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*Research Article*

# A comparative study between linear regression analysis and various codes for predicting the mechanical characteristics of polymer concrete using R-sand and M-sand

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**Abstract:** Numerous research studies have concentrated on advancing a sustainable construction industry through innovative concrete methods and materials. In this context, the present research specifically investigates polymer concrete, utilizing both River sand (R-sand) and Manufacturing sand (M-sand). The polymer content was incorporated into the concrete mix based on the weight of the cement, with varying percentages specifically 2%, 4%, 5%, 6%, and 8%. A slump cone test was conducted to assess the workability of the polymer concrete. Based on experimental studies, the optimal polymer percentage was determined to be 5%. This optimal dosage of polymer content significantly improved the mechanical properties of the polymer concrete. The Compressive Strength (CS), Split Tensile Strength (STS), Flexural Strength (FS), and Modulus of Elasticity (ME) were evaluated at both 7 and 28 days. When using R-sand, the mechanical properties of CS, STS, and FS increased by 13.65%, 12.20%, and 11.42%, respectively. Conversely, employing M-sand led to even greater improvements in strength properties: 19.18% for CS, 12.54% for STS, and 11.67% for FS. Based on the experimental results, the strength properties of polymer concrete M-sand mixes outperformed the R-sand mixes. Linear regression analysis and various codes were employed to predict the strength properties of CS, STS, FS and ME. The regression analysis and various codes successfully forecasted the strength properties of polymer concrete, with the predicted results closely correlated with the experimental results. Based on experimental investigations, the determined mix proportions are recommended for practical applications in various environmental conditions.

**Keywords:** polymer concrete, linear regression analysis, strength properties, R-sand, M-sand.

## 1. Introduction

In recent times, the construction industry has heavily relied on natural resources, particularly river sand as a fine aggregate and quarry rock as a coarse aggregate. Additionally, alternative materials such as lime, fly ash, silica fume, and ground granulated blast furnace slag have been introduced to replace cementitious materials in concrete production. Polymer-modified concretes, developed in the early 1960s, exhibit high performance. Researchers have explored the differences between individual polymers and polymer-modified concrete. Unlike traditional water-cement-based materials, polymer-modified concrete consists of well-graded aggregates bonded by a strong resin binder. These concrete offer strength, durability, and rapid curing a crucial consideration in various civil engineering applications (Yamada, 1986). Notably, polymer concrete can effectively restore spalled or damaged structural components, including buildings, hydraulic and irrigation structures, bridges, precast elements, and industrial floors (Mebarkia & Vipulanandan 1995). Its properties include high strength, resistance to freeze-thaw cycles, rapid setting times, and the ability to withstand corrosive environments. Furthermore, polymer concrete is lighter than Ordinary Portland Cement concrete, making it a valuable choice for structural applications (Rebeiz et al., 1995).

Polymer concrete consistently exhibits superior mechanical properties compared to ordinary cement concrete, although these properties can vary based on the type of polymer, its nature, and concentration. This inherent versatility allows Polymer Concrete (PC) to be adapted across a wide spectrum of structural and repair applications. When produced using conventional materials, polymer concrete yields composites with excellent mechanical properties. Additionally, by incorporating a diverse range of additive materials, polymer concrete can exhibit complex properties, enabling tailored design for specific applications. Researchers also explore the impact of commonly used polymers as binders in polymer concrete production, including poly-ester styrene, acrylic, and epoxy. Resins such as vinyl ester, furan, and urea are also employed in polymer concrete. Notably, epoxy resin serves as a suitable polymer modifier for concrete (Fowler, 1999). Among these, vinyl ester polymer concrete outperforms epoxy polymer concrete in terms of CS. The mechanical strength of both types of polymer concrete depends on the filler materials incorporated. These fillers enhance strength properties while promoting cost-effectiveness in production (Lokuge & Aravinthan, 2013).

Polymers, combined with various types of fillers, play a crucial role in enhancing the properties of polymer concrete. These polymers exhibit excellent binding properties and strong adhesion to aggregates. Their long-chain structure facilitates the development of an extensive network bonding structure, resulting in superior behaviour compared to ordinary concrete. Although only a small amount of polymer is needed to produce Polymer Concrete (PC), the specific filler material size influences the required quantity. Cheaper filters lead to reduced polymer consumption. Coarser fillers typically necessitate 5% to 15% binder, while fine fillers may require around 30%. The best practice involves achieving the most economical polymer concrete by minimizing polymer usage (Noruzman, 2019). Additionally, different filler materials, such as fly ash and silica fume, exhibit distinct properties. Polymer concrete incorporating fly ash as a filler demonstrates better CS than that with silica fume. Furthermore, fly ash-based PC exhibits high flexural strength and split tensile strength (Bărbuţă et al., 2010).

The inclusion of an acrylic polymer in mortar significantly enhances its mechanical properties and adhesion to steel fibres (Mandel & Said 1990). Meanwhile, polymer-modified mortars utilizing both epoxy and acrylic emulsion exhibit superior strength properties and improved resistance to chloride ion penetration and carbon dioxide (Aggarwal, 2007). By incorporating an aqueous polymer emulsion into fresh concrete mixes, polymer modification occurs. This enhancement is evident in concrete’s CS, STS and FS, as well as its overall performance. Researchers have determined that an optimal dosage of 15% polymer yields maximum CS. Additionally, they recommend using the polymer in a colloidal dispersion state to achieve significantly improved concrete properties at a reasonable dosage and cost (Sivakumar, 2011). Polymer concrete, also known as resin concrete, comprises a polymer binder often a thermosetting polymer and a mineral filler such as aggregate, gravel, or crushed stone. Compared to conventional Portland cement concrete, polymer concrete (PC) boasts higher strength, lower water absorption, enhanced chemical resistance, and greater freeze-thaw stability (Golestaneh et al., 201). Specifically, polyester based polymer concrete, when incorporating fly ash as a filler, exhibits approximately 75% improvement in mechanical strength and water absorption (Varughese & Chaturvedi, 1996). Furthermore, when comparing PC to cement concrete, the use of fly ash as filler material results in increased CS. Notably, PC achieves a peak modulus of elasticity of 29 GPa with this filler material (Gorninski et al., 2004).

Several researchers have reported that replacing natural sand with quarry dust in concrete is feasible, provided proper treatment of the quarry dust is undertaken. Their findings indicate that concrete made from quarry rock dust exhibits nearly 10% higher CS. STS, FS and improved durability compared to conventional concrete (Mohr et al., 2007; Muthukumar & Mohan, 2004). However, substituting sand with stone dust does reduce the workability of the concrete. On the other hand, the CS and STS of concrete mixes increase by up to 40% when sand is replaced with stone dust. Remarkably, concrete produced by replacing natural river sand with crushed stone dust waste achieves comparable CS, STS, and modulus of rupture as the control concrete. Additionally, this replacement results in a lower degree of shrinkage compared to the control concrete. The researchers concluded that the CS, STS and durability properties of concrete made from quarry rock dust are nearly 14% higher than those of conventional concrete (Vipulanandan & Paul, 1993).

Furthermore, manufactured sand serves as a suitable replacement for the increasingly scarce natural sand in premixed concrete. The Cement Concrete and Aggregates Australia (CCAA) conducted research, provided data, and developed guidelines to support the use of manufactured sand as a replacement for natural sand. While the benefits of fines on concrete have been discussed in various ICAR symposium papers, the focus typically centers on concrete made from M-sand rather than R-sand (Thomas & Ramaswamy, 2007). Researchers have explored the performance of stone dust as a fine aggregate replacement for sand in both concrete and mortar. Their findings indicate that up to 40% of sand can be effectively replaced by stone dust in concrete mixes without compromising strength. Moreover, they concluded that autoclaved stone dust concrete exhibits superior strength and durability compared to standard high-strength concrete (Jiang et al., 2014).

When it comes to concrete strength properties, partial replacement of cement with fly ash and sand with quarry dust has been investigated. The results suggest that quarry dust initially enhances strength during the early period, but the improvement diminishes after 28 days, leading to reduced workability. Additionally, the impact of manufactured sand in concrete has been studied. For optimal results, fine particles below 600 microns should constitute 35% to 45% of the mix. However, particles below 150 microns, which can weaken the concrete, should be removed. The conclusion drawn is that manufactured sand can successfully replace ordinary river sand, achieving the desired concrete strength (Garbacz & Sokołowska, 2013). Furthermore, concrete cubes incorporating crusher dust demonstrate approximately 17% higher CS, 7% more STS, and 20% greater FS compared to cubes and beams using river sand as the fine aggregate (Soroushian & Bayasi, 1991). However, it's essential to note that durability properties may be compromised when using quarry dust in concrete mixes (Muthukumar & Mohan, 2004).

(Zhou et al., 2024) investigated methods to predict the compressive strength of geo-polymer concretes (CSGPoC) with high accuracy. Geo-polymer concretes utilize gel to replace portions of cement, rendering them environmentally friendly. However, direct measurement of CSGPoC strength can be labor-intensive and costly. The study employed two methodologies: a base learner using Decision Tree (DT) models and a super learner system incorporating random forest and extreme gradient boosting (XGBoost) techniques for predicting compressive strength. (Niş & Altundal, 2023) investigated the durability of various alkali-activated concretes thoroughly under 5% sulfuric acid attack. The study employed visual inspection, weight change, and compressive strength tests to assess the influence of sulfuric acid attack on concrete performance. Alkali-Activated Slag (AAS) and Alkali-Activated Fly Ash (AFS) specimens can be utilized in structural applications due to their superior durability. Understanding the durability behavior of alkali-activated concretes under aggressive chemical environments is crucial for sustainable construction practices.

From the literature survey mentioned above, it becomes evident that traditional concrete made from Portland cement has inherent drawbacks, including low flexural and splitting tensile strength, high permeability, and limited chemical resistance. In response to these challenges, polymers have found applications aimed at enhancing strength, and durability, and facilitating rapid maintenance and repair in the construction industry. Polymers serve as matrix materials, modifiers, and adhesives in concrete. However, when used as structural and repair materials, polymers and composites must withstand substantial stresses under extreme service conditions. Research has revealed that polymers are not only valuable for repair and strengthening but also play a role in structural elements within the field of Civil Engineering. Notably, polymers significantly enhance the mechanical and durability properties of concrete due to their superior tensile strength compared to conventional concrete. In this context, a comprehensive literature review focused on studies related to the utilization of fine aggregates, specifically quarry dust or manufactured sand. The findings underscore the importance of replacing river sand with manufactured sand in concrete. The literature covers aspects such as mix design, fresh concrete properties, and the strength characteristics of polymer concrete when fine aggregate is replaced with M-sand. The current study involved 12 different mixes (6 with river sand and 6 with manufactured sand), allowing a direct comparison of the strength properties between polymer concrete and M-sand. A detailed research workflow is depicted in Figure 1.

## 2. Experimental study

### 2.1. *Materials*

The polymer concrete materials were collected, and their physical properties were tested according to BIS specifications, as detailed in Table 1. The physical properties of cement include a specific gravity of 3.16, initial and final setting times of 146 and 284 minutes, and CS at 7 and 28 days of 36.40 and 45.67 MPa, respectively, as per (IS - 8113: 2013). The physical properties of the fine and coarse aggregates are also listed in Table 1, tested per (IS – 383: 2016). For the fine aggregate used in polymer concrete (both R-sand and M-sand), the specific gravities are 2.68 and 2.69, respectively. The grading limit falls within Zone I, and the moisture content ranges from 0.28% to 0.72%. Regarding the coarse aggregate, the specific gravity is 2.70, the crushing value is 18.42%, and the moisture content is 0.42%. These properties were determined following the guidelines of (IS – 383: 2016). For mixing, portable water was used in the polymer concrete, with a pH value of 6.24, as indicated in Table 1. The chemical properties of the OPC 43 grade cement are reported in Table 2.

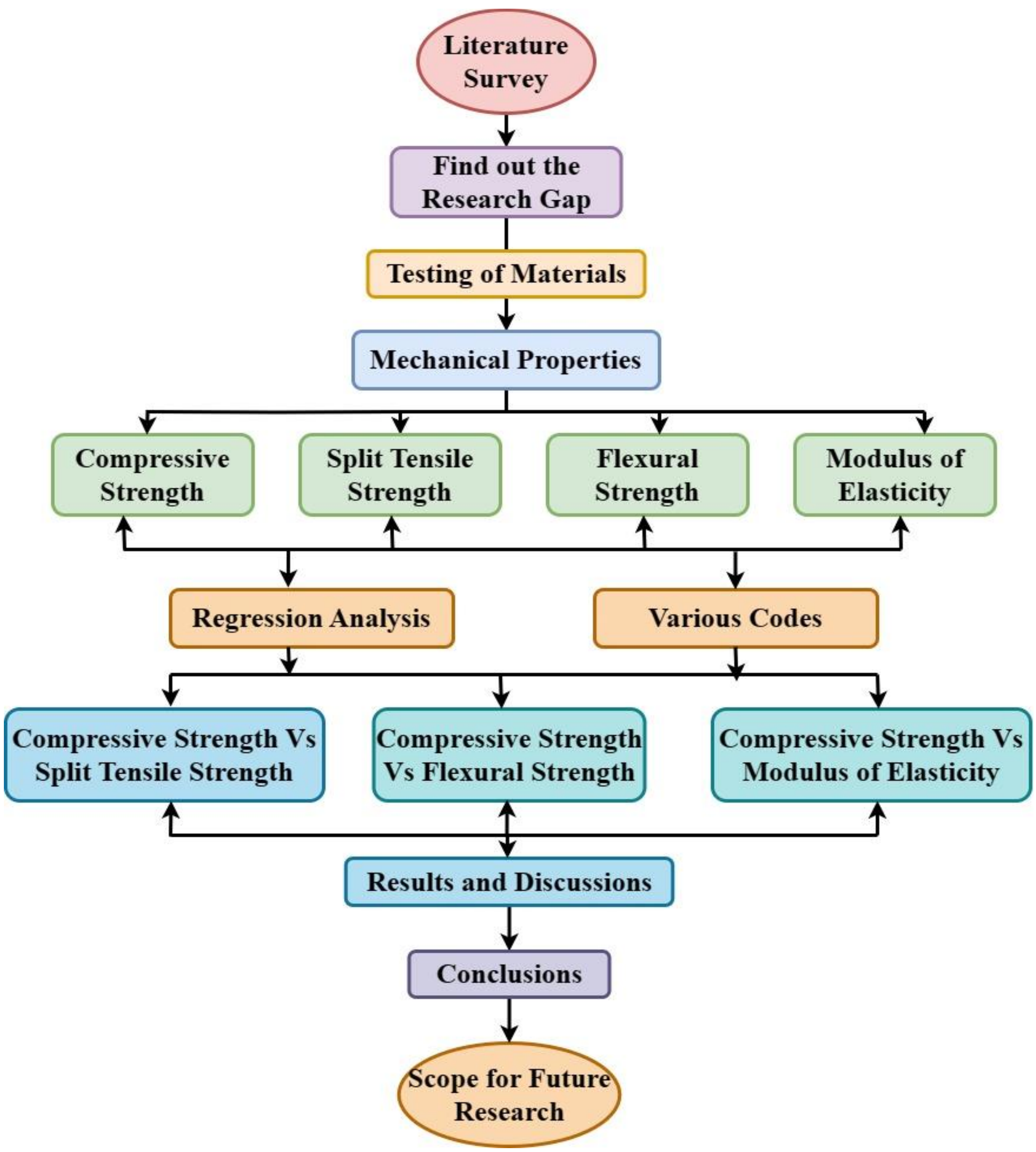



**Figure 1.** Flow char for research work.

**Table 1.** Physical properties of materials.

| S. No. | Name of the Materials | Tested values | |
|---|---|---|---|
| 1 | Cement | | |
| | Specific gravity | 3.16 | |
| | Consistency | 33% | |
| | Initial Setting time | 146 minutes | |
| | Final Setting time | 284 minutes | |
| | Compressive strength | | |
| | 7 days | 36.40 MPa | |
| | 28 days | 45.67 MPa | |
| 2 | Fine aggregate | River sand | M-sand |
| | Specific gravity | 2.68 | 2.69 |
| | Gradation limit | Zone-I | |
| | Moisture absorption | 0.28% | 0.72% |
| 3 | Coarse aggregate | | |
| | Specific gravity | 2.70 | |
| | Gradation limit | Graded aggregate as per IS 383:2016 | |
| | Crushing value | 18.42% | |
| | Moisture absorption | 0.42% | |
| 4 | Water | | |
| | $P_H$ value | 6.24 | |

**Table 2.** Chemical properties of the OPC 43 grade cement.

| Properties | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $Na_2O$ | LOI (%) |
|---|---|---|---|---|---|---|---|---|
| Cement | 22.89 | 4.93 | 3.52 | 62.17 | 2.38 | 2.59 | 0.65 | 0.53 |

### 2.2. *Mix proportions of polymer concrete*

The conventional and polymer concrete mix was prepared using 43-grade OPC cement, R-sand, M-sand, coarse aggregate, and locally sourced water. The polymer concrete was designed as M30 grade and adhered to the guidelines outlined in (IS - 10262: 2019). The mix proportions were determined as follows: 330 kg/m³ of cement, 550 kg/m³ of fine aggregate, 1200 kg/m³ of coarse aggregate, and 165 kg/m³ of water, with a water-cement ratio of 0.5. The specific mix proportions for the polymer concrete are provided in Table 3. For this research, 12 combinations were utilized. Among these, six blends were formulated using River sand (R-sand), while the remaining six mixes were developed with Manufacturing sand (M-sand). The cement content in both compounds varied at 2%, 4%, 5%, 6%, and 8%, respectively. In this study, the participants were divided into two groups, and each group had six different mix proportions. These mix proportions were labeled as ($M_{cc}$, $M_{RS2}$, $M_{RS4}$, $M_{RS5}$, $M_{RS6}$, $M_{RS8}$) for R-sand and ($M_{cc}$, $M_{MS2}$, $M_{MS4}$, $M_{MS5}$, $M_{MS6}$, $M_{MS8}$) for M-sand.

**Table 3.** Mix proportion of polymer concrete per 1m³ in kg/m³.

| Sample ID | Cement | R-sand | M-sand | Coarse Aggregate | Water | Polymer content ( %) |
|---|---|---|---|---|---|---|
| Mcc | 330 | 550 | - | 1200 | 165 | - |
| $M_{RS2}$ | 330 | 550 | - | 1200 | 165 | 2 |
| $M_{RS4}$ | 330 | 550 | - | 1200 | 165 | 4 |
| $M_{RS5}$ | 330 | 550 | - | 1200 | 165 | 5 |
| $M_{RS6}$ | 330 | 550 | - | 1200 | 165 | 6 |
| $M_{RS8}$ | 330 | 550 | - | 1200 | 165 | 8 |
| Mcc | 330 | - | 550 | 1200 | 165 | - |
| $M_{MS2}$ | 330 | - | 550 | 1200 | 165 | 2 |
| $M_{MS4}$ | 330 | - | 550 | 1200 | 165 | 4 |
| $M_{MS5}$ | 330 | - | 550 | 1200 | 165 | 5 |
| $M_{MS6}$ | 330 | - | 550 | 1200 | 165 | 6 |
| $M_{MS8}$ | 330 | - | 550 | 1200 | 165 | 8 |

Mcc-Reference concrete, $M_{RS}$-Polymer concrete made with river-sand, $M_{MS}$-Polymer concrete made with M-sand.

## 3. Experimental results and discussions

### *3.1. Fresh properties of polymer concrete*

The fresh properties of polymer concrete were studied by varying the polymer content (2%, 4%, 5%, 6%, and 8%). The polymer content was added to the concrete mix based on the weight of the cement. The process involved thoroughly mixing cement and fine aggregate in a dry state, followed by the addition of coarse aggregate. Subsequently, the calculated quantity of polymer was introduced, and water was added. The entire mixture was thoroughly blended to achieve a uniform concrete consistency. The freshly mixed concrete was then evaluated for workability using the slump cone test, with the results for both conventional and polymer concrete provided in Table 4. Notably, the slump value increased with higher polymer content. In the concrete mixes, $M_{RS6}$ and $M_{RS8}$, the slump values are zero. Beyond 5% of the polymer content, the concrete mix contains more water content, which is the reason for the slump values being zero.

**Table 4.** Slump values of conventional and polymer concrete mixes.

| Sample ID | W/C ratio | Polymer content (%) | Slump (mm) |
|---|---|---|---|
| Mcc | 0.5 | - | 45 |
| $M_{RS2}$ | 0.5 | 2 | 70 |
| $M_{RS4}$ | 0.5 | 4 | 110 |
| $M_{RS5}$ | 0.5 | 5 | 180 |
| $M_{RS6}$ | 0.5 | 6 | Collapsible |
| $M_{RS8}$ | 0.5 | 8 | Collapsible |
| Mcc | 0.5 | - | 20 |
| $M_{MS2}$ | 0.5 | 2 | 25 |
| $M_{MS4}$ | 0.5 | 4 | 34 |
| $M_{MS5}$ | 0.5 | 5 | 55 |
| $M_{MS6}$ | 0.5 | 6 | 100 |
| $M_{MS8}$ | 0.5 | 8 | 140 |

Mcc-Reference concrete, $M_{RS}$-Polymer concrete made with R-sand, $M_{MS}$-Polymer concrete made with M-sand

### *3.2. Compressive strength*

Hardened concrete cubes, both conventional and polymer were prepared with varying polymer content (2%, 4%, 5%, 6%, and 8%) based on the weight of cement. These cubes were cast in steel moulds of dimensions 150 mm x 150 mm x 150 mm. Freshly mixed concrete was placed in the moulds and compacted using a needle vibrator. Afterwards, the concrete surfaces were finished and cured in air for 24 hours at room temperature. Subsequently, the cubes were de-moulded and further cured in a curing tank. CS tests were conducted on these cubes at 7 days and 28 days using a Compression Testing Machine (CTM) following the guidelines of (IS - 516: 1959), as depicted in Figure 2. The hardened polymer concrete was prepared using 12 different mixes, utilizing both R-sand and M-sand. The CS of the polymer concrete initially increased with increasing polymer content up to 5%. However, beyond that point, adding polymer content of 6% and 8% led to a decrease in CS for both R-sand and M-sand mixes. According to the experimental study, the M-sand mixes outperformed the R-sand mixes, as summarized in Table 5 and illustrated in Figures 3 and 4. The optimal polymer content of 5% was identified for both R-sand and M-sand mixes. Notably, compared to the control mix, the CS significantly in the MRS5 and MQS5 mixes, achieving improvements of 13.65% and 19.18%, respectively. The strength properties of the polymer were diminished beyond the optimal mix due to improper bonding between the cement paste, polymer, and aggregates (Sasikumar, 2023; Sasikumar, 2024; Sasikumar & Manju, 2022; Sasikumar & Manju, 2022a; Sasikumar & Manju, 2023; Sasikumar & Manju, 2024; Sasikumar et al., 2022).

**Figure 2.** Compressive strength on test on polymer concrete.

**Table 5.** Compressive strength of polymer concrete made using R-sand and M-sand.

| Compressive strength (MPa) | | | | | |
|---|---|---|---|---|---|
| Sample ID | R-Sand | | Sample ID | M-Sand | |
| | 7 days | 28 days | | 7 days | 28 days |
| $M_{cc}$ | 17.80 | 28.42 | $M_{cc}$ | 18.2 | 29.20 |
| $M_{RS2}$ | 19.40 | 30.20 | $M_{MS2}$ | 19.8 | 31.40 |
| $M_{RS4}$ | 19.80 | 31.67 | $M_{MS4}$ | 20.2 | 32.80 |
| $M_{RS5}$ | 20.40 | 32.30 | $M_{MS5}$ | 21.8 | 34.80 |
| $M_{RS6}$ | 17.20 | 26.80 | $M_{MS6}$ | 18.0 | 28.20 |
| $M_{RS8}$ | 15.80 | 22.40 | $M_{MS8}$ | 16.4 | 23.40 |

Mcc-Reference concrete, $M_{RS}$-Polymer concrete made with R-sand, $M_{MS}$-Polymer concrete made with M-sand.

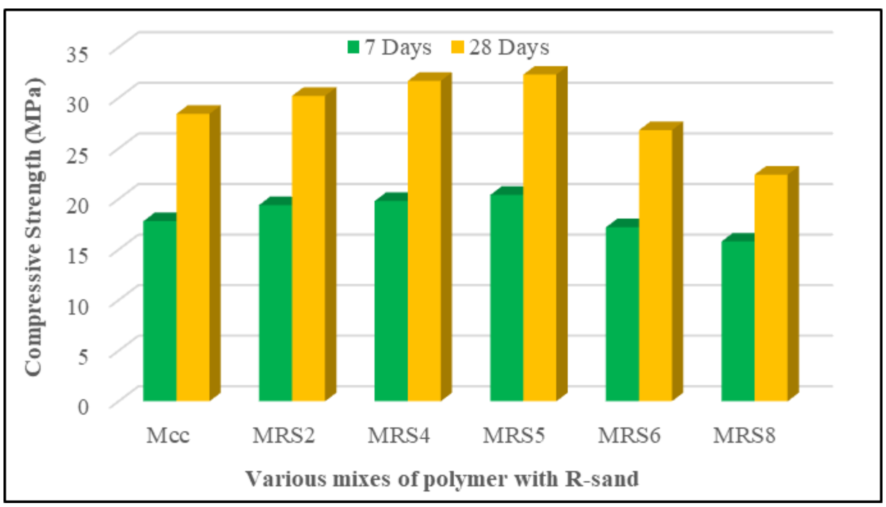



**Figure 3**. Compressive strength versus percentages of polymer with R-sand.

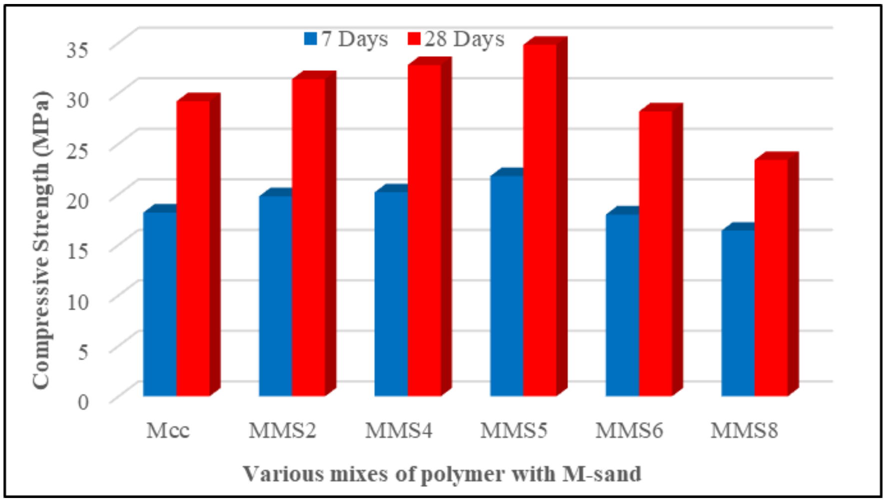



**Figure 4.** Compressive strength versus percentages of polymer with M-sand.

### *3.3. Split tensile strength*

Similarly, the STS of polymer concrete were investigated using cylindrical specimens with dimensions of 150 mm in diameter and 300 mm in height. These cylinders were cast in 12 different mixes, utilizing both River sand (R-sand) and Manufacturing sand (M-sand). After demolding from the steel moulds, the specimens underwent testing using a Universal Testing Machine (UTM) following curing periods of 7 days and 28 days, as per the guidelines outlined in (IS - 516: 1959), illustrated in Figure 5. The results revealed that the split tensile strength of polymer concrete exceeded that of the control mix by up to 5%. However, beyond this optimal polymer content, an increase in polymer led to a subsequent decrease in split tensile strength. Detailed data can be found in Table 6, and the trends are visually represented in Figures 6 and 7. Notably, the optimum percentage of polymer content based on experimental study is 5%. Specifically, the STS increased by 12.20% and 12.54% in the R-sand and M-sand mixes, respectively, when compared to the control mix. Interestingly, the M-sand mixes exhibited superior STS results compared to the R-sand mixes.

**Figure 5.** Split tensile test on polymer concrete specimen.

**Table 6.** Split tensile strength of polymer concrete made using R-sand and M-sand.

| Sample ID | Split tensile strength (MPa) R-Sand 7 days | R-Sand 28 days | Sample ID | M-Sand 7 days | M-Sand 28 days |
|---|---|---|---|---|---|
| $M_{cc}$ | 1.24 | 2.18 | $M_{cc}$ | 1.26 | 2.20 |
| $M_{RS2}$ | 1.28 | 2.40 | $M_{MS2}$ | 1.31 | 2.42 |
| $M_{RS4}$ | 1.54 | 2.52 | $M_{MS4}$ | 1.58 | 2.56 |
| $M_{RS5}$ | 1.62 | 2.66 | $M_{MS5}$ | 1.67 | 2.76 |
| $M_{RS6}$ | 1.32 | 2.18 | $M_{MS6}$ | 1.36 | 2.21 |
| $M_{RS8}$ | 1.08 | 2.06 | $M_{MS8}$ | 1.12 | 2.08 |

Mcc-Reference concrete, $M_{RS}$-Polymer concrete made with R-sand, $M_{MS}$-Polymer concrete made with M-sand.

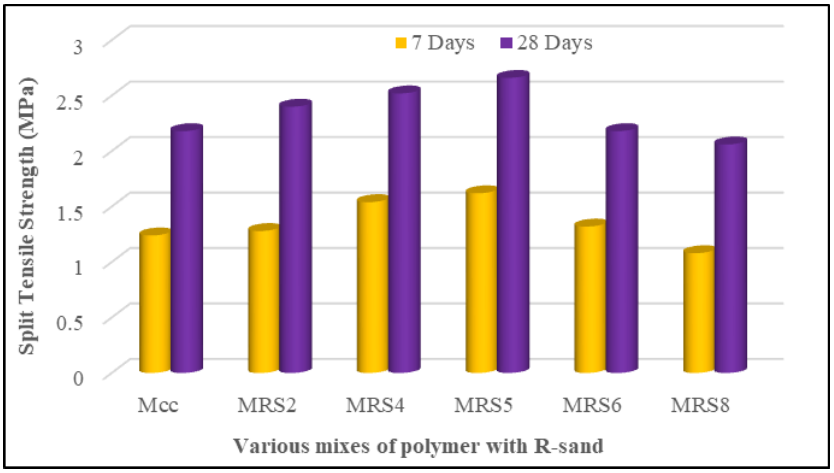



**Figure 6.** Split tensile strength versus percentages of polymer with R-sand.

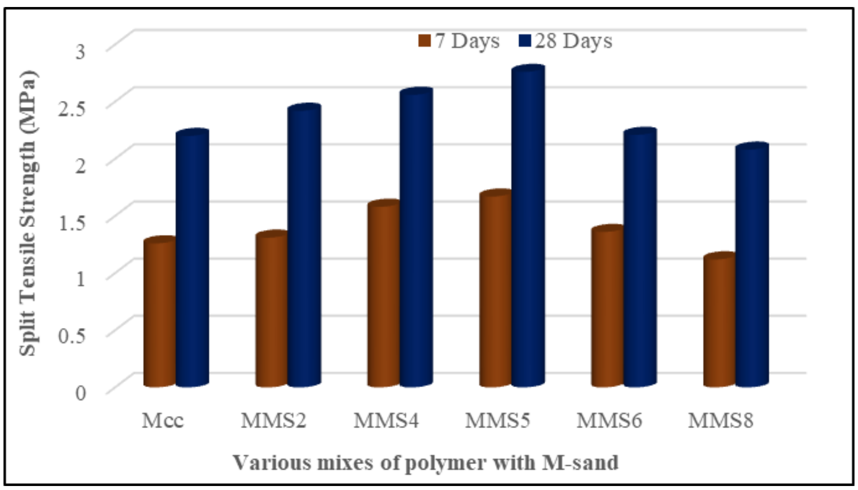



**Figure 7.** Split tensile strength versus percentages of polymer with M-sand.

### *3.4. Flexural strength*

The flexural behaviour of polymer concrete was investigated using prisms with dimensions of 100 mm x 100 mm x 500 mm, cast from both the control mix and polymer concrete containing varying polymer contents (2%, 4%, 5%, 6%, and 8%). These specimens were tested to determine their flexural strength using a Universal Testing Machine (UTM) after curing periods of 7 days and 28 days, following the guidelines of (IS - 516: 1959) as shown in Figure 8. With the addition of 2%, 4%, and 5% polymer content, the flexural strength increased by 10.56%, 11.03%, and 11.42%, respectively. However, beyond this optimal range, the flexural strength decreased by 10.18% to 9.52% when the polymer content was increased to 6% to 8% in R-sand mixes. Simultaneously, in M-sand mixes, the flexural strength increased by 10.56%, 11.12%, and 11.67% with the addition of 2%, 4%, and 5% polymer content, respectively. Subsequently, the flexural strength decreased by 10.37% and 9.63% with an increased polymer content of 6% and 8% in M-sand mixes as shown in Table 7. Notably, the polymer concrete flexural strength in the M-sand MQS5 mix increased by 10.42% compared to the R-sand MRS5 mix, as illustrated in Figures 9 and 10.

**Figure 8.** Flexural test on polymer concrete specimen.

**Table 7.** Flexural strength of polymer concrete made using R-sand and M-sand.

| Flexural strength (MPa) | | | |
|---|---|---|---|
| Sample ID | R-Sand 28 days | Sample ID | M-Sand 28 days |
| $M_{cc}$ | 2.12 | $M_{cc}$ | 2.16 |
| $M_{RS2}$ | 2.24 | $M_{MS2}$ | 2.28 |
| $M_{RS4}$ | 2.34 | $M_{MS4}$ | 2.4 |
| $M_{RS5}$ | 2.42 | $M_{MS5}$ | 2.52 |
| $M_{RS6}$ | 2.16 | $M_{MS6}$ | 2.24 |
| $M_{RS8}$ | 2.02 | $M_{MS8}$ | 2.08 |

Mcc-Reference concrete, $M_{RS}$-Polymer concrete made with R-sand, $M_{MS}$-Polymer concrete made with M-sand.

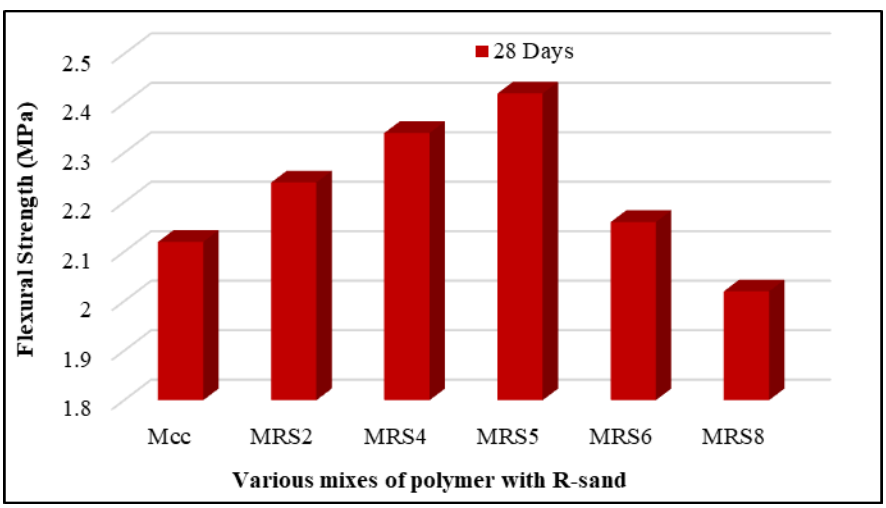



**Figure 9.** Flexural strength versus percentages of polymer with R-sand.

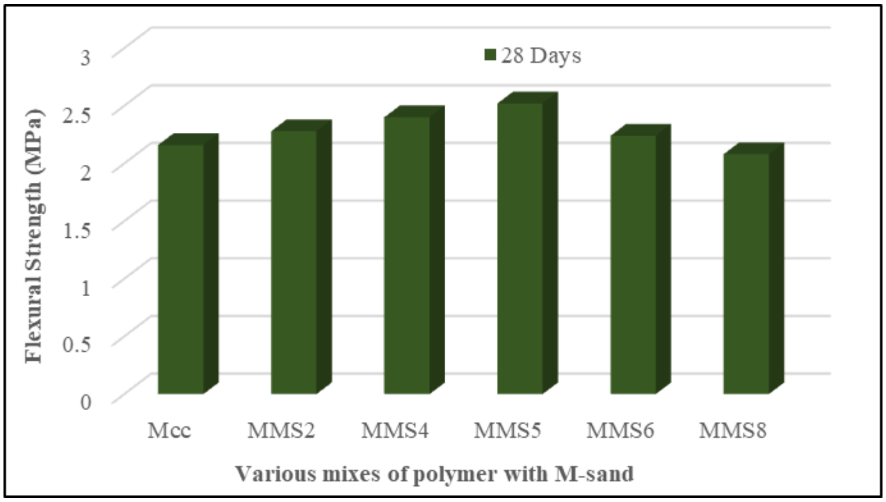



**Figure 10.** Flexural strength versus percentages of polymer with M-sand.

### *3.5. Modulus of elasticity*

The modulus of elasticity was determined for both R-sand and M-sand mixes using cylindrical specimens with a diameter of 15 mm and a height of 300 mm. These specimens were equipped with compresso and extenso meters, fixed onto the cylinders, and placed in a Compression Testing Machine (CTM). Load and deflection measurements were recorded for all samples during the experimental tests, following the guidelines of (IS - 516: 1959) as depicted in Figure 11. The modulus of elasticity in polymer concrete exhibited an increase with higher polymer content, similar to the behaviour observed in polymer concrete made using R-sand. Specifically, the modulus of elasticity values for polymer concrete made with both R-sand and M-sand increased by approximately 10.60% and 10.88%, respectively, when compared to conventional concrete with a polymer content of 5%. However, beyond this optimal range, the modulus of elasticity decreased as the polymer content increased to 6% and 8%, as summarized in Table 8 and illustrated in Figures 12 and 13.

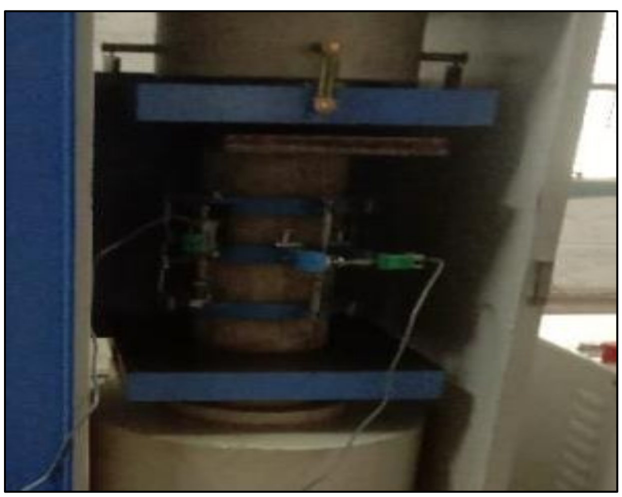


**Figure 11.** Modulus of elasticity test on polymer concrete specimen.

**Table 8.** Modulus of elasticity of polymer concrete made using R-sand and M-sand.

| Modulus of elasticity (GPa) | | | |
|---|---|---|---|
| Sample ID | R-Sand 28 days | Sample ID | M-Sand 28 days |
| $M_{cc}$ | 26.89 | $M_{cc}$ | 27.14 |
| $M_{RS2}$ | 27.58 | $M_{MS2}$ | 28.23 |
| $M_{RS4}$ | 28.26 | $M_{MS4}$ | 28.76 |
| $M_{RS5}$ | 28.52 | $M_{MS5}$ | 29.54 |
| $M_{RS6}$ | 25.93 | $M_{MS6}$ | 26.68 |
| $M_{RS8}$ | 23.78 | $M_{MS8}$ | 24.26 |

Mcc-Reference concrete, $M_{RS}$-Polymer concrete made with R-sand, $M_{MS}$-Polymer concrete made with M-sand.

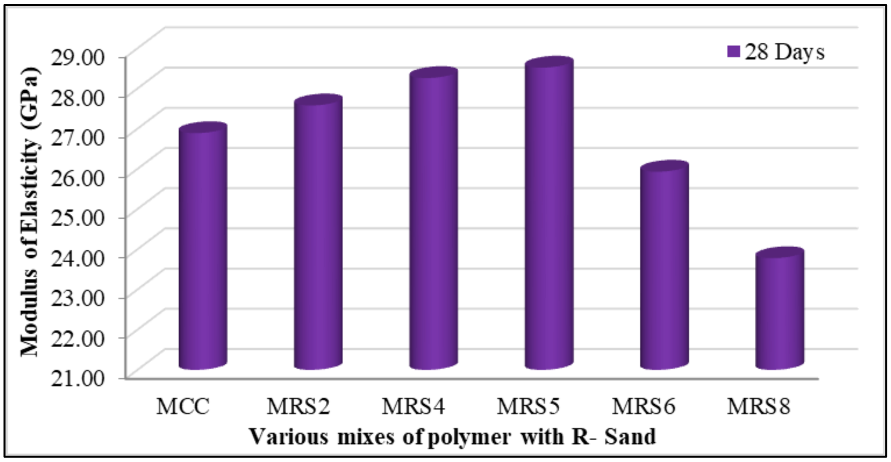



**Figure 12.** Modulus of elasticity versus percentages of polymer with R-sand.

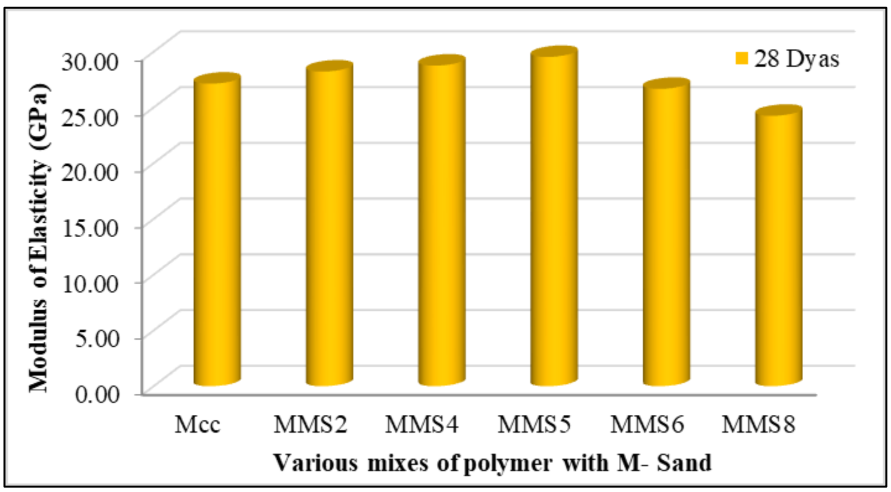



**Figure 13.** Modulus of elasticity versus percentages of polymer with M-sand.

### *3.6. Relationship between CS and STS*

Regression analysis was performed on polymer concrete made with both R-sand and M-sand, resulting in $R^2$ values of 0.84 for R-sand and 0.88 for M-sand. Two regression equations, labelled (1) and (2), were derived to predict the split tensile strength. These predicted values closely correlate with the experimental results. Additionally, various codes were employed to predict the split tensile strength, as outlined in Table 9. The regression Equations (1) and (2), denoted by codes (ACI 318-08; Iravani 2010; GB 50010 – 2010), provided more accurate predictions for split tensile strength, as summarized in Table 10 and depicted in Figure 14. The relationship between CS and STS in experimental polymer concrete samples using both R-sand and M-sand is further illustrated in Figures 15 and 16.

$$f_{sp} = 0.6818 + 0.05768 f_{ck} \text{ (R − sand)} \quad (1)$$
$$f_{sp} = 0.5752 + 0.05995 f_{ck} \text{ (M − sand)} \quad (2)$$

where:
$f_{sp}$ – Split tensile strength
$f_{ck}$ – Compressive strength

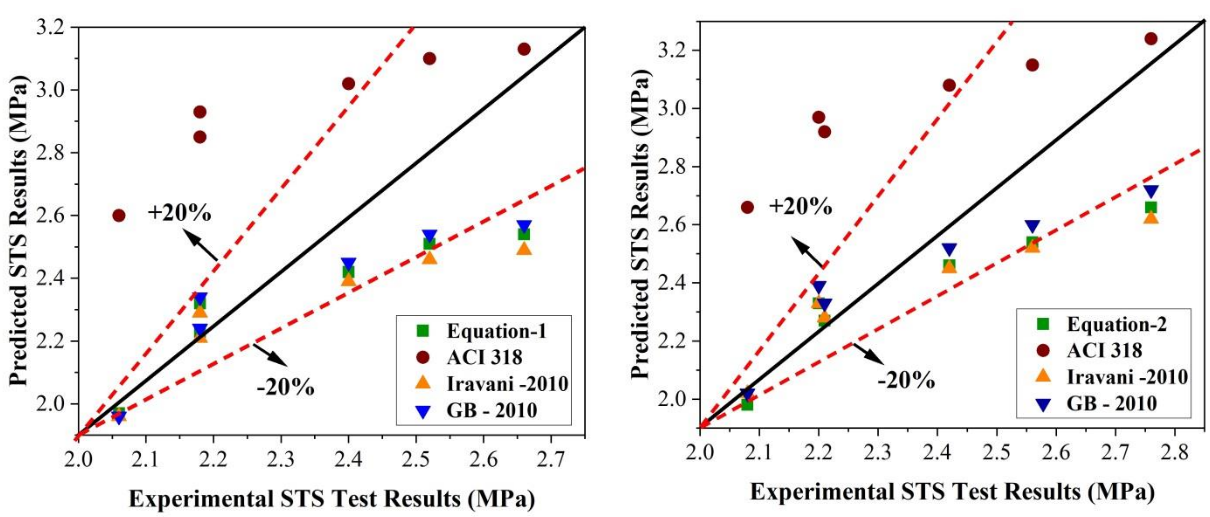
**Table 9.** Split tensile strength of polymer concrete was estimated using the existing formulas.

| Type of concrete | Split tensile strength ($f_{sp}$) |
|---|---|
| Plain cement concrete | $f_{sp} = 0.55x(f_c)^{0.5}$ (ACI 318-08) |
| | $f_{sp} = 0.301x(0.8xf_c)^{0.65}$ (Iravani – 2010) |
| | $f_{sp} = 0.19x(f_c)^{0.75}$ (GB 50010 – 100) |

**Table 10.** Comparison of the experimental split tensile strength of polymer concrete with regression equations and empirical formulas.

| Sample ID | Experimental values (MPa) | | Predicted Split tensile strength (MPa) | | | | |
|---|---|---|---|---|---|---|---|
| | $f_{ck}$ | $f_{sp}$ | Eq.1 | Eq.2 | ACI | Iravani | GB |
| $M_{cc}$ | 28.42 | 2.18 | 2.32 | - | 2.93 | 2.29 | 2.34 |
| $M_{RS2}$ | 30.20 | 2.40 | 2.42 | - | 3.02 | 2.39 | 2.45 |
| $M_{RS4}$ | 31.67 | 2.52 | 2.51 | - | 3.10 | 2.46 | 2.54 |
| $M_{RS5}$ | 32.30 | 2.66 | 2.54 | - | 3.13 | 2.49 | 2.57 |
| $M_{RS6}$ | 26.80 | 2.18 | 2.23 | - | 2.85 | 2.21 | 2.24 |
| $M_{RS8}$ | 22.40 | 2.06 | 1.97 | - | 2.60 | 1.96 | 1.96 |
| $M_{cc}$ | 29.20 | 2.20 | - | 2.33 | 2.97 | 2.33 | 2.39 |
| $M_{MS2}$ | 31.40 | 2.42 | - | 2.46 | 3.08 | 2.45 | 2.52 |
| $M_{MS4}$ | 32.80 | 2.56 | - | 2.54 | 3.15 | 2.52 | 2.60 |
| $M_{MS5}$ | 34.80 | 2.76 | - | 2.66 | 3.24 | 2.62 | 2.72 |
| $M_{MS6}$ | 28.20 | 2.21 | - | 2.27 | 2.92 | 2.28 | 2.33 |
| $M_{MS8}$ | 23.40 | 2.08 | - | 1.98 | 2.66 | 2.02 | 2.02 |

$f_{ck}$ - Compressive strength; $f_{sp}$ – Split tensile strength




(a) R – Sand (b) M - Sand

**Figure 14.** Compared the experimental split tensile strength results to regression equations and various codes.

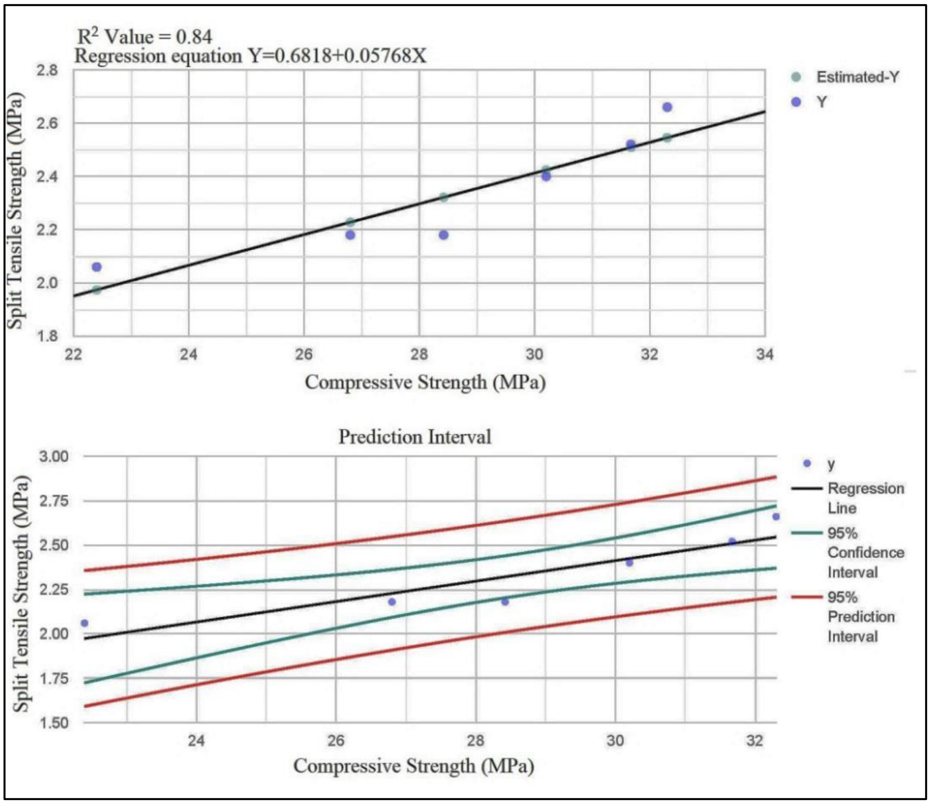



**Figure 15.** Relationship between CS and STS with mixes of R-sand.

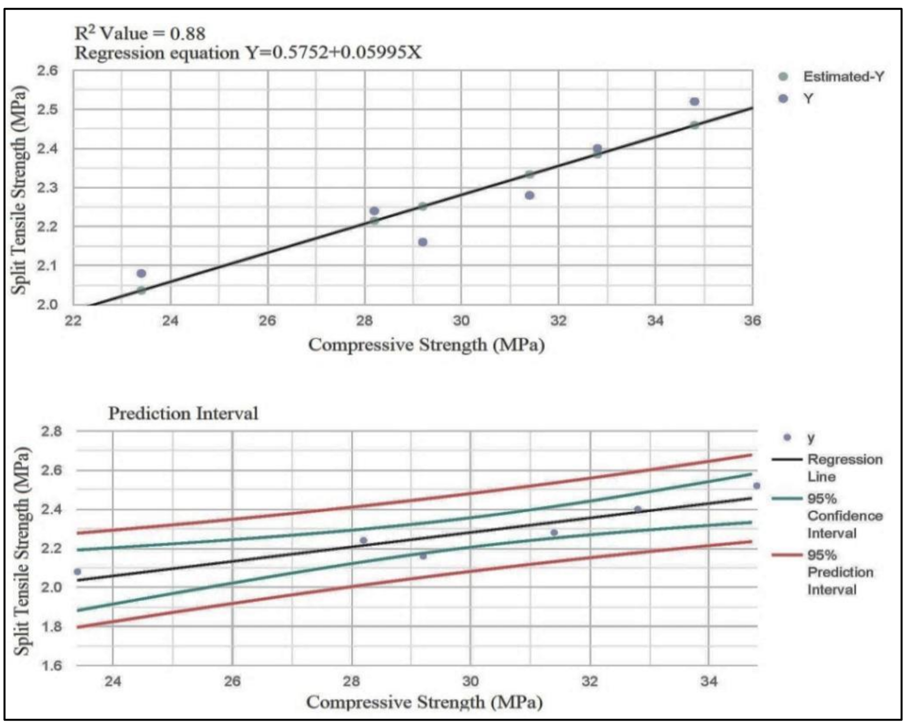



**Figure 16.** Relationship between CS and STS with mixes of M-sand.

### *3.7. Relationship between CS and FS*

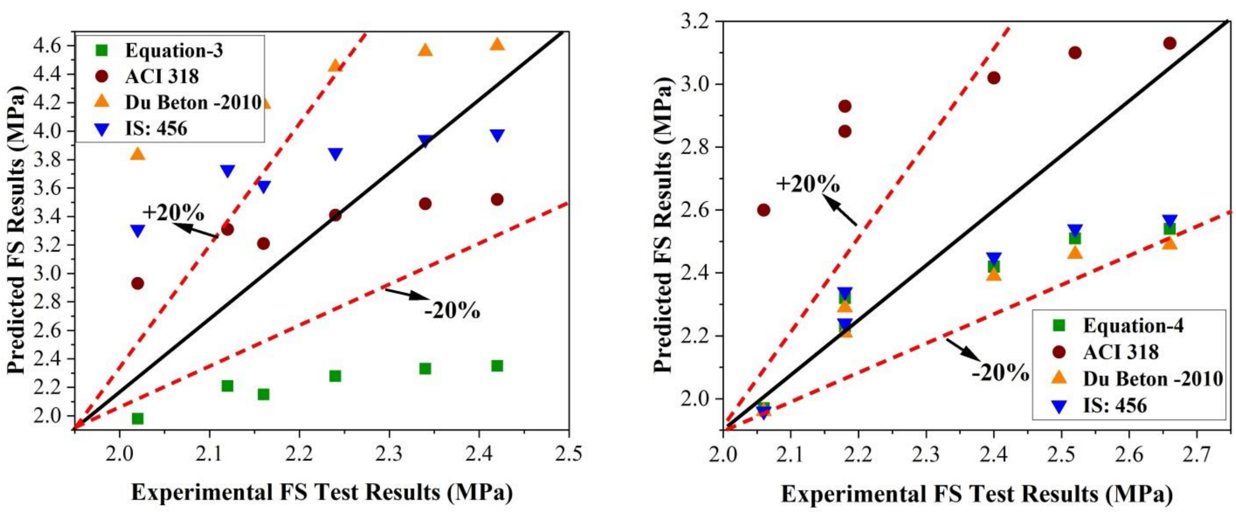
The relationship between CS and FS was compared using experimental results, and regression equations were derived for both R-sand and M-sand mixes. The plain cement concrete flexural strength was compared to the various codes listed in Table 11. The experimental values of flexural strength are compared to the regression equations (3) and (4), and multiple codes (ACI 318-08; Du Beton - 2012; IS 456) are reported in Table 12. The experimental values of split tensile strength values are compared to the regression equations (3) and (4), and various codes, the experimental values of flexural strength values are closely correlated with regression equations (3) and (4), compared to the codes is dissipated in Figure 17. The regression values ($R^2$) of R-sand and M-sand are 0.86 in both mixes, as shown in Figures 18 and 19. The regression analysis was conducted in this study to predict the strength properties of polymer concrete at 28 days of hardened concrete. This regression analysis assists in predicting the strength properties of the concrete.

$$f_b = 1.1514 + 0.0372 f_{ck} (\text{R} - \text{sand}) \quad (3)$$
$$f_b = 1.169 + 0.03707 f_{ck} (\text{M} - \text{sand}) \quad (4)$$

where:
$f_b$ – Flexural strength
$f_{ck}$ – Compressive strength

**Table 11.** Flexural strength of polymer concrete was estimated using the existing formulas.

| Type of concrete | Flexural strength ($f_b$) |
|---|---|
| Plain cement concrete | $f_b = 0.62x(fc)^{0.5}$ (ACI 318-08) |
| | $f_b = 0.81x(fc)^{0.5}$ (Du Beton 2012) |
| | $f_b = 0.70x(fc)^{0.5}$ (IS – 456: 2000) |




(a) R – Sand (b) M - Sand

**Figure 17.** Compared the experimental values of flexural strength results to regression equations and various codes.

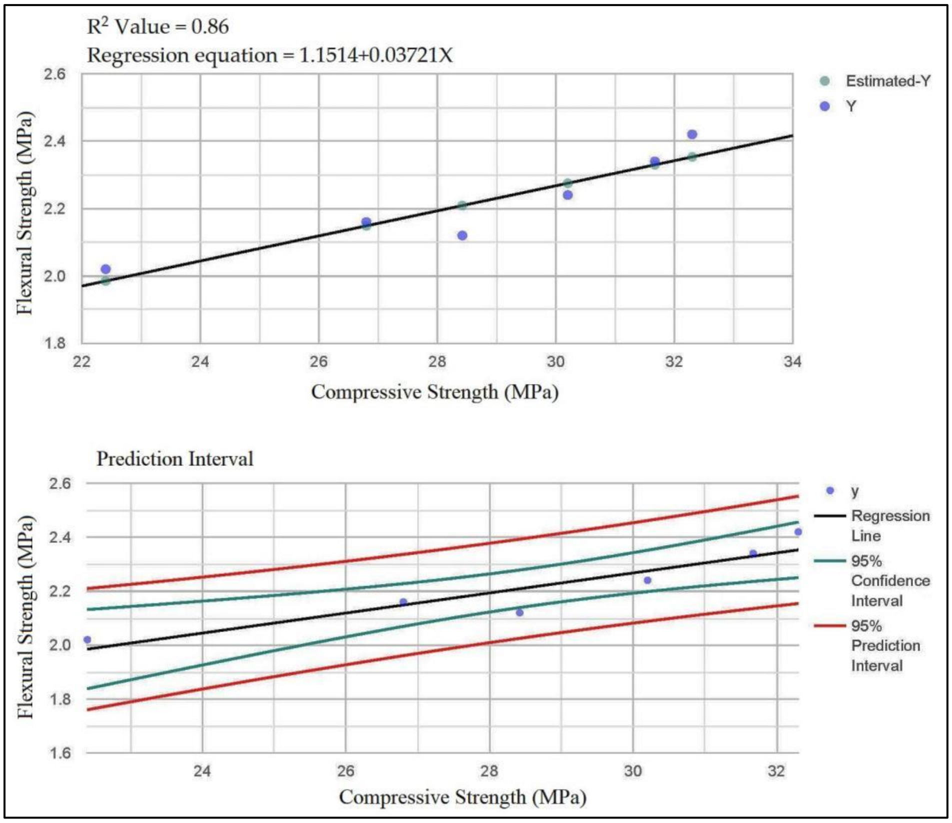



**Figure 18.** Relationship between CS and FS with mixes of R-sand.

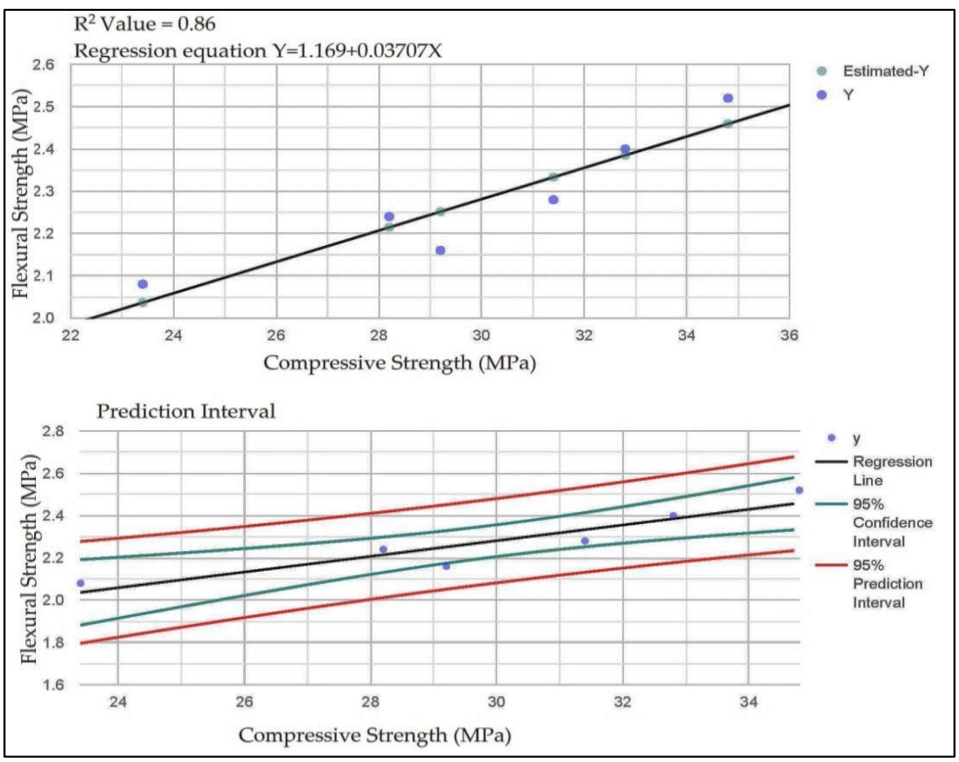



**Figure 19.** Relationship between CS and FS with mixes of M-sand.

**Table 12.** Comparison of the experimental flexural strength of polymer concrete with regression equations and code practice formulas.

| Sample ID | Experimental values (MPa) | | Predicted flexural strength (MPa) | | | | |
|---|---|---|---|---|---|---|---|
| | $f_{ck}$ | $f_b$ | Eq.3 | Eq.4 | ACI | DU | IS |
| $M_{cc}$ | 28.42 | 2.12 | 2.21 | - | 3.31 | 4.32 | 3.73 |
| $M_{RS2}$ | 30.20 | 2.24 | 2.28 | - | 3.41 | 4.45 | 3.85 |
| $M_{RS4}$ | 31.67 | 2.34 | 2.33 | - | 3.49 | 4.56 | 3.94 |
| $M_{RS5}$ | 32.30 | 2.42 | 2.35 | - | 3.52 | 4.60 | 3.98 |
| $M_{RS6}$ | 26.80 | 2.16 | 2.15 | - | 3.21 | 4.19 | 3.62 |
| $M_{RS8}$ | 22.40 | 2.02 | 1.98 | - | 2.93 | 3.83 | 3.31 |
| $M_{cc}$ | 29.20 | 2.16 | - | 2.25 | 3.35 | 4.38 | 3.78 |
| $M_{MS2}$ | 31.40 | 2.28 | - | 2.33 | 3.47 | 4.54 | 3.92 |
| $M_{MS4}$ | 32.80 | 2.40 | - | 2.38 | 3.55 | 4.64 | 4.01 |
| $M_{MS5}$ | 34.80 | 2.52 | - | 2.46 | 3.66 | 4.78 | 4.13 |
| $M_{MS6}$ | 28.20 | 2.24 | - | 2.21 | 3.29 | 4.30 | 3.72 |
| $M_{MS8}$ | 23.40 | 2.08 | - | 2.04 | 3.00 | 3.92 | 3.39 |

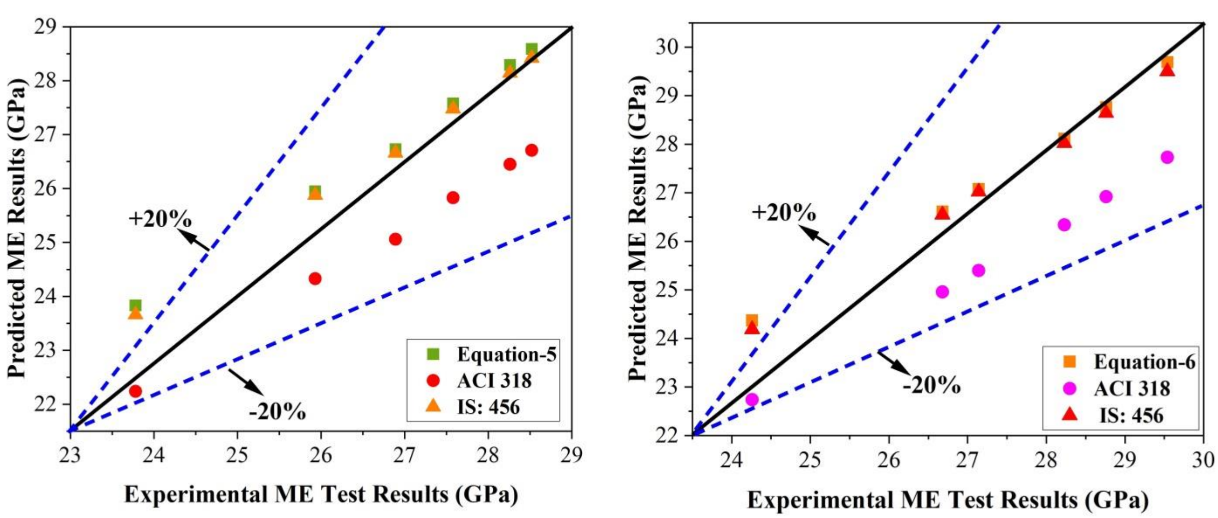
$f_{ck}$ - Compressive strength; $f_b$ - Flexural strength

### *3.8. Relationship between CS and ME*

The regression analysis was studied in the experimental values of CS and ME in polymer concrete made with R-sand and M-said. The regression equations of (5) and (6) of R-sand and M-sand mixes of polymer concrete were derived, and the ($R^2$) value is 0.99. Table 13 reported the ACI and IS codes were used to predict the ME. The two regression equations (5) and (6) were expected to be the modulus of elasticity. The predicted modulus of elasticity values closely correlates to the experimental values presented in Table 14. The regression equations (5) and (6), the codes (IS – 456: 2000; ACI 318 – 08) were used to predict the ME values. The regression equations (5) & (6) and IS code (IS – 456: 2000) have better correlations compared to the ACI code (ACI 318-08), which is presented in Figure 20. The relationship between the CS and ME of experimental values of polymer concrete made with both R-sand and M-sand are illustrated in Figures 21 and 22.

$$E_c = 13.075 + 0.4803 f_{ck}\,(\mathrm{R-sand}) \quad (5)$$
$$E_c = 13.445 + 0.4669 f_{ck}\,(\mathrm{M-sand}) \quad (6)$$

where:
$E_c$ – Modulus of elasticity
$f_{ck}$ – Compressive strength




(a) R – Sand (b) M - Sand

**Figure 20.** Compared the experimental values of modulus of elasticity results to regression equations and various codes.

**Figure 13.** Modulus of elasticity of polymer concrete was estimated using the existing formulas.

| Type of concrete | Modulus of elasticity ($E_C$) |
|---|---|
| Plain cement concrete | $E_C = 4700x(f_c)^{0.5}$ (ACI 318-08) |
| | $E_C = 5000x(f_c)^{0.5}$ (IS – 456: 2000)] |

**Table 14.** Comparison between the experimental modulus of elasticity of polymer concrete values with regression equations and code practice formulas.

| Sample ID | Experimental values | | Predicted modulus of elasticity (GPa) | | | |
|---|---|---|---|---|---|---|
| | $f_{ck}$ (MPa) | $E_C$ (GPa) | Eq.5 | Eq.6 | ACI | IS |
| $M_{cc}$ | 28.42 | 26.89 | 26.73 | - | 25.06 | 26.66 |
| $M_{RS2}$ | 30.20 | 27.58 | 27.58 | - | 25.83 | 27.48 |
| $M_{RS4}$ | 31.67 | 28.26 | 28.29 | - | 26.45 | 28.14 |
| $M_{RS5}$ | 32.30 | 28.52 | 28.59 | - | 26.71 | 28.42 |
| $M_{RS6}$ | 26.80 | 25.93 | 25.95 | - | 24.33 | 25.88 |
| $M_{RS8}$ | 22.40 | 23.78 | 23.83 | - | 22.24 | 23.66 |
| $M_{cc}$ | 29.20 | 27.14 | - | 27.08 | 25.40 | 27.02 |
| $M_{MS2}$ | 31.40 | 28.23 | - | 28.11 | 26.34 | 28.02 |
| $M_{MS4}$ | 32.80 | 28.76 | - | 28.76 | 26.92 | 28.64 |
| $M_{MS5}$ | 34.80 | 29.54 | - | 29.69 | 27.73 | 29.50 |
| $M_{MS6}$ | 28.20 | 26.68 | - | 26.61 | 24.96 | 26.55 |
| $M_{MS8}$ | 23.40 | 24.26 | - | 24.37 | 22.74 | 24.19 |

$f_{ck}$ - Compressive strength; Ec – Modulus of elasticity

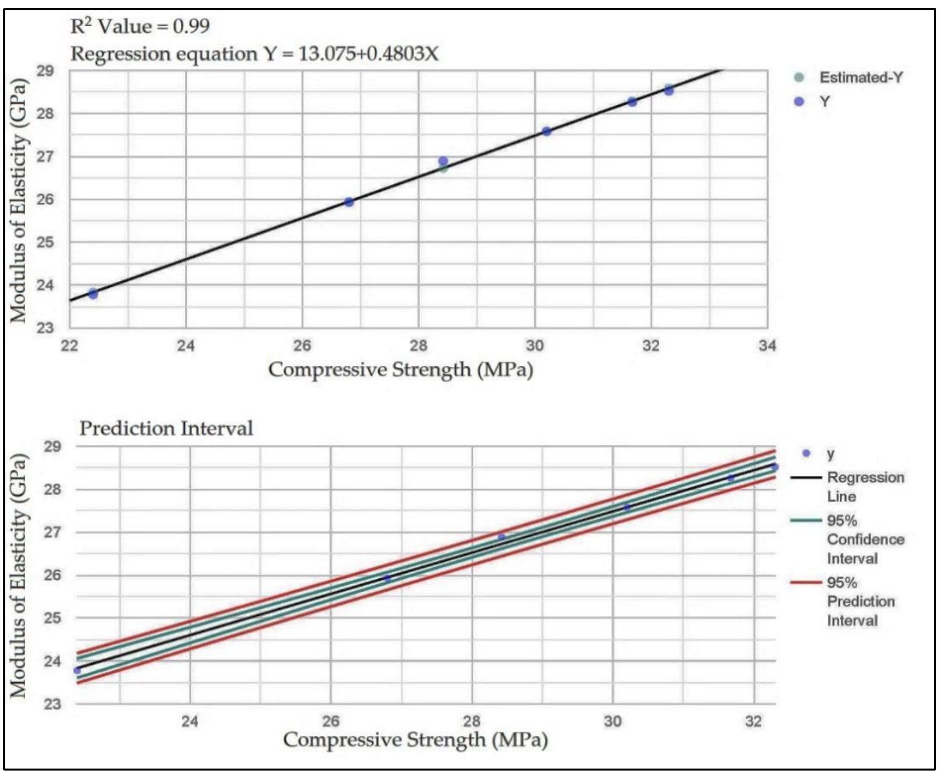



**Figure 21.** Relationship between compressive strength and modulus of elasticity with mixes of R-sand.

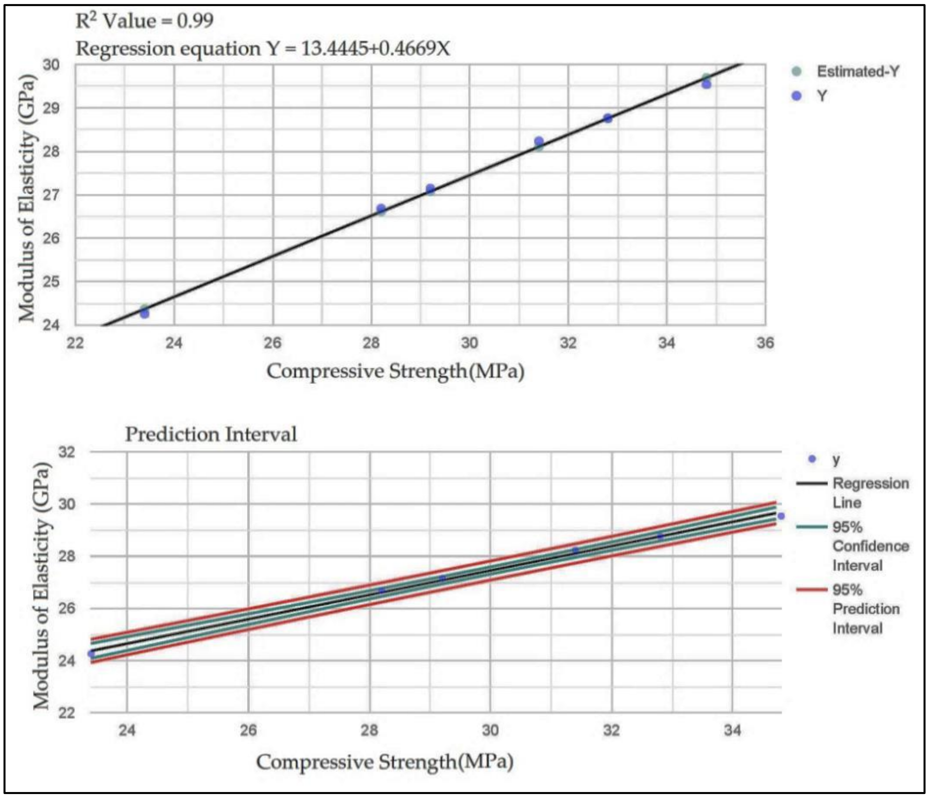



**Figure 22.** Relationship between compressive strength and modulus of elasticity with mixes of M-sand.

## 4. Conclusions and comments for future studies

The present study investigated the strength properties of the polymer concrete, incorporating varying proportions of polymer content (2%, 4%, 5%, 6% and 8%), demonstrating improved workability and cohesiveness in the fresh state. Furthermore, hardened-stage tests reveal that the polymer enhances the CS, STS, FS and ME of polymer concrete made with both R-sand and M-sand. The addition of 5% polymer content proves promising for producing polymer concrete using either R-sand or M-sand. Interestingly, concrete made with M-sand outperforms concrete made with R-sand across various polymer content percentages. Based on the test results, the following conclusions were drawn:

1. The optimum polymer content tends to increase the compressive strength at 13.65% & 19.18%, split tensile at 12.20% & 12.54% and flexural strength at 11.42% & 11.67% compared to the conventional concrete by using the R-sand and M-sand.
2. The modulus of elasticity is also simultaneously increased up to 5% of the optimum polymer content.
3. The role of optimum polymer content was much appreciated more than the conventional towards increasing CS, STS and FS using M-sand.
4. Beyond the optimal polymer content, the polymer concrete strength properties (CS, STS, and FS) exhibited a decrease in strength properties. This reduction can be attributed to the lack of bond between the cement paste, aggregates, and polymer content.
5. Regression analysis was used to predict the strength properties of polymer concrete. The existing formulas and regression equations were strongly associated with the experimental test results.
6. Regression analyses were conducted for CS & STS, CS & FS, and CS & ME. The coefficients of determination ($R^2$) values were 0.84 & 0.88 for CS & STS, 0.86 for CS & FS, and 0.99 for CS & ME.

### Scope for future studies:

1. The strength properties of polymer concrete depend on filler material, and the study may be continued by evaluating their properties employing different types of filler materials.
2. This study may be extended with the change in cement content and water-cement ratio, and it may be tried with different grades of concrete.
3. The polymer concrete may be extended to study its behaviour in reinforced structural elements such as beams and columns.

### Nomenclature

| List of symbol and abbreviations | |
|---|---|
| AFS | Alkali-activated fly ash |
| AAS | Alkali-activated slag |
| ACI | American concrete institute |
| $f_{ck}$ | Characteristic compressive strength at 28 days |
| CS | Compressive strength |
| FS | Flexural strength |
| $f_b$ | Flexural strength |
| IS | Indian standard |
| M-sand | Manufacturing sand |
| $M_{MS}$ | Mix for manufacturing sand |
| $M_{RS}$ | Mix for river sand |
| ME | Modulus of elasticity |
| $E_c$ | Modulus of elasticity |
| Mcc | Reference sample |
| R-sand | River sand |
| STS | Split tensile strength |
| $f_{sp}$ | Split tensile strength |

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