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The Effect of Plant-Based Polysaccharide (Gum Arabic) as a Super-Plasticizer on the Mechanical Properties of Concrete

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Abstract

This study aimed to determine how plant-based polysaccharide (Gum Arabic), a super-plasticizer, affected concrete fresh and strength characteristics. Workability test, compressive strength, and flexural strength of concrete at various percentages of addition of Gum Arabic (GmAc) were determined to assess the impact of Gum Arabic on concrete using a concrete mix of M25 grade created with the inclusion of 0.1%, 0.3%, 0.6%, 0.9%, and 1.2% GmAc. X-ray diffraction spectroscopy was carried out on the concrete with GmAc which gave the optimum strength value. The results showed that the effect of GmAc on concrete depends on the dosage added to the concrete mix, as an increase in dosage of GmAc yield higher compressive strength and flexural strength of the concrete up to 0.3% dosage where the optimum value was obtained. After that, the effect proved counter-productive because the values obtained for dosages beyond 0.3% were low compared to the control sample. The study has shown that GmAc can be used as an alternative water-reducing admixture in concrete production.

Keywords: Admixture, Gum Arabic, Plant-based polysaccharide, Super-plasticizers, X-ray diffraction spectroscopy.

Introduction

The massive rise in building and civil engineering works in Nigeria brought on by the necessity to provide housing and infrastructure for the country's expanding population has significantly led to an increase in the use of concrete. Since cement, sand, and aggregate have always been the traditional materials for concrete production and their prices are rising, there has recently been an increase in the search for locally sourced materials that are considered waste (Anitha *et al.*, 2016). Cement, typically Portland cement, along with other cementitious materials such as fly ash, slag cement, coarse aggregates (comprising gravel or crushed stone), fine aggregates (sand), water, and admixtures constitute the primary components of concrete, a composite construction material (Bert-Okonkwor *et al.,* 2019).To enhance the mechanical and chemical qualities of concrete and mortar, additives are frequently used in the constituents of concrete (Björnström and Chandra, 2003). Chemical admixtures, which include plasticizers, super-plasticizers, set retarders, accelerators, and air-entraining agents, change the properties of concrete in a variety of ways, including by lowering the amount of water required for mixing, lowering bleeding and segregation, lowering slump loss, and adjusting the setting time, among other things (Abiodun and Adeosun, 2023). In the Northern regions of Nigeria, a perennial tree known as Gum Arabic (Acacia species) grows in huge commercial numbers. Nigeria is the world's third-biggest producer and exporter of Gum Arabic, after Sudan and Chad. It is also the major producer in West Africa. The combined cultivated and wild varieties of Gum Arabic in Nigeria's forest reserves have a potential output capacity estimated at 491,034.1 tonnes. When combined, Yobe and

Borno can provide up to 46% of Nigeria's potential Gum Arabic production, with Jigawa state contributing 20% (Ojiekpon, 2020). Figure 1 is the map showing the biggest producing States of GmAc in Nigeria (Finelib, 2023).

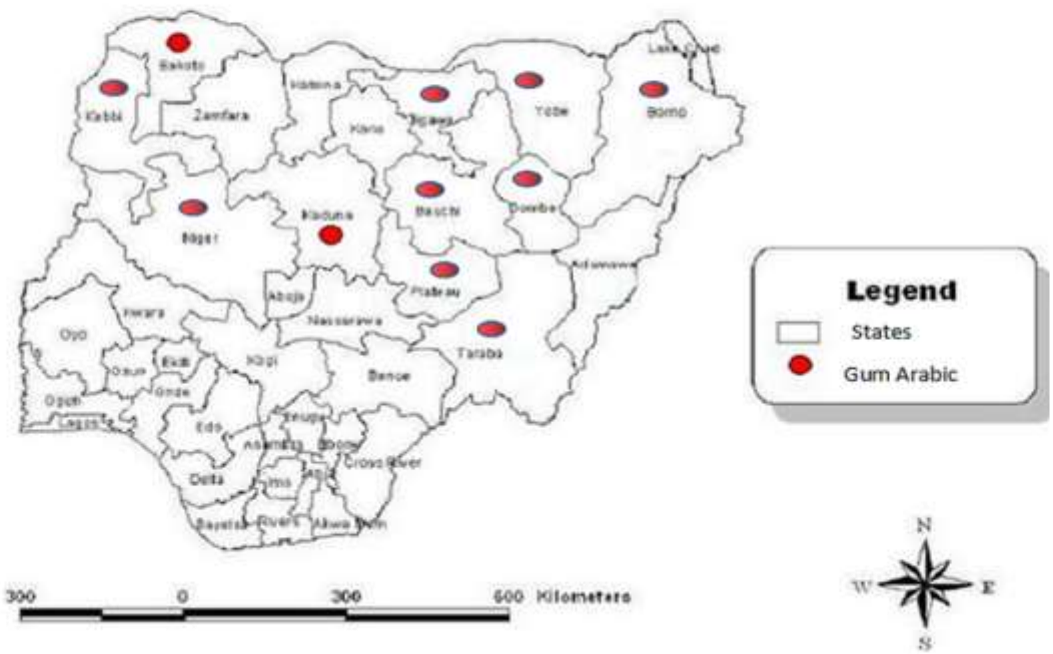


Figure 1: Nigerian States where gum Arabic is cultivated

Gum Arabic (GmAc), a polysaccharide must grow and develop for roughly five years (Omokhafe, 2019). When a mature tree is struck by or punctured by a sharp metal implement, such as a knife, it flows out a white sticky glittering fluid (Rubber Research Institute of Nigeria, 2011). When used in moderation, wild plant derivatives provides a valuable source of these sustainable resources, which are increasingly desired as alternatives to conventional products across all industrial sectors (Abdeliazim *et al.*, 2017). Gum Arabic, a sustainable biopolymer, bear the image of being environmentally more acceptable than synthetic polymers produced in a chemical plant (Subhadeep and Anjali, 2021) and it is recognized for its low viscosity and high solubility in water. Sudan and other tropical African countries produce 70–85% of the global output of 10,000 million tonnes (Rimbarngaye *et al.*, 2021). GmAc has been employed in a variety of sectors, including textiles, cosmetics, lithography, medicines, encapsulation, and even the food industry, because of these attractive qualities (Amira *et al.*, 2024). Some researches have been carried out on other forms of polysaccharides such as okra extract, seaweed powder, mulberry leaf extract (Patel and Deo, 2016; Wang *et al.*, 2023). The construction sector, known for its substantial resource use, would represent a significant market if applications for polysaccharides could be recognized within it (Verbeken *et al.*, 2003). The state of the Nigerian environment is constantly in decline due to various human activities, one of these being urbanization. The drive towards creating more durable construction materials has prompted the manufacture of various chemical additives whose manufacturing processes result in the release of greenhouse gases such as CO_2 and CH_4 into the atmosphere, causing the depletion of the ozone layer (Abiodun *et al.*, 2022). It is therefore essential to investigate the use of sustainable materials with less toxic compositions (Schutzenhofer *et al.*, 2022). Most super-plasticizers currently used in Nigeria are imported from other countries outside of Africa, these products might not be able to reach their expected potential due to it being used in climatic conditions different from those it was designed for.

Therefore, local solutions are required since chemical admixtures are scarce and to promote environmentally friendly building practices. The usage of plant-based polysaccharide (Gum Arabic) as a possible admixture in the production of concrete has been identified by this study as an alternative to chemical admixtures.

Materials and Methods

Materials

Gum Arabic (GmAc) Powder was purchased at Ojota Market, Lagos State. It was obtained as tightly-packed specks of fine powder as shown in Figure 2. Its moisture was removed by passing it in an oven for 1 hour at 100˚C. To ensure lump-free hydration, the powder was thoroughly mixed with the other dry ingredients before water was added.

Figure 2: Gum Arabic Powder

Cement: Dangote Cement of grade 47.5N was selected for use in this research and has been found to satisfy the conformity evaluations as prescribed in BS EN 197-2 (2020).

Aggregates: Sharp sand sourced from a river was used as the fine aggregate in this research due to its bonding properties and its relative cleanliness as opposed to ocean sand that contains salt. The coarse aggregate used ranges between 12mm (½ inch) and 19mm (¾ inch)

Water: Portable water was used in this research.

Experimental Tests

To ascertain the impact of different replacement levels on the mechanical and crystallographic properties of hardened concrete, laboratory tests such as X-Ray Fluorescence (XRF), workability (slump test), compressive strength, flexural strength and X-Ray Diffraction Spectroscopy (XRD) were conducted.

Compressive Strength

At a mix ratio of 1:1:2 (grade M25) and water cement ratio of 0.4, GmAc powder was added to concrete mixes at 0.0%, 0.1%, 0.3%, 0.6%, 0.9%, and 1.2% by weight of cement. The concrete specimens were tested for compressive strength after 7, 21 and 28 days of water-curing. Cubes of size 150mm x 150mm x

150mm were used for the test. Each testing age had three cubes for each dosage of GmAc, amounting to a total of 54 cubes.

Flexural Strength

Flexural Strength test was also carried out on concrete with GmAc dosages at 0.0%, 0.3%, 0.6%, 0.9%, and 1.2% on beam sizes of 150mm x 150mm x 750mm at 28 and 56 days of water-curing. Mix-ratio of 1:1:2, and water-cement ratio of 0.4 were employed. Each testing age had three beams for each dosage of GmAc, amounting to 30 beams. The samples of GmAc -infused concrete could not be demoulded after 24 hours, therefore the cubes were demoulded after 72 hours when they had adequately hardened, and then put in the curing tank.

X-Ray Diffraction Spectroscopy

A non-destructive method known as X-ray diffraction analysis (XRD) which gives precise details on a material's crystallographic structure was employed in this study. Two concrete samples, one being the control, 0.0% and the other the percentage addition that yielded the maximum compressive strength, 0.3%, were selected. XRD was carried out on the two categories of concrete samples at the National Geoscience Research Laboratory, Kaduna, Nigeria.

X-ray Fluorescence (XRF) Test

XRF is a non-destructive analytical method for analyzing materials to ascertain their elemental makeup, and can be adapted as oxide composition. XRF was used to confirm the chemical compounds present in the GmAc. This test was carried out because the chemical composition of Gum Arabic from different parts varies depending on various factors, such as the season of harvest, the region, and the processing method.

Results and Discussion

Chemical Composition of Gum Arabic

Table 1 presents the chemical compound of the study GmAc obtained from the XRF test. Generally, gum Arabic contains a mixture of polysaccharides, proteins, and minerals. The most abundant polysaccharide component of gum arabic is arabinogalactan, primarily composed of arabinose and galactose units. Another significant polysaccharide component is glucuronic acid, which is thought to contribute to the gelling properties of Gum Arabic.

Table 1: Chemical composition of study Gum Arabic

Composition	Amount
Galactose	41.6 %
Arabinose	28.1 %
Rhamnose	14.2 %
Glucuronic Acid	14.0 %
4-O-methyl glucuronic acid	1.7 %
Nitrogen	0.4 %
Specific rotation	-30.8°
Molecular Mass (On average)	380,000

Sieve analysis Aggregates

The sieve analysis for both the fine and coarse aggregates was carried out following BS 1377-2 (2022). For fine aggregate, the coefficient of uniformity (Cu) was 2.75 and 0.915 for coarse aggregate. The coefficients of curvature (Cc) for both fine and coarse aggregates were 1.195 and 1.02 respectively. The fineness modulus of 2.44 and 7.8 was obtained for both the fine and coarse aggregates respectively.

Workability (Slump) Test

BS 12350-2 (2009) was followed for conducting the slump test. Figure 3 below summarizes how adding more GmAc affects the workability of modified concrete.

It can be observed in Figure 3 that there is an upward trend in the slump values. There is a significant increase in slump value with increasing dosages of GmAc with the control giving the lowest slump value at 50mm and a percentage addition of 1.2% giving the maximum slump value at 250mm. This increase in workability can be attributed to the low viscosity of GmAc.

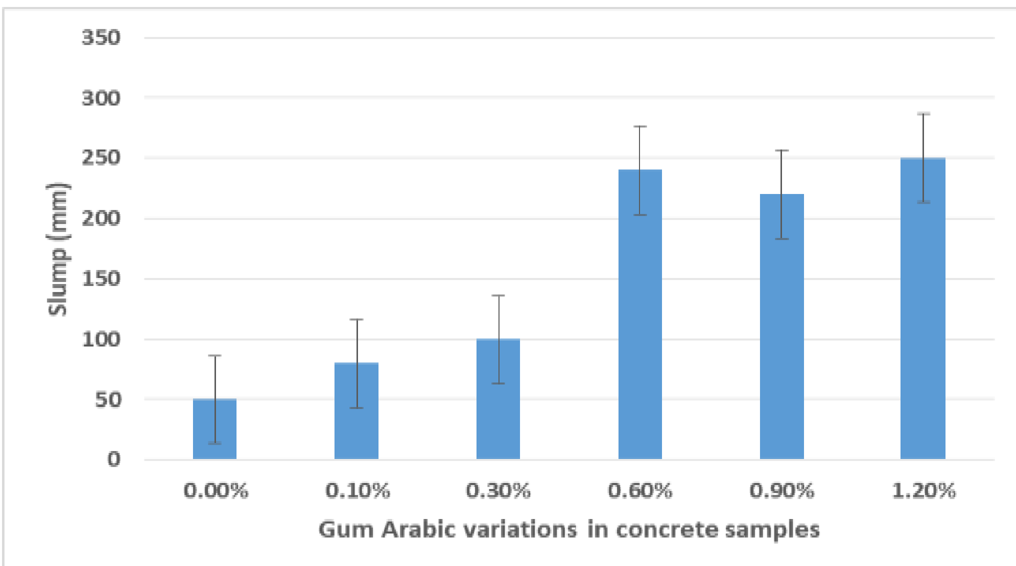


Figure 3: Slump Values at Varying Percentage Addition of Gum Arabic

Tests on Hardened Concrete

Compressive Strength Test

BS 12390-3 (2019) was followed while measuring compressive strength. The samples containing Gum Arabic had a long time to set, requiring three days before they were strong enough to be demoulded, compared to the control samples, whose setting time was within 24 hours. Gum Arabic contains sugar, which has been linked to the delayed setting time (Mbugua *et al.*, 2016). The results obtained are presented in Figure 4.

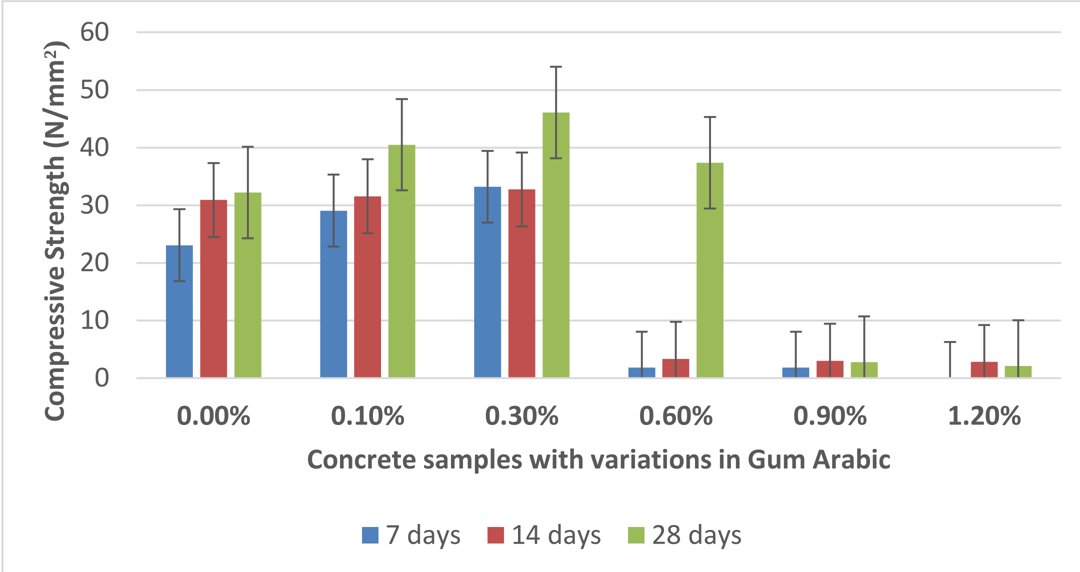


Figure 4: Compressive Strength at Varying Percentages Addition of Gum Arabic

It can be observed that at 28 days, the percentage addition with the highest compressive strength of 46.09 N/mm^2 is at 0.3% addition with GmAc. Compared to other dosages, 0.3% addition shows the greatest improvement when compared to the control sample with 32.2 N/mm^2. 0.6% addition yielded low compressive strength values at 7 and 14 days but showed a great improvement in strength at 28 days.

An experiment by Okafor (2008) claimed that the residual retarding effect is less significant after 14 days and the strength developed at this age was due to other factors. 0.9% and 1.2% increases yielded low values for 7, 14 and 28 days. These lower strengths were attributed to the prolonged retarding actions of monosaccharides and polysaccharides present in the admixture on hydration due to high dosages of admixture. The general trend of the compressive strength results obtained is similar to the report of Rasheed *et al.* (2018) on research to determine the impact of sugar on the compressive strength of concrete where there was a gradual decrease in compressive strength with increasing admixture dosage. The maximum strengths obtained were between dosages of 1-5% of sugar, dosages of 6-10% had relatively lesser compressive strength values and lesser difference between the compressive strength values at 3, 7 and 28 days. The loss in strength was attributed to the presence of sucrose ($C_{12}H_{22}O_{11}$). Galactose ($C_6H_{12}O_6$) which is a major component of Gum Arabic is similar to sucrose in that they are both forms of sugar.

Flexural Strength Test

Flexural strength testing was carried out in line with BS 12390-5 (2019). From Figure 5, it could be observed that the flexural strengths at all curing days decrease with increase in the addition of GmAc. At 28 days, the control sample with 0.0% addition of GmAc attained flexural strength of 9 N/mm^2. Flexural strength of 8.25 N/mm^2 was achieved with 0.3% addition, which was 91.67% of the strength of the control, 0.0% addition.

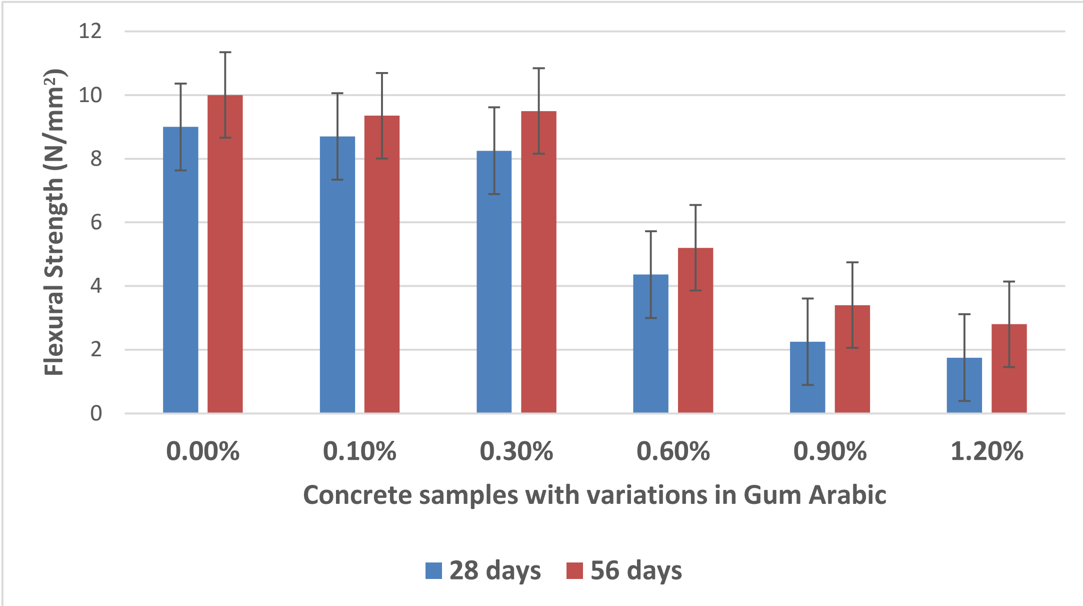


Figure 5: Flexural Strength Values at Varying Percentage Addition of Gum Arabic

X-Ray Diffraction Spectroscopy on Concrete with 0.0% and 0.3% dosages of Gum Arabic

XRD studies were carried out after 28 days of the specimens. The control sample, 0.0% and the percentage addition that yielded the maximum compressive strength, 0.3% were analyzed. The studies revealed almost a similar pattern in both samples with and without Gum Arabic, but with different intensities, as shown in Figures 6 and 7.

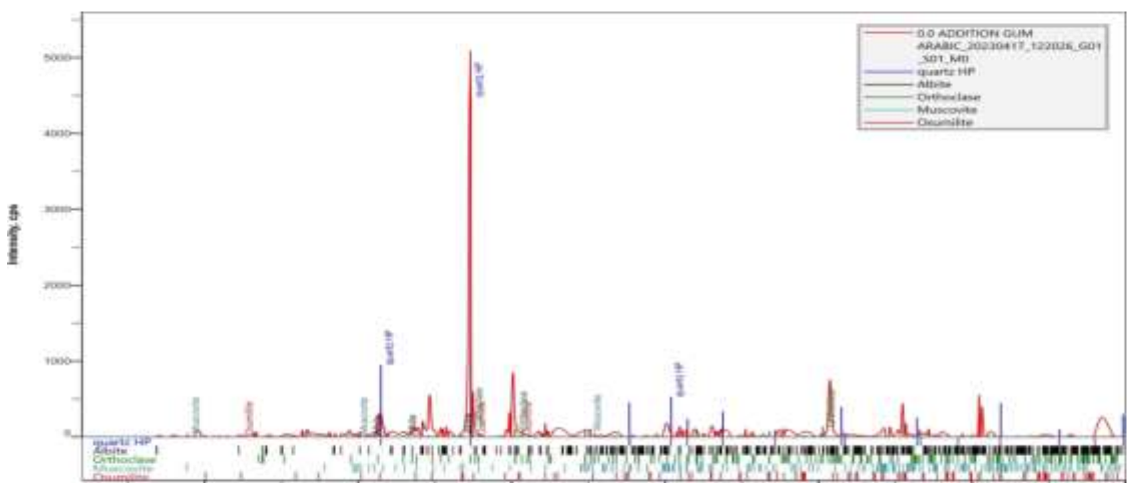


Figure 6: X-ray diffraction analysis of concrete sample with 0.0% addition of GmAc

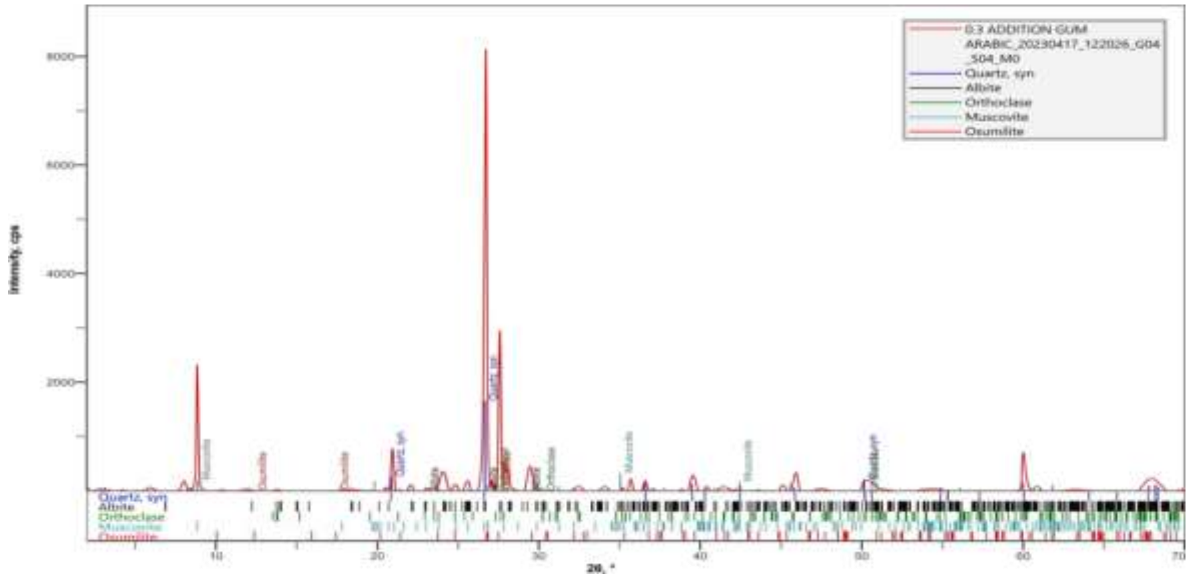


Figure 7: X-ray diffraction analysis of concrete sample with 0.3% addition of GmAc

The micrographs showed the levels of transformations that have taken place in the mineralogical characteristics of Gum Arabic. These transformations are due to the interactions of GmAc with cement during the hydration process. The analysis also showed that there were no new chemical reactions during hydration and no existence of new chemicals. The breakdown of the mineralogical results obtained from XRD analysis on the control sample and sample with the dosage of GmAc that yielded the highest strength (0.3%) are presented in Figure 8.

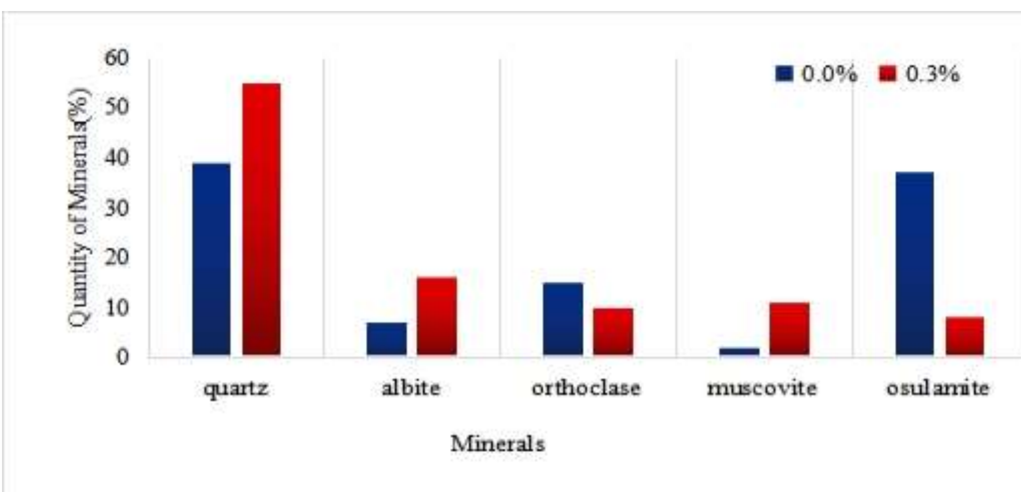
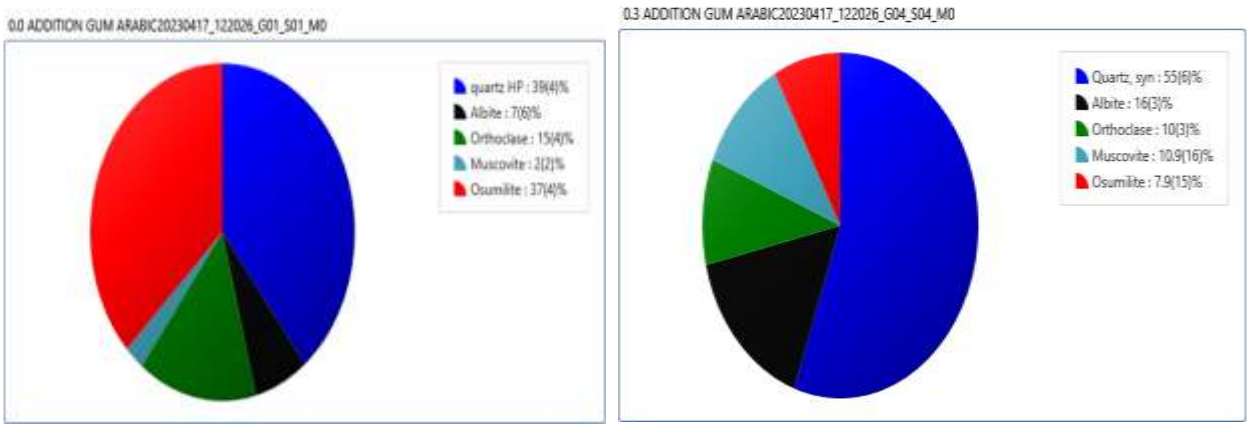


Figure 8: Mineral composition of concrete samples with 0.0% and 0.3% dosages of GmAc

Figure 9 (a and b) presents the mineral composition present in concrete containing 0.0% and 0.3% addition of Gum Arabic respectively. Comparing the results, it can be observed that the quartz (SiO_2) content in concrete with 0.3% dosage is higher at 55% compared to the control at 39%. Quartz is the most abundant mineral in concrete and it’s responsible for its strength which explains the difference in strength between the two dosages. Albite ($NaAlSi_3O_8$) is a feldspar mineral that can improve the workability of concrete and reduce the risk of segregation as reported by Selvamony *et al.* (2009). Again, the percentage of albite in concrete with 0.3% dosage is higher at 16% than the control at 7%. Orthoclase ($Al_2O_3.K_2O.SiO_2$) and Osulamite (K.Na.Ca.Mg.Fe.Al.S) are rare minerals respectively and they also contribute to the strength of concrete (Usman *et al.*, 2016). The quantity of both minerals is greater in the control at 15% and 37% respectively compared to the values of 10% and 7.9% present in the concrete sample with 0.3% dosage. Muscovite ($H_2KAl_3(SiO_4)_3$) on the other hand, is a mica mineral that can increase the workability of concrete and reduce the risk of cracking. The concrete sample with 0.3% dosage of GmAc has a higher percentage of muscovite at 10.9% compared to the control sample which yielded a quantity of 2% as presented in Figure 9. This explains the difference in slump between the two dosages as similar result was reported by Wang *et al.* (2023).



(a) concrete with 0.0% addition of GmAc (b) concrete with 0.3% addition of GmAc

Figure 9: The mineral composition of concrete with 0.0% and 0.3 % addition of Gum Arabic

Conclusions

Concrete with a percentage addition of Gum Arabic powder ranging from 0.1% to 0.3% by weight of cement at a water-cement ratio of 0.4 is adequate for structural applications with a maximum compressive strength of 46 N/mm2 for grade 25 concrete. Gum Arabic greatly increases the setting time of concrete, as seen by the number of days (three days) required to de-mould samples containing Gum Arabic vs those without. Self-compacting concrete with Gum Arabic additive requires less effort and is slightly more workable than conventional concrete. The use of Gum Arabic will produce green concrete and also contribute to the economic growth of farmers in the arid areas of northern Nigeria. Gum Arabic is an environmentally beneficial additive, and its usage in self-compacting concrete can help promote the green economy and combat climate change.

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