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Evaluation of Geopolymer Concrete Based on Fly Ash Containing Steel Fibers and Rubber Crumbs Using Cement as a Partial Substitute for Fly Ash

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ABSTRACT

In this study, geopolymer concrete made from fly ash was utilized, with different proportions of cement (0%, 10%, and 20%) replacing fly ash to examine the influence of cement presence in geopolymer concrete. To increase tensile strength and impact resistance, 0.5 and 1 percent steel fibers were used. Adding 0.5 percent fibers improved compressive strength by 9 percent, and for 1 percent fibers, it was 26 percent. The tensile strength also significantly increased with the addition of fibers. Adding 0.5% fibers, on average, increased the tensile strength by 25%, with the increase being 34% for 1% fibers. It was also noted that substituting cement for fly ash had little effect on compressive strength, but replacing 10% cement could be considered as the optimal substitution level in terms of tensile strength in the samples.

The test results for impact resistance indicated a significant effect of steel fibers on the number of impacts until the first crack appeared and the complete rupture of the samples. Adding fibers increased the resistance to complete rupture by 12 to 22 percent with 0.5 percent fibers, and between 49 to 64 percent for 1 percent fibers. Replacing 10 percent rubber crumbs improved the impact energy of concrete, increasing the energy until the first crack by 10 percent on average and the energy until complete rupture by 15 percent.

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1. Introduction

The concrete industry is facing various challenges due to the increasing use of Portland cement, primarily because of limited cement resources. On one side, reducing production and carbon dioxide emissions, on the other hand the increasing construction activities and high demand for cement have led researchers to seek suitable alternatives for cement in concrete. Researchers have introduced fly ash, metakaolin, iron slag and other pozzolans as suitable substitutes for cement [1-3]. Substituting these pozzolans for cement not only

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effectively reduces environmental pollution but also enhances the mechanical properties of concrete and decreases the widespread need for cement [4]. Using rubber crumbs as a partial substitute for aggregates in geopolymer concrete can reduce the environmental effects caused by the accumulation of waste rubber tires. However adding rubber crumbs to concrete reduces its resistance properties due to the lower hardness of rubber crumbs compared to natural aggregates and their weak bonding with cement paste [5]. This can be compensated for by adding steel fibers which not only offset a considerable portion but also overall enhance the geopolymer concrete's resistance [6]. Therefore, in this study geopolymer concrete based on fly ash has been used. Additionally the effects of adding rubber crumbs and steel fibers as well as cement as a partial substitute for fly ash on the mechanical properties of concrete have been evaluated.

1.1. Case studies on the mechanical properties of geopolymer concrete based on fly ash and the impact of steel fibers, rubber crumbs, and cement in it

In recent years, there has been a significant amount of research focused on geopolymer concrete, aiming to enhance its quality, strength, and longevity through the addition of various materials like different types of fibers and other additives below are some of these studies:

In 2018, Guo conducted a study on the mechanical properties of geopolymer concrete reinforced with steel fibers [7]. The results of this research indicate that adding steel fibers up to 0.4% increases the compressive strength of geopolymer concrete. However further additions of steel fibers decrease the compressive strength. Moreover, the flexural strength of concrete decreases with the addition of 0.1% fibers but then increases by 20% with the addition of up to 0.5% fibers.

In another study, Islam investigated the effect of adding 0.5% steel fibers to fly ash-based geopolymer concrete on its mechanical properties [8]. The results suggest that adding fibers leads to a slight increase in compressive strength and a significant increase in tensile strength. However, the increase in tensile and impact resistance due to the addition of fibers is much greater. For example the increase in compressive strength is 33-35% higher than the increase in tensile strength. Additionally it was observed that adding 0.5% fibers had no significant effect on the elastic modulus of geopolymer concrete.

Vijai [6] examined geopolymer concrete composed of 90% fly ash and 10% cement. The impact of adding 0.25%, 0.5%, and 1% steel fibers on the concrete strength was measured. The results indicate that adding fibers increases the compressive, tensile and flexural strength by 73%, 128%, and 17%, respectively.

In a study conducted by Park in 2016 [5] it was determined that adding rubber powder up to 20% significantly reduces the compressive strength of fly ash-based geopolymer concrete. Researchers suggested an optimal use of rubber powder to minimize the reduction in concrete strength, typically between 10% to 15%.

Hongen [9, 10] investigated the addition of cement to fly ash-based geopolymer concrete and its impact on compressive strength. Adding cement enables the concrete to perform well at ambient temperatures due to cement hydration. Hydration leads to increased compressive and tensile strength as well as providing energy for polymerization. In this research, adding 5% cement resulted in increased compressive strength. Many studies have reported a reduction in compressive strength when rubber powder is added to geopolymer concrete attributed to poor adhesion between rubber crumbs and other materials and the low inherent strength of rubber crumbs. Reductions in strength of up to 33% have been reported.

1.2. Objectives and Necessity of the Project

Geopolymer is a novel material in the construction industry with desirable performance and efficiency. It is made using natural pozzolans and industrial waste containing aluminum silicate making it environmentally friendly. It can serve as a substitute material to reduce pollution caused by the production of Portland cement used in concrete. On the other hand the mechanical properties and durability of this concrete have prompted further research into the factors influencing these two characteristics. Given the importance of sustainable development and recycling of waste rubber, using rubber crumbs in concrete can reduce environmental impacts resulting from the accumulation of waste rubber. However, adding rubber crumbs to concrete reduces its resistance properties due to the lower hardness of rubber crumbs and their weak bonding with other concrete components. Therefore steel fibers have been used to increase the concrete's resistance and compensate for the decrease in resistance due to rubber crumbs. Past research has shown that adding rubber crumbs reduces the concrete's resistance but reinforcing the concrete with steel fibers not only prevents the reduction but also increases its resistance. The combined effect of steel fibers and rubber crumbs in normal concrete has been investigated in many studies, and the current study aims to examine the parameters affecting fly ash-based geopolymer concrete containing rubber crumbs and steel fibers. Some studies have considered fly ash-based geopolymer concrete to have a similar structure to normal concrete[16, 17] but the addition of steel fibers and rubber crumbs due to their different bonding with fly ash compared to cement, can have different effects.

Table1
Concrete mixture proportion.

Number	Mix Id	Cement	Fly ash	Crum rubber	Coarse aggregate	Fine aggregate	Steel fiber
	(Kg/m^3)						
1	G100%SF0%	0	408	19.67	1347	491.83	0
2	G100%SF0.5%	0	408	19.20	1347	479.95	39
3	G100%SF1%	0	408	18.72	1347	468.08	78
4	G90%SF0%	40.8	367.2	20.23	1347	505.83	0
5	G90%SF0.5%	40.8	367.2	19.76	1347	493.95	39
6	G90%SF1%	40.8	367.2	19.28	1347	482.08	78
7	G80%SF0%	81.6	326.4	20.79	1347	519.83	0
8	G80%SF0.5%	81.6	326.4	20.32	1347	507.95	39
9	G80%SF1%	81.6	326.4	19.84	1347	496.08	78
10	G100%SF0%CR0%	0	408	0	1347	576.63	0

The necessity of assessing the strength of geopolymer concrete through different tests is heightened by above factors. Tests such as compressive and tensile strength and modulus of elasticity are conducted to determine the concrete's resistance and ultrasonic wave velocity tests are used to assess the quality of concrete and the effect of steel fibers and rubber crumbs in concrete. Additionally, impact tests are conducted to assess the dynamic impact resistance and the effect of rubber crumbs and steel fibers and the substitution of cement instead of fly ash are analyzed and investigated.

2. Laboratory Experimental Design

2.1. Consumables

Portland Type II cement produced by Deilaman Cement plant with a specific weight of 33.3 kilograms per cubic meter and a specific surface area of 3200 square centimeters per gram was used in this study. Fly ash in powdered form with a density of 2.45 grams per cubic centimeter was utilized. The fine aggregate used was washed natural sand with a fineness modulus of 2.95 and a specific weight of 2.75 grams per cubic centimeter and the coarse aggregate was crushed stone with a maximum size of 19 millimeters and a specific weight of 2.65 grams per cubic centimeter in accordance with ASTM-C33 requirements. Steel fibers with hooked ends 0.5 centimeters in length, a diameter of 0.8 millimeters, and an aspect ratio of 62.5 and a density of 7.87 grams per cubic centimeter produced by Daroocham Factory were used. The rubber crumbs used in this research have a specific weight of 0.95 grams per cubic centimeter. The curing process in this research was carried out at 60 degrees Celsius in accordance with geopolymer concrete standards.

2.2. Mixing Design

For this project, 10 mixing designs were selected. Given that geopolymer concrete is the material of choice, no water content was used in their formulation. Design 1 to 9 incorporate 10% by volume of fine rubber crumps, and the geopolymer concrete samples are grouped into three main categories.

The first group contains 100% fly ash with varying volumes of steel fibers (0%, 0.5%, and 1%). The second group contains 90% fly ash with 10% cement and varying volumes of steel fibers (0%, 0.5%, and 1%). The third group contains 80% fly ash and 20% cement with varying volumes of steel fibers (0%, 0.5%, and 1%).

Mixing design number 10 consists of 100% geopolymer concrete without fibers and rubber crumbs. To achieve consistent workability in each mixing design and to achieve a slump of approximately 20 ± 100 millimeters, a superplasticizer of 6.2 kilograms per cubic meter and an alkali solution of 163.2 kilograms per cubic meter were added to each mixing design. The mixing design for the samples is provided in "Table 1".

2.3. Conducted Experiments

In this study, the compressive strength test was conducted based on the BS EN 12390 standard [18], using cubic specimens with dimensions of 100 millimeters. Additionally, the splitting tensile strength test was performed according to ASTM C496 [19] regulations. The specimens for this test were cylindrical with a diameter of 15 millimeters and a height of 30 centimeters. The ultrasonic pulse velocity test [20] was carried out following ASTM C597 standards using a DUNDIT MODEL PC1012 with an accuracy of ±0.1 microseconds for a transducer frequency of 55 KHz and ±2% for time-of-flight measurement. The parameter measured by the ultrasonic testing device was the transit time in microseconds, from which the wave velocity through the samples was determined considering their dimensions. The concrete resistance against dynamic (impact) loads was assessed based on the ACI 544-2R committee report [21] using the drop weight hammer test. In the current investigation, the weight-drop testing device with repeated impact loads was applied to disc specimens with a diameter of 15 centimeters and a height of 63.5 centimeters. The number of repetitive impacts (a weight of 4.54 kilograms dropped from a height of 457 millimeters) on a steel anvil placed at the center of the sample's surface was recorded to reach a specific level of cracking (first visible crack and complete spalling).

3. Results and Discussion

3.1. Compressive and Tensile Strength Test Results

In this section, the results of the conducted evaluations and the influence of parameters on compressive and tensile strength test results, including the presence of rubber crumbs, substitution of cement for fly ash, and the impact of steel fibers, are presented.

As illustrated in "Figure 1," the compressive strength values increase with the addition of steel fibers. In the current study, the reason for the increased compressive strength in specimens containing steel fibers can be explained as follows: since concrete containing rubber crumbs has lower and softer resistance compared to ordinary concrete, the fibers present in the concrete act before the complete failure of the sample due to cracks created in the concrete. These fibers enhance the resistance of the specimen. Under axial loads, cracks occur in the microstructure of the concrete. The most significant effect of fibers is preventing crack propagation in geopolymer concrete. Therefore, the ability of fibers to transfer stress prevents the development and propagation of microcracks caused by internal stresses in the concrete.

Considering the shape and quantity of fibers, they bear some of the stresses occurring within the fly ash matrix and transfer the rest to the stable portions of the fly ash matrix [6, 22]. Similarly, Seymouz et al. stated in their research that, in general, the compressive strength of concrete mixtures increases with the addition of fibers. This increase is due to the constraints imposed by the fibers in the concrete. Under compressive force, concrete tends to expand due to the Poisson effect, while fibers counteract this effect, resulting in an increase in compressive strength [23]. According to Figure 2, the increase in compressive strength with the addition of 0.5% steel fibers in mixtures containing 80%, 90%, and 100% fly ash is 9%, 4%, and 2%, respectively, and the increase in compressive strength with the addition of 1% steel fibers is 21%, 8%, and 26%, respectively.

Substituting cement as part of the fly ash, as previously mentioned, can increase hydration and may enhance compressive strength. According to Figure 2, replacing 10% of cement has either maintained or decreased compressive strength in the samples, and replacing 20% of cement instead of fly ash has decreased compressive strength in all samples. This can be attributed to two related factors. First, based on previous research [9], the optimal replacement percentage for substituting cement instead of fly ash in geopolymer concrete has been stated as 5%, and higher amounts have led to a decrease in compressive strength. The second factor is the curing temperature, which becomes significant with the addition of cement. As mentioned earlier, geopolymer concrete curing is conducted at a temperature of 60 degrees Celsius, while adding cement may alter the curing temperature and the required time for curing to increase compressive strength.

Adding steel fibers to geopolymer concrete (containing fly ash and rubber particles) increased the tensile strength. In Figure 3, it can be observed that with an increase in the volume percentage of fibers from 0 to 1%, the tensile strength of the mixtures in the first to third groups increased from 2.3, 3.92, and 3.26 MPa to 3.4, 4.9, and 3.86 MPa, respectively. The ability of fibers to prevent crack propagation can be considered a factor in this increase. The mechanism of increasing tensile strength is due to the presence of fibers, which involve stress transfer through surface shear between the matrix and fibers or through interlocking of fibers and matrix (if the fiber surface undergoes deformation). This stress sharing between the matrix and fibers continues until the matrix cracks, after which all stresses are transferred to the fibers. Thomas and Ramaswamy also attributed the increase in tensile strength of concrete containing steel fibers to the bridging effect of fibers in the cement matrix. Substituting 10% of cement resulted in an increase in tensile strength in all samples, and then, with further substitution up to 20%, the tensile strength decreased. In other words, the optimal percentage of cement substitution considering tensile strength is stated as 10%.

3.1.1. The relationship between compressive strength and tensile strength

In Table 2, the relationship between compressive strength and tensile strength is presented by various researchers. Relationship number 1 is derived for conventional concrete, Relationship number 2 represents the correlation between strengths in low-calcium geopolymer concrete cured at ambient temperature and Relationship number 3 is suitable for geopolymer concrete

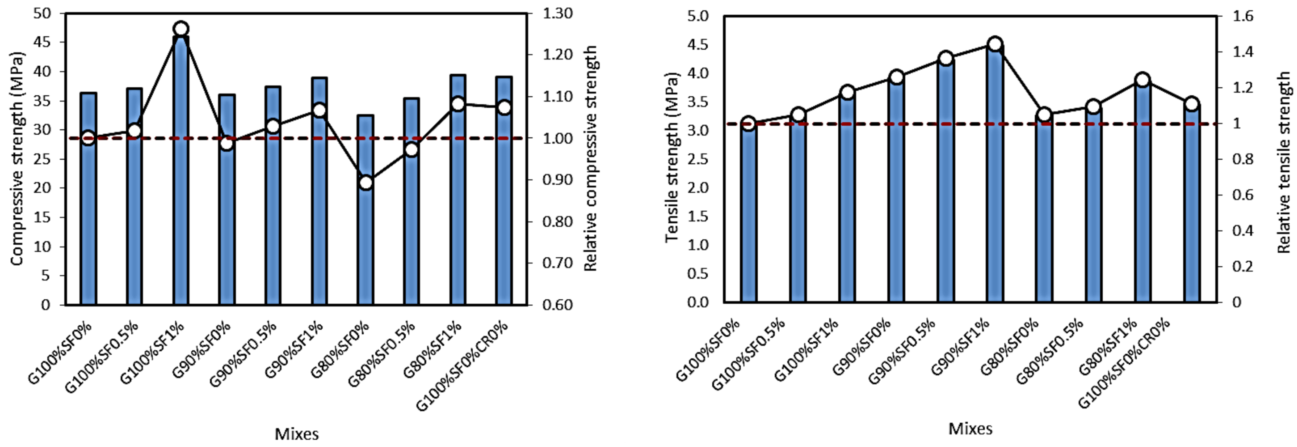

Figure 1: Variations in the values of compressive and tensile strengths of the specimens

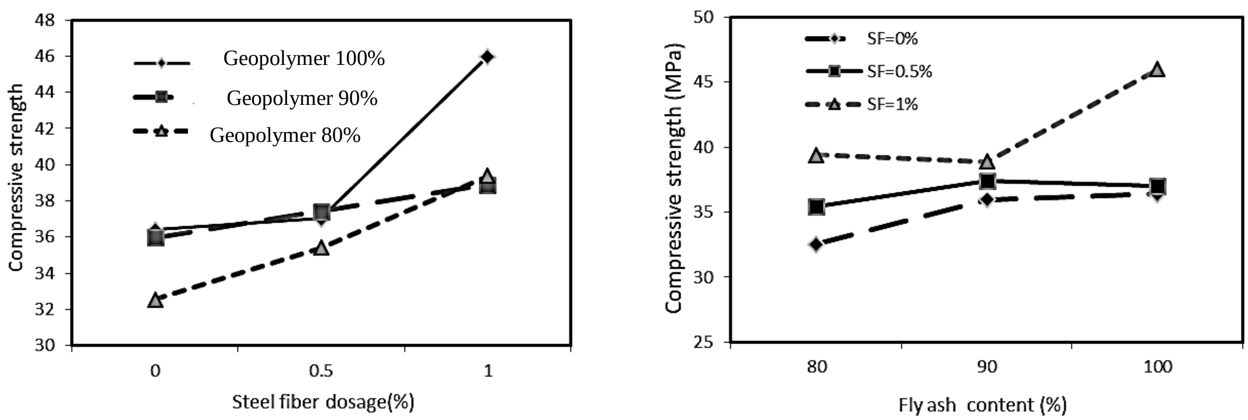

Figure 2: The effect of steel fibers and cement substitution instead of fly ash on the compressive strength of the specimens

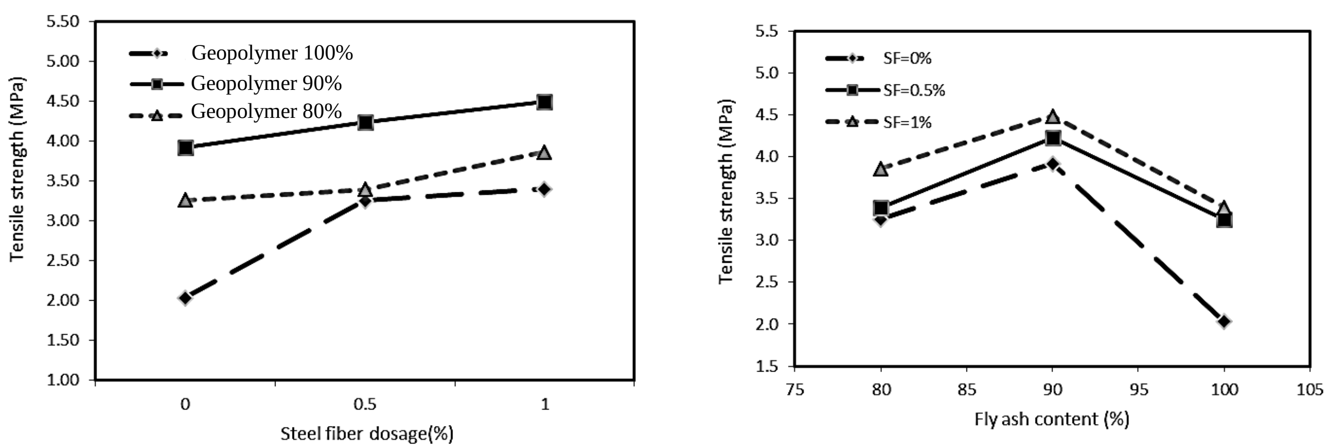

Figure 3: The effect of steel fibers and cement substitution instead of fly ash on the tensile strength of the specimens

cured in a furnace at 60 degrees Celsius. Relationship number 4 is derived in this study. As shown in Figure 5 Relationship number 1 which is used for conventional concrete, is very close to the relationship obtained in this study, with only a 7% difference between them. Relationship 1 predicts lower tensile strength values.

Relationship number 2, due to curing at ambient temperature has a significant difference from the relationship obtained with an average error percentage of 48% indicating that this standard cannot be used for geopolymer concrete cured at 60 degrees Celsius. Relationship number 3 presented here also has good agreement with the current study with an average error of 8%, and the predicted tensile strengths by this standard are higher than the obtained results.

Table 2
Predicted Equations between Tensile Strength and Compressive Strength

Number Eq	Equations	Reference
1	$f_t = 0.59\sqrt{f_c}$	ACI363R-92[26]
2	$f_t = 0.93(f_c)^{0.5}$	Nath [27]
3	$f_t = 0.69(f_c)^{0.5}$	Diaz[28]
4	$f_t = 0.7225(f_c)^{0.4632}$	This study

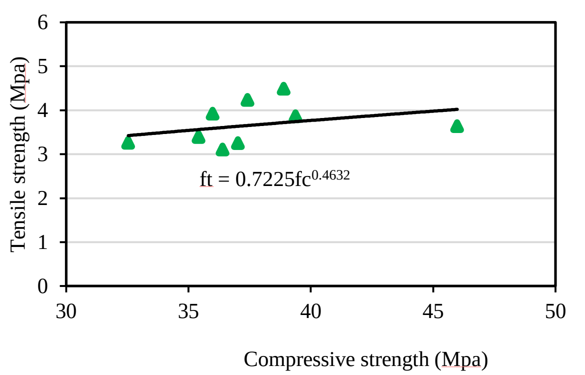

Figure 4: Relationship between Compressive Strength and Tensile Strength in Different specimens

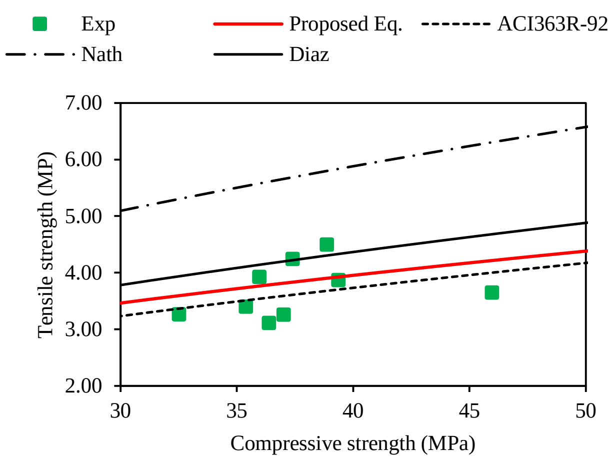

Figure 5: Relationship between Compressive Strength and Tensile Strength by the Current Study and Others

3.2. Results of the elastic modulus tests

Overall, it has been reported that geopolymer concretes processed at high temperatures have lower elastic moduli compared to normal concrete. According to the study by Olivia et al. [29], geopolymer concrete based on fly ash processed by heat with compressive strength of about 55 MPa showed an elastic modulus 14.9 to 28.8% lower than that of normal concrete at equivalent compressive strength. Hardjito et al. [30] reported that the elastic modulus of geopolymer concrete based on fly ash processed by heat is about 10% lower than that of OPC (ordinary Portland cement) concrete with similar compressive strength. Yost et al. [31] found that the elastic modulus of geopolymer concrete based on fly ash is 11 to 16% lower than the theoretical values predicted using ACI 318.

Regarding the effect of steel fibers on the modulus of elasticity of concrete, results are highly contradictory. Some researchers believe that concrete containing steel fibers has a higher elastic modulus compared to plain concrete [32], while others have suggested that there is very little difference between the elastic moduli of concrete containing steel fibers and plain concrete, and some have reported the opposite behavior [33, 34]. For example, Neves [35] observed that the presence of fibers slightly reduces the elastic modulus of concrete and explained that fibers oriented parallel to the loading direction act like voids, and additionally, the addition of fibers creates extra voids in the mix. Research on the effect of fibers on the elastic modulus of geopolymer concrete is very limited, and in a study conducted by Li Y on the effect of rubber particles and steel fibers on concrete, the influence of fibers on the modulus of elasticity of rubber-containing concrete was insignificant, similar to this investigation, and they explained that steel fibers act as good bridges between cracks, distributing and dispersing the load effectively, thus preventing crack propagation, resulting in increased compressive strength and modulus of elasticity [36].

In "Figure 6," the elastic modulus of the samples is plotted. The increase in the elastic modulus due to the addition of 0.5% fibers in samples containing 80, 90, and 100% fly ash was 6.9%, 6.4%, and 5%, respectively, and by adding 1% fibers, it was 10%, 15%, and 11% compared to the fiber-free sample in the same group. The effect of substituting cement for fly ash has also been such that the modulus increased with 10% cement replacement and decreased with further substitution.

3.2.1. Relationship between elastic modulus and compressive strength

Figure 7 illustrates the variations of elastic modulus with changes in compressive strength. The elastic modulus increases with increasing compressive strength. The prediction of elastic modulus of the samples was made based on the compressive strength obtained in the present study and using the equations provided in Table 3. The predicted values are presented in Figure 7. Equation number 1 is for normal concrete, while equations number 2 and 3 are for geopolymer concrete. As evident from Figure 7 although equation number 1 is provided for normal concrete, it showed good alignment with the present research with an average error of 5%. Equation number 2 specific to geopolymer concrete with fly ash, exhibited an average error of 10%, and equation number 3 for geopolymer concrete with low-calcium fly ash cured at room temperature, showed a discrepancy of approximately 16% compared to laboratory results. This emphasizes the importance of curing temperature, and in this study, conducted at a curing temperature of 60 degrees Celsius, the use of codes prescribing curing at room temperature may not be appropriate.

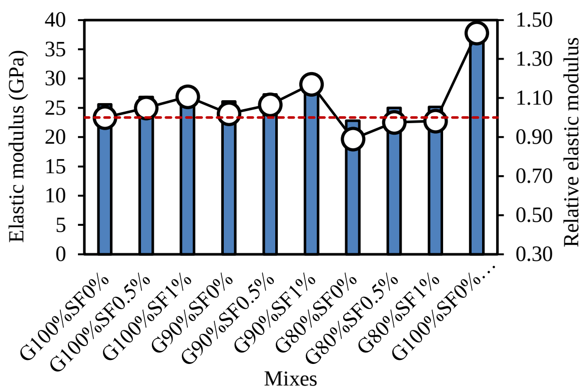

Figure 6: Variations in the values of elastic modulus for the specimens

Table 3
Relationship between elastic modulus and compressive strength of specimens

Number Eq	Equations	Reference
1	$E_c = 3320\sqrt{f_c'} + 6900$	ACI 363[37]
2	$E_c = 0.037 \times \rho^{1.5} \times \sqrt{f_c}$	Diaz-Loya et al.(GC)[41]
3	$E_{cj,a} = 3510\sqrt{f_c}$	Pradip and Sarker(GC)[27]
4	$\boldsymbol{E_c = 3116.9(f_c)^{0.5881}}$	This study

3.3. Results of Ultrasonic Pulse Velocity (UPV) Test:

3.3.1. Results of UPV Test:

The UPV is influenced by various physical and mechanical properties of the samples. Therefore, multiple parameters such as operational conditions, concrete porosity, aggregate type, Interfacial Transition Zone (ITZ) characteristics, sodium hydroxide concentration, additives

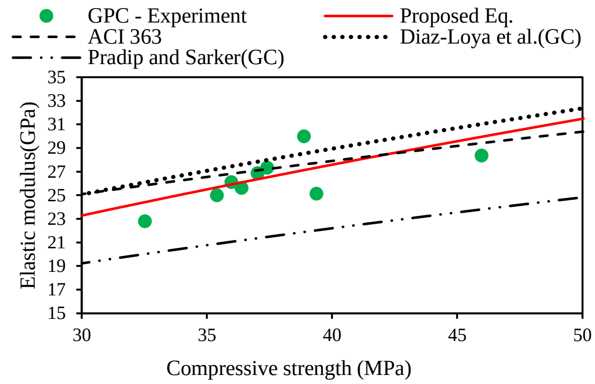

Figure 7: Comparison of the relationship between elastic modulus and compressive strength in the current study and other researches, along with the calculation of prediction error

(like steel fibers, rubber crumbs, etc.), aggregate ratio, size, geopolymer material type (e.g., fly ash, slag, metakaolin, etc.), test ambient temperature, concrete age, etc. play a significant role in this test. This method serves to estimate concrete quality by employing regression analysis between compressive strength and UPV. The UPV passing through the samples is observable in Figure 8.

The findings indicate that the addition of fibers leads to an increase in ultrasonic wave velocity. However, this increase is relatively small, typically less than 12.5%. Similar minimal impacts of fibers on UPV have been reported elsewhere with researchers attributing negligible variations to uniformity in the concrete matrix across all mixtures [44]. This rise may be due to the fact that UPV in steel is typically 1.2 to 1.9 times higher than in geopolymer concrete [45].

According to Chart 6 all designs fall within the good range [46]. As long as UPV values are within this category, it indicates that the concrete in question lacks cracks or voids that could compromise its structural integrity [47]. Conversely substituting cement for fly ash had little effect on wave velocity. In geopolymer concrete, operating in dry environment of an oven leads to the formation of fine cracks, voids and micro-fractures which diminish the material's integrity resulting in lower ultrasonic wave transmission rates. However, fly ash exhibits a lower reduction in speed due to its effective pore-filling properties. These cracks are typically fine and mainly affect ultrasonic wave velocity with minimal impact on sample compressive strength [48].

In design 10, 100% fly ash geopolymer concrete without fibers and rubber crumbs was used with results indicating an increase in ultrasonic wave velocity in samples without rubber crumbs. This phenomenon can be attributed to the nature of rubber crumbs and their cavities which reduce wave velocity. Specifically, the UPV in the sample containing rubber crumbs (design 1) decreased by 12%

compared to the sample without rubber crumbs (design 10).

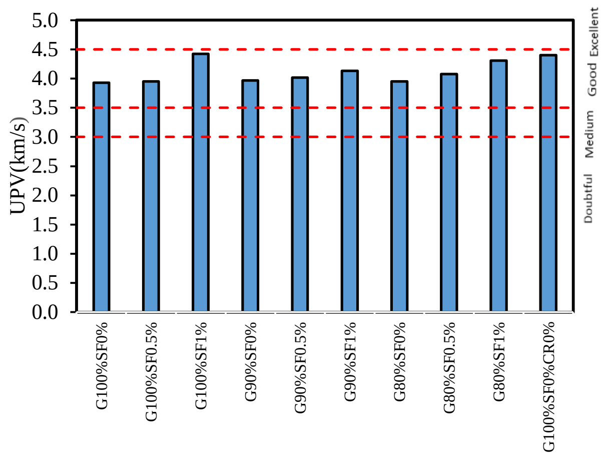

Figure 8: Variation in UPV Values of Samples

3.4. Results of Impact Resistance Tests

The impact test results for the mixing designs are presented in Figure 10. In a study, adding 10% rubber crumbs to geopolymer concrete increased the impact energy for the initiation of the first crack and ultimate failure by less than 20% [49]. In all groups, as the percentage of steel fibers increased to 0.5% and 1%, the number of impacts increased both for the initial crack and final fracture. This implies that the energy absorption capacity in geopolymer concrete increases with the addition of fibers. In another study by Aziza Islam et al. [8], it was found that adding 0.5% steel fibers increased the impact resistance for the initiation of the first crack by 1.1 to 1.3 times. They attributed this improvement to the fibers preventing the growth of microcracks and reducing the propagation of small cracks before they connect and form a larger, more effective crack. However, the greatest effect of fibers is observed in preventing complete fracture, which delays the complete failure of specimens. In the study [8], adding steel fibers increased the energy required for complete failure by 3.1 to 3.6 times. The improvement in performance due to the addition of steel fibers to geopolymer concrete against impact tests has also been observed in other studies [50-52]. As it is evident, the effects of steel fibers on impact resistance are much greater than those of rubber crumbs, which is why the replacement percentage of rubber crumbs remains constant (10%), and the effects of steel fibers on impact resistance have been observed. In normal concrete [53], adding 0.5% fibers increased the impact energy to initiate the first crack by approximately 30% and complete fracture by about 40%. The increase for 1% fibers was 120% and 150%, respectively, indicating that the effect of steel fibers on increasing impact energy in geopolymer concrete is greater than in ordinary concrete. In the present study, adding 0.5% steel fibers to specimens containing 80%, 90%, and 100% fly ash increased the impact energy for initiating the first crack by 5%, 6%, and 5.6%, respectively, and adding 1% fibers increased this value to 13%, 12%, and 19%, respectively. Furthermore, adding 0.5% steel fibers increased the impact energy for complete fracture by 16%, 12%, and 22%, and adding 1% fibers increased this value to 64%, 49%, and 50%, respectively. As the results show, adding fibers has a greater effect on complete fracture than on the initiation of the first crack. The flexibility index, obtained by dividing the absorbed energy until complete fracture by the energy required to initiate the first crack, indicates that adding steel fibers has increased the flexibility index of geopolymer concrete, with a much higher increase observed for adding 1% fibers than for adding 0.5% fibers. The absorbed energy, which is equal to the difference between the energy required for the first crack and the energy required for complete fracture, is shown in Figure 11. It is evident that adding steel fibers increases the absorbed energy, with a greater increase observed for concretes with 20% cement replacement. The percentage of absorbed energy also indicates the significant effect of steel fibers after the initiation of the first crack until complete fracture. On the other hand, based on the obtained results, it can be concluded that replacing cement with fly ash in geopolymer concrete has no significant effect on the impact resistance of the specimens.

3.4.1. The Impact of Rubber Crumbs on Impact Resistance

This section examines the effect of rubber crumbs on impact resistance. For this purpose, 100% geopolymer concrete containing various amounts of steel fibers was used in two conditions: without rubber crumbs and with 10% rubber crumbs. The energy required to initiate the first crack, the energy required for complete failure of the specimens, and the energy absorbed by the concrete are shown in Figure 12. It is evident from the results that adding 10% rubber crumbs increases the amount of impact energy until the initiation of the first crack, with the increase being 5.7% for specimens without steel fibers, 5.6% for those with 0.5% fibers, and 11.1% for those with 1% fibers. The energy required for final failure has also increased, with increases of 1.9%, 12.2%, and 17.8%, respectively. The amount of energy absorbed by the concrete due to the addition of fibers has also increased by 36.4%, 53.1%, and 41.7%, respectively, with the values increasing from 224 to 305, from 651 to 997, and from 1221 to 1730 joules. It is evident that the improvement in impact energy with the help of rubber crumbs is slightly higher in concrete with higher percentages of steel fibers. The increase in absorbed energy due to the addition of

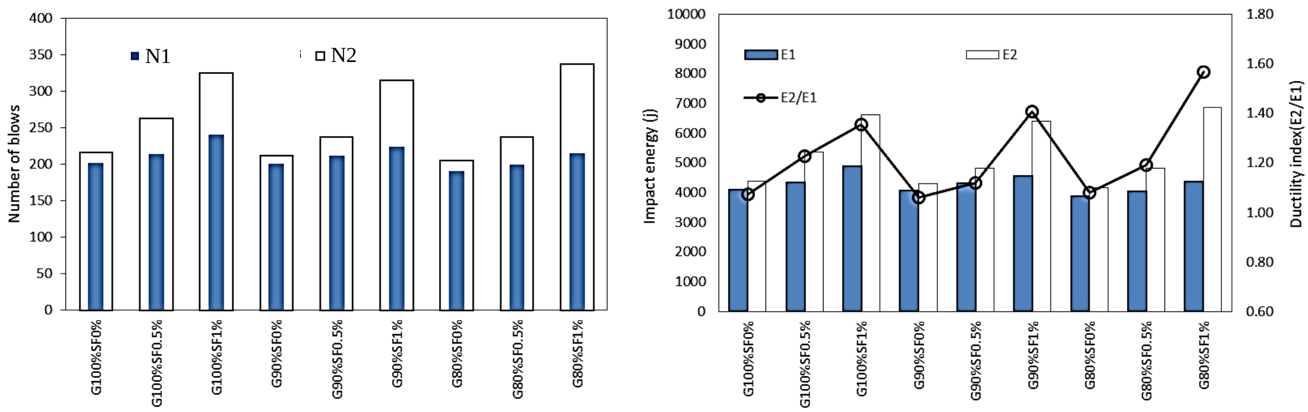

Figure 10: Number of impacts and impact energy until the initiation of the first crack and final fracture of specimens

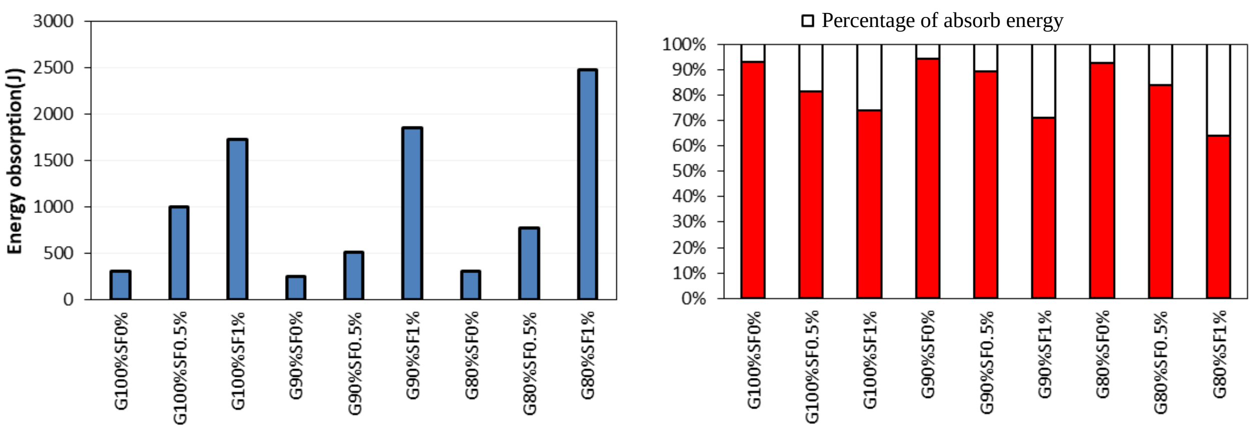

Figure 11: Variations in the amount and percentage of absorbed energy with different fiber contents for various fly ash and cement compositions

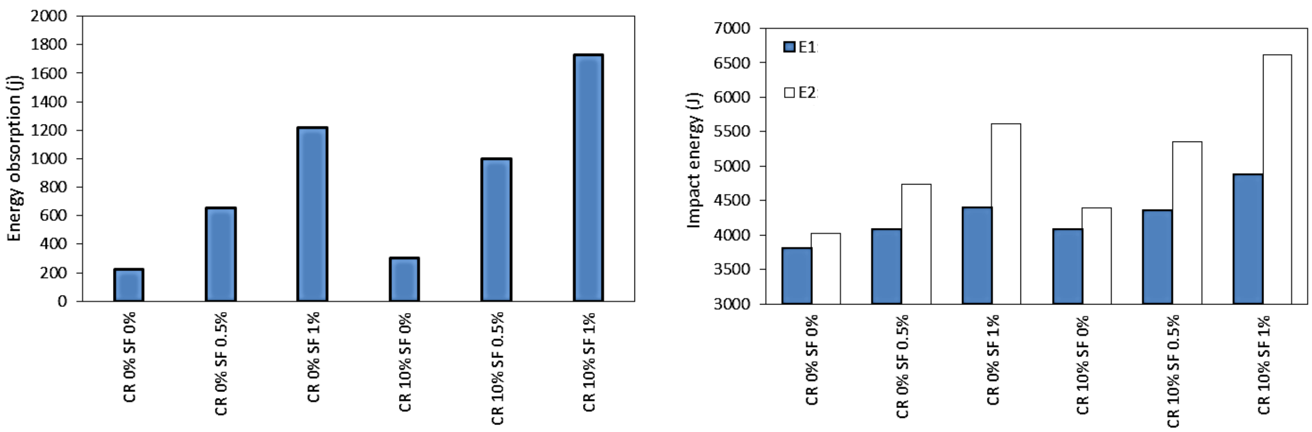

Figure 12: Comparison of the impact energy and the amount of energy absorbed for the sample without rubber crumb and containing 10% rubber crumb

rubber crumbs can also be justified by the decrease in ultrasonic wave velocity resulting from the addition of rubber crumbs. In this study, adding 10% rubber crumbs has resulted in a 12% reduction in ultrasonic wave velocity, indicating that rubber crumbs, due to their material properties and inherent porosity, have been able to attenuate some of the ultrasonic wave energy. This phenomenon holds true for impact energy as well, as adding rubber crumbs has increased the energy absorbed during impact testing.

3.5. Results of SEM, XRD, and XRF

The outcomes from scanning electron microscopy (SEM) can significantly aid in identifying the structure and behavior of concrete. In Figure 13 on the left side the steel fibers used in design 3 are evident. Steel fibers with their bridging properties between cracks and cohesive effect on concrete have a significant impact on enhancing geopolymer concrete [54]. Panda and Padhi [55] conducted an SEM analysis in their study on the characteristics of rubber-containing concrete to examine the bond properties of rubberized concrete. They stated that rubber crumps act as a barrier against crack propagation and reduce the initiation of primary cracks [56]. According to their findings rubber crumps appear as voids within the geopolymer paste forming a weak bond with it. Researchers in SEM experiments on rubber-containing concrete have indicated the presence of gaps (voids) between the geopolymer paste and rubber particles [57, 58]. They attributed the existence of these gaps to the weak bond between the geopolymer paste and rubber particles. On the right side of Figure 13 the microstructure presents in design 9 geopolymer concrete is evident. There are numerous voids in the concrete, which can be attributed to the presence of rubber crumps. Many researchers in SEM experiments on rubber-containing concrete have pointed out the presence of voids between the cement or pozzolan paste and rubber crumps [57, 58]. They attributed the existence of these voids to the weak bond between the rubber crumps and other concrete constituents. In a study [59, 60] that examined the effect of geopolymer concrete microstructures based on fly ash after adding Portland cement to it, it was acknowledged that the addition of cement leads to a denser and more compact concrete due to the improved microstructure resulting from the proximity of hydrated products along with the alumina silicate polymer structure.

The chemical analysis and physical characteristics of geopolymer concrete based on fly ash according to ASTM C618 [61] standard is provided in the table below. As evident from the XRF results in Table 4, with the addition of 10% cement to the fly ash-based geopolymer concrete, the levels of SiO_2 and Al_2O_3, which are the main constituents of geopolymer concrete, have decreased by 13.6% and 36.8%, respectively, while the levels of CaO and Fe_2O_3 have increased significantly. LOI indicates the weight loss due to combustion at 1000°C, providing a good estimate of the carbon content as a meaningful constituent, which is 27% higher in Design 6 compared to Design 1.
The XRD results for Designs 1 and 6 are illustrated in Figure 14. For this experiment, sections of the central parts of the specimens were separated and ground into uniform powders for testing. According to researchers' findings, the peak intensities are displayed between 15° to 40°, indicating variations in atomic arrangements and structures. By studying the angles at which the XRD peaks are formed and their relative intensities, the materials and their phases can be identified. It is evident that the major difference in the results of the two designs lies in the peak intensity, which is higher in Design 6. The primary reason for this increase is the presence of calcium.

4. Conclusion

This study investigated the mechanical properties of fly ash-based geopolymer concrete containing steel fibers and crumb rubber. The variations included 0.5% and 1% steel fibers and the substitution of cement with fly ash by 10% and 20%. The following conclusions were drawn from the conducted experiments:

1- Compression and tensile strength tests revealed that adding steel fibers to geopolymer concrete increases both strengths. Specifically, the addition of 0.5% steel fibers increased compressive strength by 4% to 60%, while for 1% steel fibers it ranged from 14.5% to 67%.

2- Regarding tensile strength, adding 1% steel fibers improved it by 14.5% to 70%. Additionally, it was observed that replacing cement with fly ash did not significantly affect compressive strength but adding 10% cement could be considered the optimal replacement amount in terms of tensile strength with further replacement resulting in reduced tensile strength.

3- Elastic modulus testing indicated that adding steel fibers increased the modulus of elasticity and replacing 10% of cement with fly ash also increased it.

4- Ultrasonic wave testing results demonstrated good quality for all samples. The increase in fibers led to an increase in the speed of wave transmission through the concrete. The substitution of cement with fly ash had little effect on wave speed.

5- Impact resistance test results showed a significant impact of steel fibers on the number of impacts until the first crack initiation and complete failure of the specimens. Adding fibers increased the resistance to complete failure by 12% to 22% for 0.5% fibers and 49% to 64% for 1% fibers. Moreover, replacing cement with fly ash had minimal effect on concrete resistance to impact. Substituting 10% crumb rubber improved the impact energy of the concrete increasing the energy until the first crack initiation by 10%, energy until complete failure by 15%, and absorbed energy by 43% on average.

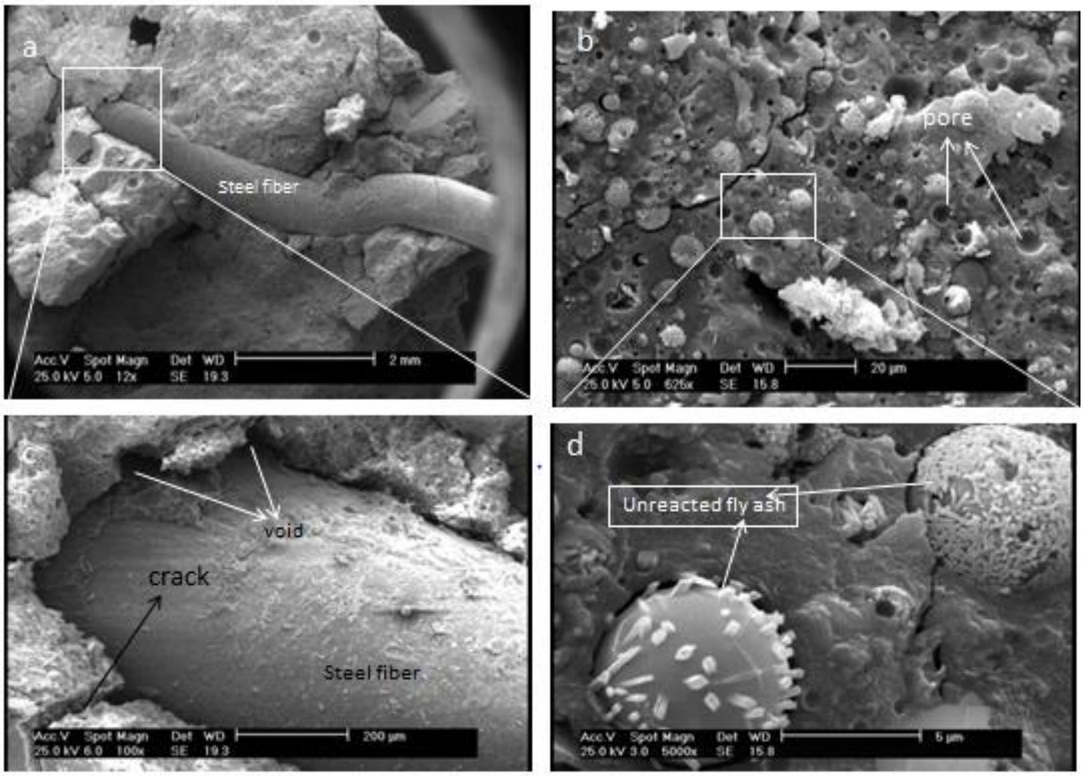

Figure 13: SEM microstructure for geopolymer concrete containing rubber crumps and steel fibers: (a, c): mix 3; (b, d): mix 9

Table 4
XRF Test Values for Samples of mixes 1 and 6

Chemical composition of materials in the composition of concrete								Mix Id
LOI	Fe_2O_3	NA_2O	K_2O	MgO	CaO	AL_2O_3	SiO_2	
7.97	0.03	1.13	0.0	2.62	0.04	17.1	71.1	Mix 1
10.18	3.13	1.89	2.4	1.45	7.9	10.8	61.4	Mix 6

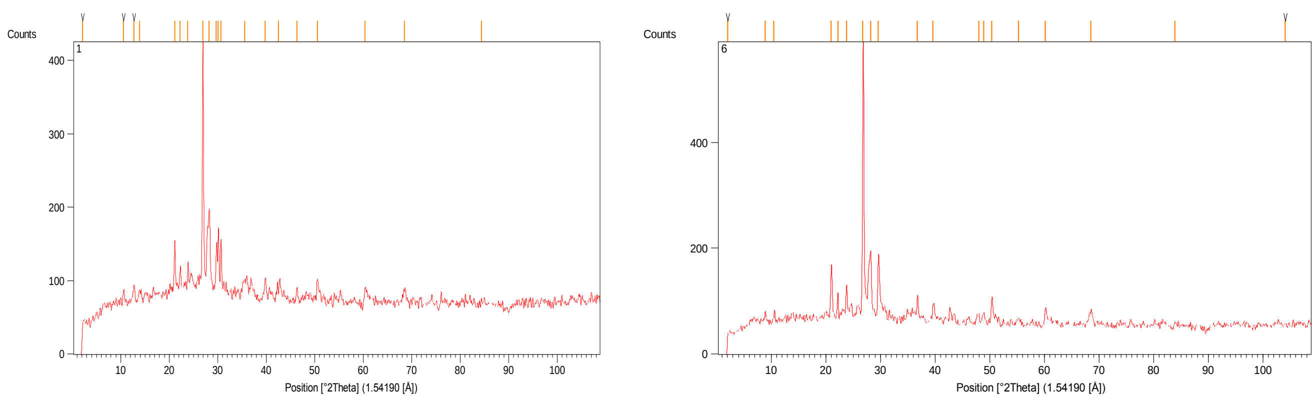

Figure 14: XRD for Samples of mixes 1 and 6

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