If too much bentonite is added, there will be an increase in water demand and excessive plasticity; these effects can impede proper compaction and create more pores, thus reducing both load-bearing capacity and the effectiveness of ion transport control. Therefore, bentonite can serve as a beneficial rheological modifier if the quantity of bentonite is kept within appropriate limits.

Fifth, sodium alginate stands out for combining cohesion, water retention, and improvements in mechanical properties and durability under underwater conditions, with an optimal dosage of around 2.50% of the cement weight. In fresh concrete, calcium alginate gels increase cohesion, significantly reduce leaching, moderate the release of alkalinity, and accelerate setting, resulting in a mix that rapidly develops structure. In hardened concrete, the three-dimensional network densifies the paste, reduces pore connectivity, and increases both compressive and tensile strength as well as resistance to chloride penetration. However, higher dosages make the gel network too rigid and heterogeneous, hindering workability in the fresh state and causing agglomerations and microvoids that reduce its overall efficiency.

Finally, the overall findings of the research indicate that the comparative evaluation of biopolymers and mineral additives offers a solid path toward the design of underwater concrete that is safer, more durable, and consistent with the regulatory and environmental requirements for infrastructure exposed to chlorides. However, the study has limitations associated with the laboratory scale, the use of a single type of cement, and an evaluation focused on certain mechanical and durability properties; therefore, future research could delve deeper into long-term behavior under thermal cycling, sulfate attack, fatigue, and real-world construction conditions. The results support the recommendation of optimal intermediate dosages of biopolymers as a technical alternative to improve concrete in piles, foundations, riverbank protection structures and marine structures constructed underwater at an applied level, always controlled through rigorous rheology and construction process. It is thus recommended to further optimize both the dosage and the combination of additives, as well as their integration into more sustainable design solutions that can inhibit the environmental impact caused by concrete without compromising its structural functionality or durability.

Conflicts of Interest

We declare that there is no conflict of interest regarding the publication of this article.

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