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Research Article

Enhancing the mechanical properties of fibre reinforced concrete using diatomaceous earth powder: fresh and hardened properties of concrete

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Abstract: This research investigated enhancing the mechanical properties of fibre-reinforced concrete (FRC) by incorporating diatomaceous earth powder. A total of six mix groups were designed as M40 grade concrete according to IS -10262: 2019. Each mix group consisted of six mixes. The study examined the fresh and hardened properties of the FRC, including workability, compressive strength (CS), split tensile strength (STS), flexural strength (FS), and modulus of elasticity (ME) at various ages. The first three groups incorporated electronic waste (E-waste) fibres, added to the concrete by weight of cement (i.e., 0.2%, 0.4%, 0.6%, 0.8%, 1%) with lengths of 30 mm, 40 mm, and 50 mm, respectively. Additionally, diatomaceous earth powder partially replaced cement in amounts of 5%, 10%, 15%, 20%, and 25%. Based on experimental observations, the optimum fibre content was 0.8% for group 1 and 0.6% for groups 1I & III. Similarly, the same optimum fibre content was used for groups IV-VI. Including E-waste fibres and diatomaceous earth powder enhanced the mechanical properties of the concrete. The experimental study revealed groups I and VI performed better than the remaining mixed groups. Specifically, for Group I, the CS, STS, and FS improved by 9.86%, 4.85%, and 4.96%, respectively, while for Group VI, these properties improved by 8.82%, 5.60%, and 4.57%. The primary aim of this study is to enhance the mechanical properties of the concrete and develop sustainable structures. The mechanical properties of concrete strength were also compared using linear regression analysis and various codes. The regression equations aligned well with the experimental test results and aided in predicting those results.

Keywords: Diatomaceous earth powder, E-waste, fibre reinforced concrete, linear regression analysis, strength properties of concrete.

1. Introduction

E-waste, or electronic waste, encompasses discarded electrical and electronic equipment from consumers, bulk consumers, or manufacturing, refurbishment, and repair processes. This category includes computers, mobile phones, large household appliances, and medical equipment. Regrettably, E-waste is the fastest-growing solid waste stream globally, expanding three times faster than the global population. In 2019, an estimated 53.6 million tonnes of E-waste were generated worldwide. Shockingly, only 17.4% of this E-waste was formally collected and recycled annually. The rapid rise of e-waste presents significant challenges in waste management and environmental protection. Improper treatment, disposal, or recycling of E-waste can release up to 1,000 chemical substances into the environment, including harmful neurotoxicants like lead. Inadequate recycling methods, such as open burning, can release toxic materials into the air and soil. Despite international regulations, the illegal transboundary movement of e-waste to low- and middle-income countries persists. This situation is exacerbated by insufficient regulations, recycling infrastructure, and training in Low- and Middle-Income Countries (LMICs). E-waste is classified as hazardous due to toxic components like dioxins, lead, and mercury. However, E-waste also contains valuable and finite resources that can be reclaimed through proper recycling. It has emerged as a significant source of income for individuals and communities.

Electronic waste, also known as E-waste, presents notable environmental obstacles as a result of its restricted biodegradability. Across the globe, professionals are investigating sustainable building materials that integrate E-waste and its reclaimed elements in order to tackle this problem. This analysis reassesses the utilization of E-waste in the manufacturing of concrete, taking into account its physical, structural, and durability characteristics (Bamigboye et al., 2024). The increase in the use of electrical and electronic devices (e.g. personal computers, televisions, and mobile phones) has presented considerable difficulty in the proper disposal of Plastic-waste (P-waste), specifically Acrylonitrile Butadiene Styrene (ABS) originating from discarded electrical and electronic equipment (E-waste). This research delves into the use of granulated ABS as a substitute material for aggregates in concrete. The research evaluates the CS and abrasion resistance of concrete containing granulated ABS obtained from E-waste at various replacement intervals (i.e., 0%, 5%, 10%, 25%, 50%, 75%, 100%) (Parsons & Nwaubani, 2024).

E-waste poses significant environmental challenges due to its limited biodegradability. Researchers globally are investigating sustainable building materials that integrate electronic waste and its recycled components to tackle this problem. This review reevaluates the use of E-waste in concrete production, considering physical, structural, and durability aspects (Mishra et al., 2024). Effectively handling plastic waste. Specifically, ABS originating from obsolete electrical and electronic devices poses a notable obstacle. In this study, we explore the incorporation of granulated ABS as an aggregate replacement material in concrete. The research evaluates the CS and abrasion resistance of concrete containing granulated ABS obtained from E-waste at various replacement intervals (ranging from 0% to 100%) (Jittamaro et al., 2024). Plastic waste management is a global concern, while the construction industry continually seeks innovations to become more sustainable. In this context, recycling plastic waste as fibres for reinforcing concrete is a promising alternative to address both environmental challenges. Over the last decade, numerous reviews have explored how plastic fibres affect concrete properties and how waste can be transformed into these fibres (Hamada et al., 2024).

Concrete, as a structural material, plays a crucial role in construction. Nevertheless, the need for adjustments arises due to its shortcomings in terms of tension and environmental consequences. One approach is to incorporate fibres into concrete, enhancing its properties. In this study, we explore using plastic waste fibres, specifically PVC fibres from electronic waste and PP fibres from cement bags, as reinforcement in concrete (Bashir & Singh, 2024). Demolition of concrete structures often results in a significant amount of debris and waste on a global scale. These leftover materials can be repurposed as coarse aggregate in fresh concrete mixes. Numerous buildings worldwide require dismantling either due to the end of their lifespan, the need for new developments, or failure to meet local and international regulations. By reusing this concrete waste, valuable landfill space can be conserved while promoting sustainability in utilising natural resources. The research delves into the feasibility of incorporating recycled concrete as coarse aggregate in new concrete mixes and its influence on CS development. Samples extracted from demolished concrete structures were subjected to compression tests to ascertain their strength. These test outcomes are utilized as the aggregate characteristics for the fresh concrete.

The CS and STS of recycled aggregate concrete (RAC) were determined through the casting of cubes and cylinders, respectively, in experimental settings (Halahla et al., 2019). A substantial volume of Fresh Concrete Waste (FCW) is produced daily from ready-mix concrete plants. Historically, this waste has been transported to landfills for proper disposal. However, with landfills reaching capacity, there is a need to explore alternative techniques for utilising FCW. This study investigates the feasibility of using crushed FCW to replace natural coarse granite aggregates in new concrete mixes (Kou et al., 2012). The depletion of natural resources is a common phenomenon in developing countries like India due to rapid urbanisation and industrialisation involving infrastructure construction and other amenities. To address this challenge, researchers have explored alternative materials for concrete production, aiming to preserve natural resources for future generations. In this context, various industrial waste materials have been investigated as viable substitutes for conventional aggregates in concrete (Sekar et al., 2011). Concrete, as the most widespread construction material, contributes to the depletion of natural resources during its production. Additionally, building waste generated from expired structures poses environmental challenges. To maintain ecological balance, efficient utilisation of available resources is crucial. In this study, waste concrete of known class and age is repurposed as coarse and fine aggregates for concrete production. Two aggregate sizes (0 - 4 and 4 - 22.4) are used, replacing normal aggregates at various ratios (i.e., 0%, 10%, 20%, 30%, 40%, 50%, 100%) (Günçan, 1995). Construction and demolition wastes constitute a major component of global waste generation.

Large quantities of aggregates were used in concrete production and construction. However, when structures end their useful life, they are demolished, and the resulting waste often ends up in landfills. Finding suitable landfill areas is becoming increasingly challenging. Simultaneously, the continuous extraction of natural aggregates for construction depletes natural resources (Monish et al., 2013). Using waste glass as a substitute for natural coarse aggregates in concrete manufacturing has attracted interest because of its environmental advantages and the possibility of conserving resources. This review examines the challenges and prospects of using waste glass in concrete (Johnston, 1974). In this rapidly industrialised world, recycling construction materials is important in preserving natural resources. This research investigates the use of RCA obtained from site-tested concrete specimens. These specimens consist of 28-day concrete cubes collected from a local construction site after compression tests. The crushed concrete cubes were reused as recycled coarse aggregate (Yong & Teo, 2009).

Concrete is a common material used for constructing various structures worldwide due to its low cost, availability, durability, and weather resistance. Waste glass and plastics are now essential to our daily existence, resulting in increased consumption. These materials were found in municipal solid waste (MSW) and could be used in construction, primarily as containers or building materials. The primary objective of this research is to substitute certain fine and coarse aggregates in concrete with discarded plastic and glass materials (Mohammed et al., 2020). Disposing of waste materials, especially from construction sites, poses environmental challenges. Researchers have explored using certain waste materials as substitutes for primary materials in Ordinary Portland Cement Concrete (OPCC) to address this issue. This study considered waste materials such as glass, plastics, and demolished concrete for recycling (Batayneh et al., 2007).

Although the concrete properties are reduced, the use of P-waste as a partial replacement can be suitable for various lower-grade strength applications. Examples include precast bricks, partition walls, panel walls, and canal lining (Lokeshwari et al., 2019). The optimal replacement ratio was 10% glass waste, resulting in equivalent CS compared to conventional concrete lining (Srivastava et al., 2014). Using waste glass as fine aggregate in concrete makes the structure denser, reduces water absorption, and improves durability. Glass powder addition to concrete shows improvements in CS, FS, and TS (Gautam et al., 2012). Utilising E-plastic waste in concrete reduces landfill costs and energy consumption. It reduces waste and promotes eco-friendly construction practices (Manjunath, 2016). RAC can be used for various purposes, including building gutters, pavements, revetments, and landscaping. It suits structural applications such as precast bricks, partition walls, and panel walls.

In summary, recycled aggregate concrete offers a sustainable solution while maintaining acceptable strength properties, contributing to waste reduction and resource conservation in construction (Sonawane & Pimplikar, 2013). RAC provides durability and weather resistance. Utilising RCA reduces the need for disposal, con-serves natural aggregates, and minimises landfill waste (Rao & Dasai, 2014). Utilising waste glass and demolished brick in concrete promotes eco-friendly practices. It reduces the demand for natural aggregates and addresses environmental concerns (Sharma et al., 2022; Dawande et al., 2016). The possibility of using solid waste materials in concrete is a promising solution to reduce waste problems. Incorporating waste materials into concrete contributes to resource conservation and environmental sustainability (Ahmed et al., 2014; Rahal, 2007).

Reactive powder concrete (RPC) with diatomaceous earth (DE) as a cement replacement offers a unique blend of strength, durability, and sustainability. Researchers and engineers continue to explore its full potential, and its application in high-performance structures is gaining momentum (Saidi et al., 2020; Hasan et al., 2020a). Diatomaceous earth, a pozzolanic substance, can be easily found in nature and presents advantageous characteristics for eco-friendly building projects. Its use in geopolymer concrete can contribute to environmentally friendly building practices. Researchers should explore its full potential and address the gaps identified in existing studies to advance the field of geopolymer-based concrete materials (KIpsanai et al., 2022). This study highlights the potential of DE as a protective vehicle for bacteria in self-healing concrete. By harnessing the properties of DE and bacterially induced calcium carbonate, sustainable and resilient concrete materials can be developed, contributing to environmentally friendly construction practices (Wang et al., 2012; Hasan et al., 2020b; Hasan et al., 2022).

The mixture without calcined DE was more workable than the one containing DE. The CS of concrete with DE was nearly the same for all mixtures. However, the CS of the diatomaceous earth-containing concrete was lower (approximately 14.6%) than that of concrete without calcined diatomaceous earth (Hasan et al., 2020c; Hasan et al., 2023a; Hasan et al., 2023b). Using 5% and 10% Calcined Diatomaceous Earth (CDE) to replace cement increased the CS of UHPC (Maharani et al., 2023). Similar improvements were observed in FS. UHPC with CDE exhibited enhanced splitting tensile strength. CDE-reinforced UHPC demonstrated improved durability against chloride and sulfate exposure.

Interestingly, UHPC with CDE showed resistance to temperatures of 400°C, 500°C, and 600°C. However, the mixture flow was reduced due to the inclusion of CDE (Hasan et al., 2023c). Green concrete with CDE and limestone strikes a balance between performance and sustainability. It addresses the significant environmental impact of concrete CO_2 emissions during cement production by reducing cement usage (Li et al., 2019; Hasan & Saidi, 2020). Lightweight concrete with calcined diatomaceous earth balances performance and sustainability (Hasan et al., 2021). Using CDE in foamed fine-grained concrete balances performance and sustainability (Paylik et al., 2017). Incorporating DE into cement pastes has significant effects on their fresh properties. While it enhances viscosity and reduces bleeding, it also influences setting times and heat evolution. These findings contribute to our understanding of how natural pozzolans impact concrete behaviour (Hasanzadeh & Sun 2018). The present study research methodology is depicted in Figure 1.

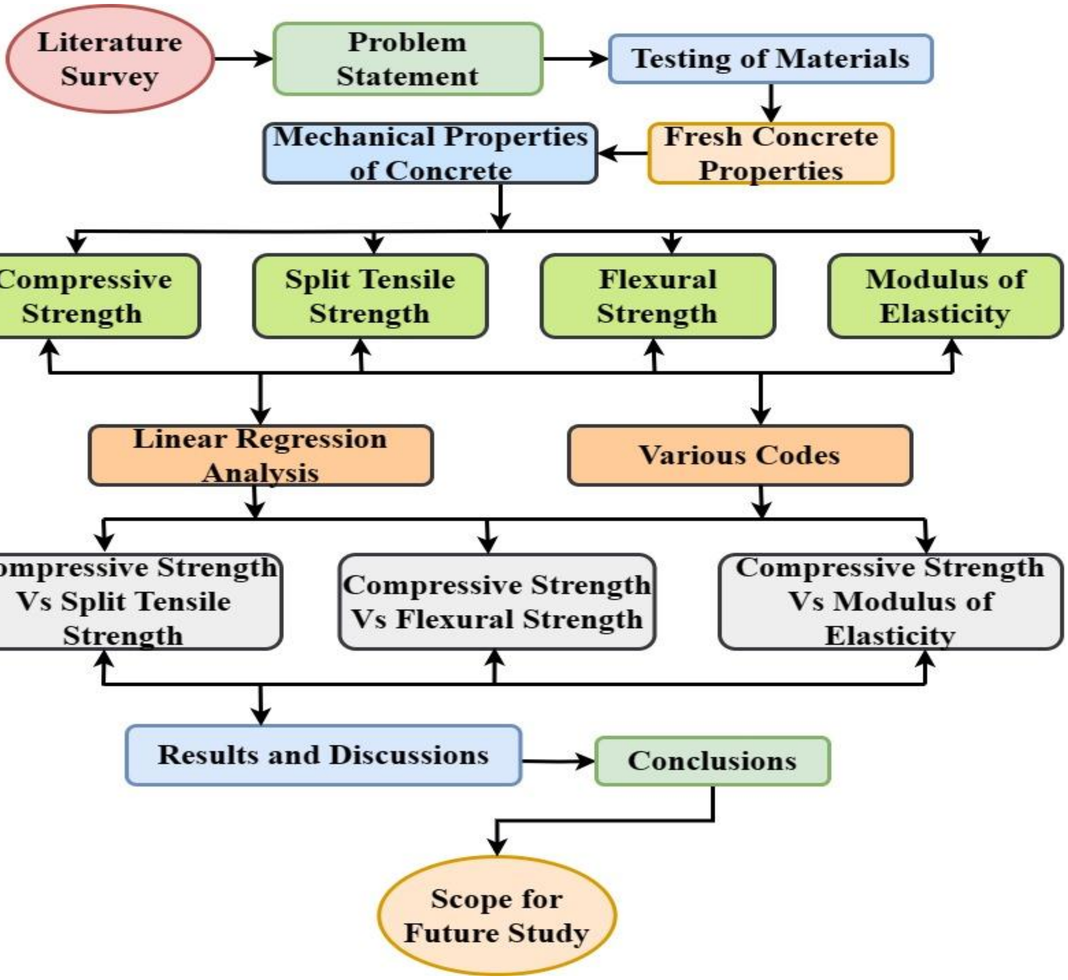


Figure 1. Flow chart for this study.

2. Experimental study

2.1. *Cement*

The present study was completed using the Ordinary Portland Cement (OPC) 53 grade, its conforming (IS: 12269 – 1987). The cement was purchased from the local market. The physical and chemical properties of the cement are reported in Tables 1 and 2.

Table 1. Physical properties of cement.

Properties	Test values	Limit
Specific gravity (g/cm^3)	3.10	3.10 to 3.16
Consistency (%)	30.48	25 to 35
Fineness modulus (%)	3.26	0 to 10
Initial setting time (Minutes)	36	>30
Final setting time (Minutes)	267	<600
Compressive strength (MPa)	51.20	53

Table 2. Chemical properties of the OPC 53 grade of cement.

Properties	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	LOI (%)
Values	23.52	5.36	3.27	61.82	2.48	2.64	0.72	0.63

2.2. *Fine aggregate*

This study used manufactured sand (M-sand) as the fine aggregate. The M-sand was collected from a local quarry, and its physical properties conform (IS: 383 – 2016). Additionally, the grain distribution confirms Zone II. The grain distribution of the fine aggregate is shown in Figure 2, and the physical properties are presented in Table 3.

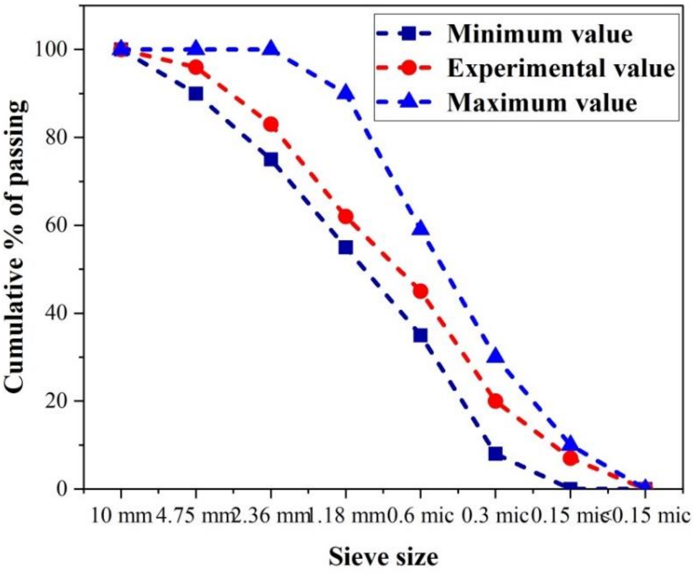


Figure 2. Grain distribution of fine aggregate.

Table 3. Physical properties of fine aggregate.

Properties	Test values	Limit
Specific gravity (g/cc)	2.68	2.5 to 3.0
Fineness modulus (%)	3.57	2.0 to 4.0
Water absorption (%)	1.24	0 to 2.0

2.3. *Coarse aggregate*

The coarse aggregate plays a crucial role in concrete, significantly enhancing its strength. Angular-shaped aggregates are highly recommended for concrete mixes because they establish a strong bond between the cement paste and the aggregate. The coarse aggregate used in this study was sourced from a local quarry, and its physical properties are detailed in Table 4. Additionally, the grain distribution of the aggregate aligns with the specifications outlined in (IS: 383 – 2016), as shown in Figure 3.

Table 4. Physical properties of coarse aggregate.

Properties	Test values	Limit
Specific gravity	2.72	2.5 to 3.0
Fineness modulus (%)	6.34	2.0 to 4.0
Water absorption (%)	0.38	0.1 to 2.0
Crushing value (%)	32.48	>30
Impact values (%)	24.16	<30

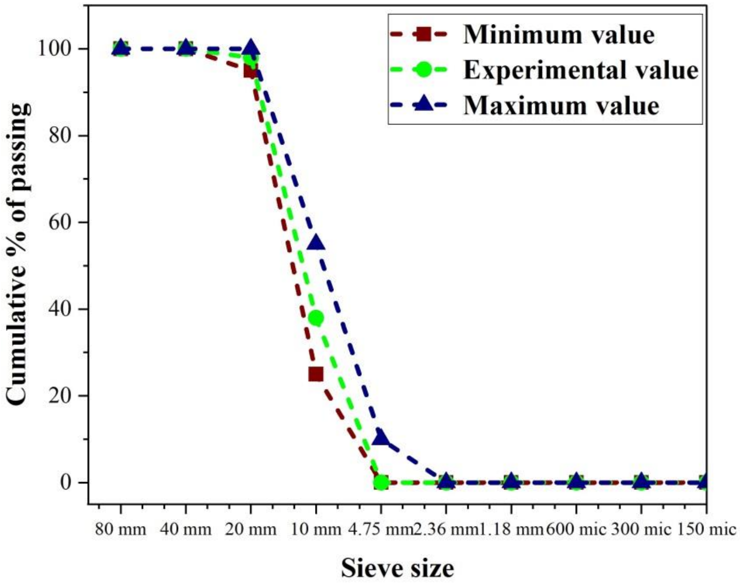


Figure 3. Grain distribution of coarse aggregate.

2.4. *Chemical admixture*

The chemical admixture played a crucial role in reducing the water content in the concrete mix. Specifically, the high-range water-reducing agent contributed to enhancing the concrete strength. In this research work, the chemical admixture employed is Conplast SP 430. The physical properties of chemical admixtures are presented in Table 5.

Table 5. Physical properties of superplasticiser.

Properties	Test values
Specific gravity (g/cc)	1.08
Colour	Dark brown
Chloride content	Nil

2.5. *Chemical admixture*

Much research indicates that incorporating diatomaceous earth powder can substantially increase compressive strength and enhance resistance to alkali-silica reactions in concrete. The diatomaceous earth powder is depicted in Figure 4. Simultaneously, it effectively reduces porosity and enhances resistance to chloride ion penetration. The diatomaceous earth powder adheres to the specifications outlined in (ASTM C 1202-97), and the physical properties are presented in Table 6.

Table 6. Physical properties of diatomaceous earth powder.

Properties	Test values	Limit
Specific gravity	2.27	2.25 to 2.35
Bulk density (kg/m^3)	928	-
Fineness modulus (%)	2.62	-
Colour	Pink white	-
Total acid soluble (%)	5	-
Loose density (g/cm^3)	0.210	-
Packed density (g/cm^3)	0.407	-

Figure 4. Diatomaceous earth powder.

2.6. *Chemical admixture*

The fibre collected from the E-waste is illustrated in Figure 5, and the segregation of the E-waste fibre is shown in Figure 6. The E-waste was collected from the locally available recycling centres. This study used three types of fibre lengths: 30mm, 40mm, and 50mm. The E-waste fibre is added to the concrete mix in various percentages (0.2%, 0.4%, 0.6%, 0.8% and 1.0%). E-waste fibres contribute to sustainable construction materials, reduce landfill waste, and protect the environment. Their impact on concrete strength varies, but proper design and testing can harness their benefits effectively. The physical properties of the E-waste are given in Table 7. Consistently distributed fibres improve the general performance of concrete. E-waste fibres primarily engage with the matrix through friction. Uneven sur-faces boost frictional adhesion. To summarise, ensuring uniform dispersion and comprehending the interactions between fibres and the matrix is crucial for optimising the advantages of E-waste fibres in concrete.

Table 7. Physical properties of E-waste fibre.

Properties	Test values
Specific gravity	1.04
Fibre length (mm)	30, 40 & 50
Diameter (mm)	0.5
Aspect ratio	15, 20 & 25
Tensile strength (MPa)	2.60
Density (g/cm^3)	1.38

Figure 5. E-waste Fibre.

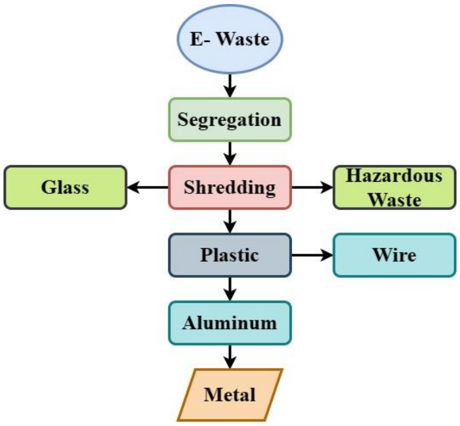


Figure 6. Segregation of the E-waste.

2.7. *Mix proportion of the fibre-reinforced concrete*

The concrete mix proportion was designed for M40 grade as per (IS: 10262 - 2019). The study included six mix groups, each comprising six mixes, as detailed in Table 8. Groups I to III investigated the addition of E-waste fibre. Additionally, groups IV to VI explored using E-waste fibre and partial replacement of diatomaceous earth powder. The materials required for the mix were calculated as follows: cement (412 kg/m³), fine aggregate (658 kg/m³), coarse aggregate (1150 kg/m³), superplasticiser (4.12 kg/m³), water content (148 kg/m³), water-to-cement ratio (0.36), E-waste fibre (0.2%, 0.4%, 0.6%, 0.8% and 1.0%), diatomaceous earth powder (5%, 10%, 15%, 20% and 25%).

Table 8. Mix proportion of the FRC per 1m^3 in kg/m^3.

Mix Group	Mix ID	C	FA	CA	SP	WC	W/C	F (%)	DEP (%)
I	M40-CC	412	658	1150	148	0.36	4.12	0	-
	M40-FL30-0.2	412	658	1150	148	0.36	4.12	0.2	-
	M40-FL30-0.4	412	658	1150	148	0.36	4.12	0.4	-
	M40-FL30-0.6	412	658	1150	148	0.36	4.12	0.6	-
	M40-FL30-0.8	412	658	1150	148	0.36	4.12	0.8	-
	M40-FL30-1.0	412	658	1150	148	0.36	4.12	1	-
II	M40-CC	412	658	1150	148	0.36	4.12	0	-
	M40-FL40-0.2	412	658	1150	148	0.36	4.12	0.2	-
	M40-FL40-0.4	412	658	1150	148	0.36	4.12	0.4	-
	M40-FL40-0.6	412	658	1150	148	0.36	4.12	0.6	-
	M40-FL40-0.8	412	658	1150	148	0.36	4.12	0.8	-
	M40-FL40-1.0	412	658	1150	148	0.36	4.12	1	-
	M40-CC	412	658	1150	148	0.36	4.12	0	-
III	M40-FL50-0.2	412	658	1150	148	0.36	4.12	0.2	-
	M40-FL50-0.4	412	658	1150	148	0.36	4.12	0.4	-
	M40-FL50-0.6	412	658	1150	148	0.36	4.12	0.6	-
	M40-FL50-0.8	412	658	1150	148	0.36	4.12	0.8	-
	M40-FL50-1.0	412	658	1150	148	0.36	4.12	1	-
IV	M40-FL30-F0.8	412	658	1150	148	0.36	4.12	0	0
	M40-FL30-F0.8-D5	412	658	1150	148	0.36	4.12	0.8	5
	M40-FL30-F0.8-D10	412	658	1150	148	0.36	4.12	0.8	10
	M40-FL30-F0.8-D15	412	658	1150	148	0.36	4.12	0.8	15
	M40-FL30-F0.8-D20	412	658	1150	148	0.36	4.12	0.8	20
	M40-FL30-F0.8-D25	412	658	1150	148	0.36	4.12	0.8	25
V	M40-FL40-F0.6	412	658	1150	148	0.36	4.12	0	0
	M40-FL40-F0.6-D5	412	658	1150	148	0.36	4.12	0.6	5
	M40-FL40-F0.6-D10	412	658	1150	148	0.36	4.12	0.6	10
	M40-FL40-F0.6-D15	412	658	1150	148	0.36	4.12	0.6	15
	M40-FL40-F0.6-D20	412	658	1150	148	0.36	4.12	0.6	20
	M40-FL40-F0.6-D25	412	658	1150	148	0.36	4.12	0.6	25
VI	M40-FL50-F0.6	412	658	1150	148	0.36	4.12	0	0
	M40-FL50-F0.6-D5	412	658	1150	148	0.36	4.12	0.6	5
	M40-FL50-F0.6-D10	412	658	1150	148	0.36	4.12	0.6	10
	M40-FL50-F0.6-D15	412	658	1150	148	0.36	4.12	0.6	15
	M40-FL50-F0.6-D20	412	658	1150	148	0.36	4.12	0.6	20
	M40-FL50-F0.6-D25	412	658	1150	148	0.36	4.12	0.6	25

Note: C - Cement; FA – Fine aggregate; CA – Coarse aggregate; SP – Superplasticizer; WC – Water content; W/C – Water cement ratio; F – Fibre; DEP - Diatomaceous earth powder.

2.8. *Fabrication of the samples*

The fabrication of the cubes, cylinders and prisms were cast, and the strength properties of the concrete, including CS, STS, FS, and ME, were evaluated at various angles. The CS and STS were examined at 7 and 28 days, respectively, while FS and ME were determined at 28 days. The mould sizes for CS, STS, FS, and ME were 150mm x 150mm x

150mm, 150mm diameter and 300mm length, 100mm x 100mm x 500mm, and 150mm diameter and 300mm length, were used in the study to examine the strength properties of the concrete. The concrete was mixed in a machine mixer, and the fresh concrete was poured into the steel mould in three layers. Each layer was compacted 25 times to prevent the formation of honeycomb structures. After being placed at room temperature for 24 hours, the samples were removed from the steel mould and left for curing at 28 days, as displayed in Figure 7.

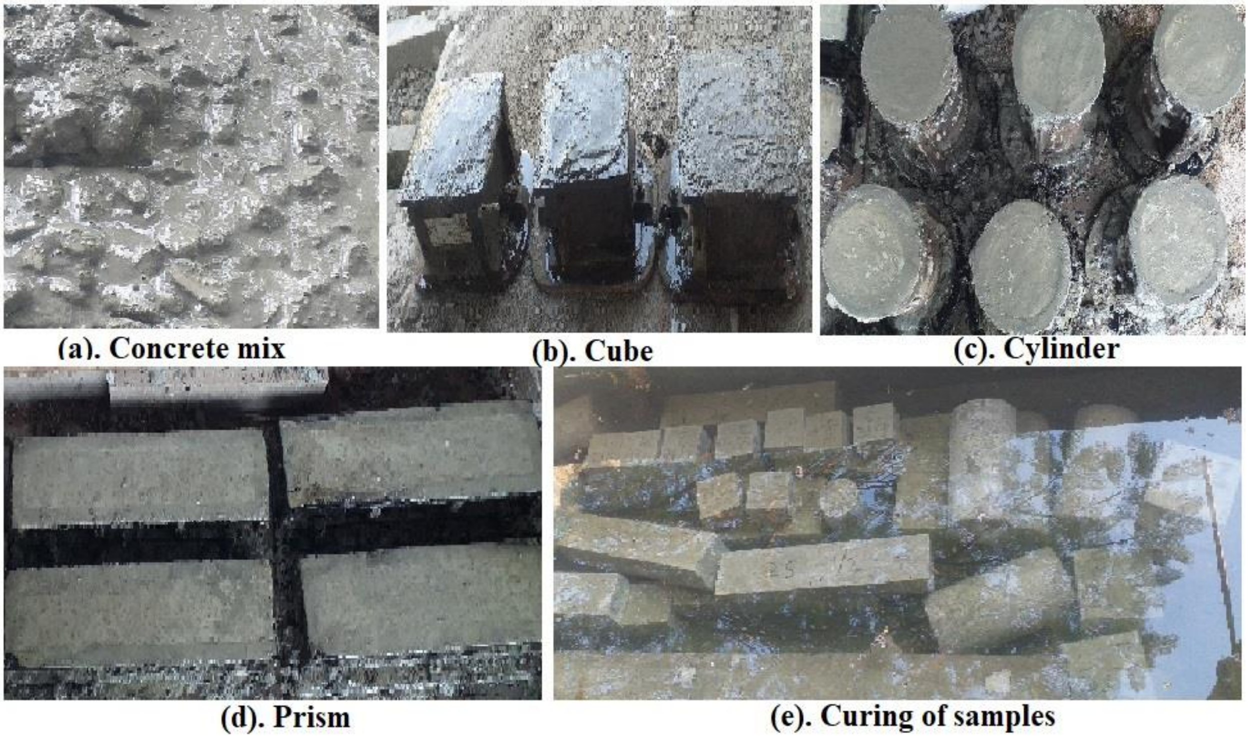


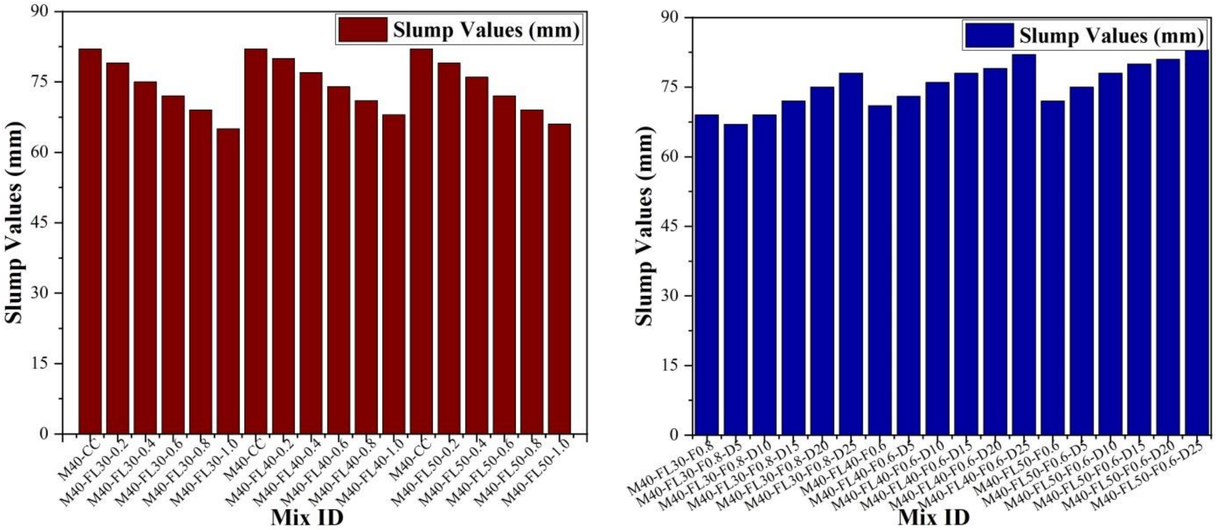
Figure 7. Fabrication of the samples.

3. Experimental results and discussion

3.1. Fresh properties of the concrete

In this study, the workability of fresh concrete properties was evaluated using the slump cone test, as depicted in Figure 8. The slump values of the concrete were observed from the experimental study and are presented in Table 9. With the addition of the E-waste fibre, the slump values decreased from 82mm to 65mm for the Group I mix, 82mm to 68mm for the Group II mix, and 82mm to 66mm for the Group III mix. This decrease was attributed to increased fibre content; fibre length percentages are depicted in Figure 9 (a). Conversely, adding diatomaceous earth powder increased slump values Figure 9 (b). Specifically, the slump increased from 69mm to 78mm for the Group III mix. The Group IV mix increased from 71mm to 82mm, and the Group VI mix increased from 72mm to 83mm. Based on experimental observations, the fibre content significantly impacts the workability of concrete, while the diatomaceous earth powder enhances the workability of fresh concrete.

Figure 8. Slump cone test.



(a). Group I – III

(b). Group IV-VI

Figure 9. Slump cone test.

3.2. Compressive strength of FRC

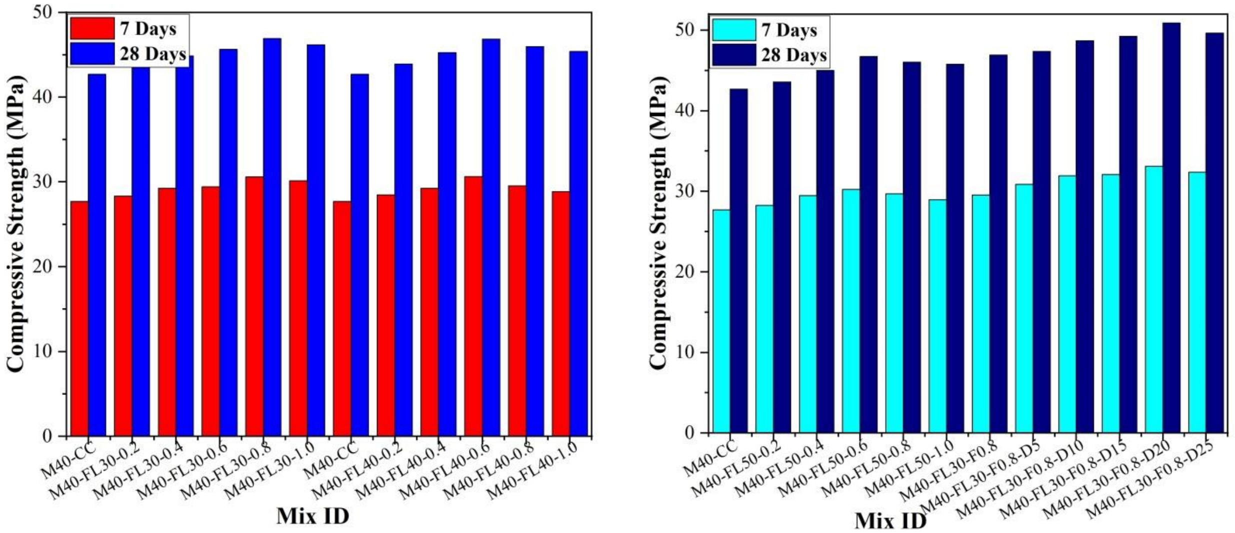
The physical properties of hardened fibre-reinforced concrete were evaluated at 7 and 8 days, as presented in Table 9. The concrete was placed on a Compression Testing Machine (CTM) capable of 3000 kN, and the CS was calculated as per (IS: 516 – 1959). The CS of concrete improved by 1.97%, 5.11%, 6.89%, 9.86%, and 8.18% for Group I; 2.84%, 5.97%, 9.75%, 7.69%, and 6.30% for Group II; and 2.06%, 5.39%, 9.47%, 7.85%, and 7.26% for Group III, compared to the control samples is shown in Figure 10 (a) & (b). In addition to the E-waste fibre in the concrete mix, the strength properties of the concrete were enhanced. The optimum fibre content was 0.8% for Group I mix, and 0.6% for Group II and III mixes. The optimum fibre content mix was used to investigate the three mix groups IV-VI.

Concrete CS exhibited varying improvements across different groups. Specifically, for Group IV, the CS increased by 0.98%, 3.82%, 5.01%, 8.49%, and 5.82% compared to the control sample. Similarly, Group V saw improvements of 1.11%, 3.95%, 5.83%, 8.07%, and 5.40%, while Group VI experienced enhancements of 2.40%, 3.94%, 6.42%, 8.82%, and 5.22%. These findings are depicted in Figure 10 (b) and (c). Based on the experimental study, the optimum mix was M40-FL30-F0.8-D20, M40-FL40-F0.6-D20 and M40-FL50-F0.6-D20 for group mix IV-VI. Overall, observation from the experimental study showed the E-waste fibre 0.6% and diatomaceous earth powder 20% enhanced the strength properties of the concrete. The loading rate of 0.14MPa/s was consistently maintained in all specimens until failure occurred.

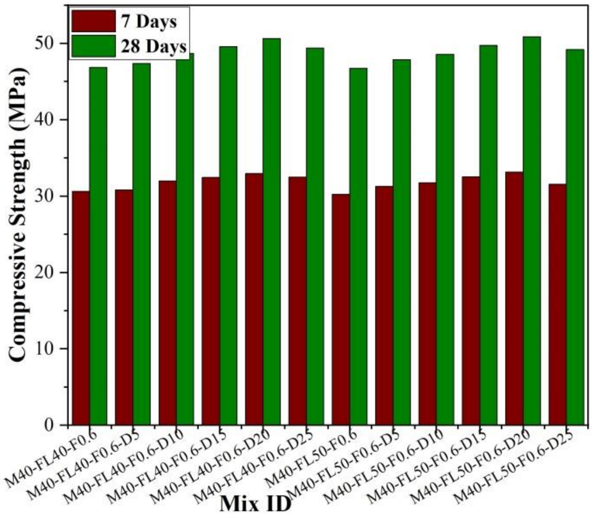
Table 9. Mechanical properties of FRC (MPa).

Mix group	Mix ID	CS		STS		FS	ME (GPa)	Slump values (mm)
		7 Days	28 Days	7 Days	28 Days	28 Days	28 Days	
I	M40-CC	27.68	42.68	2.58	3.92	6.02	32.67	82
	M40-FL30-0.2	28.34	43.52	2.64	3.96	6.09	32.99	79
	M40-FL30-0.4	29.25	44.86	2.74	4.02	6.14	33.48	75
	M40-FL30-0.6	29.42	45.62	2.86	4.05	6.27	33.76	72
	M40-FL30-0.8	30.58	46.89	2.96	4.11	6.32	34.26	69
	M40-FL30-1.0	30.12	46.17	2.83	4.02	6.26	33.95	65
II	M40-CC	27.68	42.68	2.58	3.92	6.02	32.63	82
	M40-FL40-0.2	28.47	43.89	2.76	3.98	6.14	33.13	80
	M40-FL40-0.4	29.25	45.23	2.92	4.01	6.24	33.64	77
	M40-FL40-0.6	30.62	46.84	2.98	4.05	6.36	34.24	74
	M40-FL40-0.8	29.54	45.96	2.86	4.02	6.29	33.82	71
	M40-FL40-1.0	28.86	45.37	2.78	3.98	6.25	33.66	68
III	M40-CC	27.68	42.68	2.58	3.92	6.02	32.64	82
	M40-FL50-0.2	28.25	43.56	2.62	3.94	6.12	33.02	79
	M40-FL50-0.4	29.47	44.98	2.74	3.98	6.23	33.55	76
	M40-FL50-0.6	30.24	46.72	2.85	4.08	6.34	34.19	72
	M40-FL50-0.8	29.67	46.03	2.78	4.02	6.25	33.91	69
	M40-FL50-1.0	28.96	45.78	2.72	4.06	6.23	33.88	66
IV	M40-FL30-F0.8	29.54	46.89	2.96	4.12	6.32	34.29	69
	M40-FL30-F0.8-D5	30.86	47.35	2.98	4.16	6.38	34.37	67
	M40-FL30-F0.8-D10	31.92	48.68	3.04	4.22	6.48	34.84	69
	M40-FL30-F0.8-D15	32.08	49.24	3.12	4.26	6.54	35.03	72
	M40-FL30-F0.8-D20	33.12	50.87	3.22	4.32	6.58	35.63	75
	M40-FL30-F0.8-D25	32.36	49.62	3.14	4.24	6.53	35.28	78
V	M40-FL40-F0.6	30.62	46.84	2.98	4.10	6.28	34.21	71
	M40-FL40-F0.6-D5	30.82	47.36	3.06	4.17	6.34	34.32	73
	M40-FL40-F0.6-D10	31.97	48.69	3.14	4.22	6.42	34.87	76
	M40-FL40-F0.6-D15	32.45	49.57	3.22	4.26	6.54	35.21	78
	M40-FL40-F0.6-D20	32.96	50.62	3.34	4.32	6.57	35.54	79
	M40-FL40-F0.6-D25	32.47	49.37	3.24	4.24	6.52	35.19	82
VI	M40-FL50-F0.6	30.24	46.72	2.67	4.11	6.34	34.19	72
	M40-FL50-F0.6-D5	31.26	47.84	2.85	4.16	6.43	34.56	75
	M40-FL50-F0.6-D10	31.74	48.56	2.94	4.19	6.47	34.83	78
	M40-FL50-F0.6-D15	32.52	49.72	3.05	4.20	6.55	35.22	80
	M40-FL50-F0.6-D20	33.14	50.84	3.18	4.34	6.63	35.66	81
	M40-FL50-F0.6-D25	31.56	49.16	3.12	4.22	6.47	35.03	83

Note: CS – Compressive strength; STS – Split tensile strength; FS – Flexural strength; ME – Modulus of elasticity.



(a) Group 1-2 (b) Group 3-4

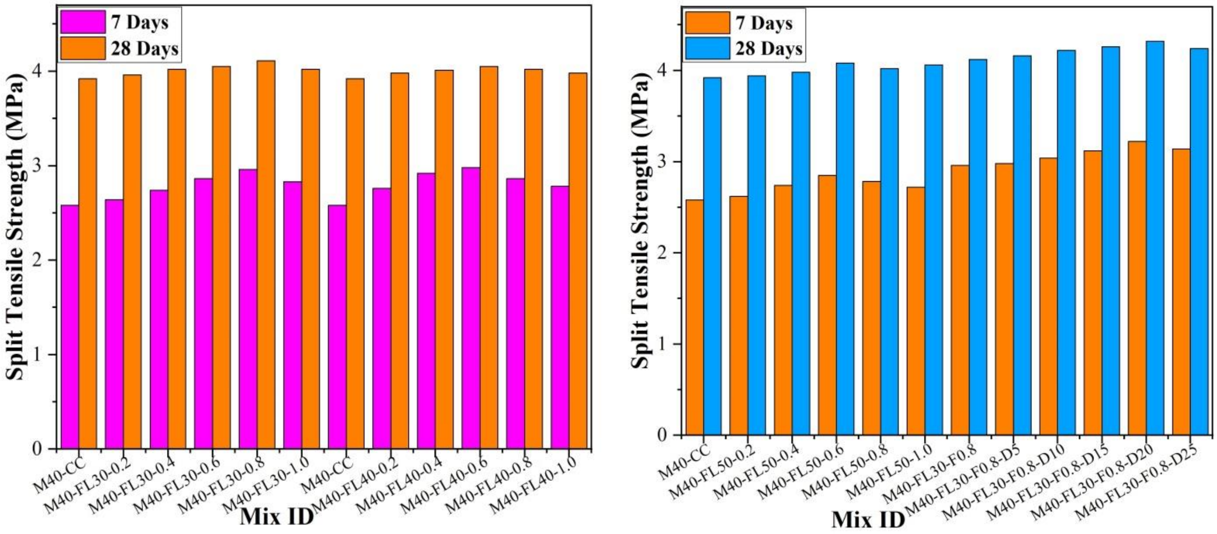


(c) Groups 5-6

Figure 10. Compressive strength of FRC at various ages.

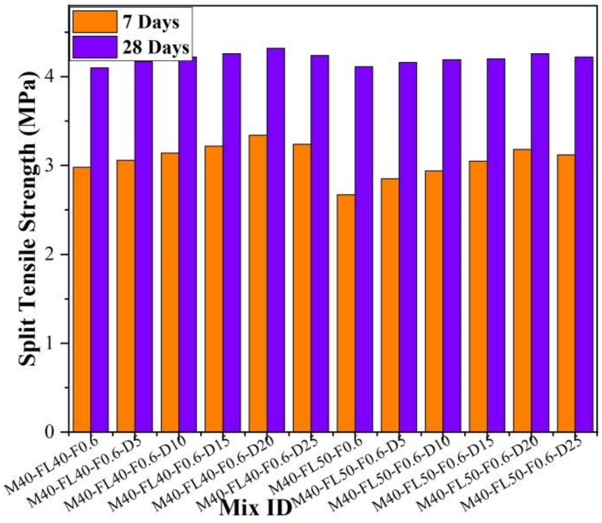
3.3. Split tensile strength of FRC

Similarly, the STS of the fibre-reinforced concrete (FRC) was examined after curing periods of 7 and 28 days, using a compression testing machine (CTM) with a capacity of 3000 kN, as per the (IS: 516-1959). The evaluated STS results are reported in Table 9. The STS of mix groups I-VI showed improvements of 4.92%, 5.65%, 5.32%, 4.11%, 4.62%, and 4.57% for the compositions M40-FL30-F0.8, M40-FL40-F0.6, M40-FL50-F0.6, M40-FL30-F0.8-D20, M40-FL40-F0.6-D20, and M40-FL50-F0.6-D20, respectively, compared to the control mix is shown in Figure 11 (a) - (c). Additionally, these mixes were found to be the optimum mix. By incorporating E-waste fibres into the concrete mix, the fibres interlock with the cement paste and aggregate. Diatomaceous earth powder, which has high silica content, also fills the existing voids. As a result, the STS of the concrete increased compared to the control mix. Concrete is relatively weak in tension, with its STS much lower than its CS. When subjected to tensile forces, concrete tends to crack and deform. However, under compressive forces, it has a higher resistance to deformation.



(a) Groups 1-2

(b) Groups 3-4

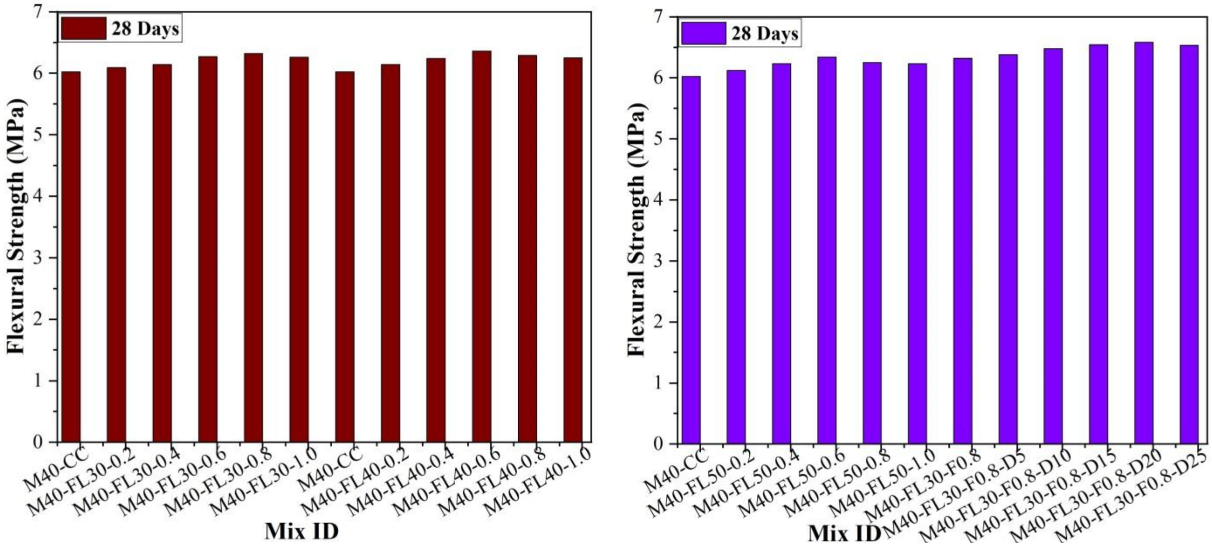


(c) Groups 5-6

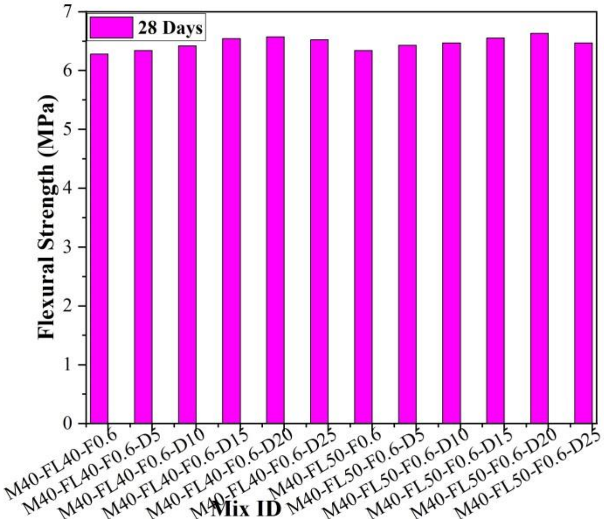
Figure 11. Split tensile strength of FRC at various ages.

3.4. Flexural strength of FRC

The FS of the FRC was examined in hardened concrete at 28 days using the Universal Testing Machine (UTM) with a capacity of 400 kN, as per (IS: 516-1959). The tested results are reported in Table 9. The FRC concrete's flexural strength was evaluated by adding various percentages of E-waste fibre and DE powder. A total of six mix groups were divided: the first three involved additions of E-waste fibre, while the remaining three focused on the partial replacement of cement using diatomaceous earth powder. The flexural strength increased with the addition of E-waste fibre and diatomaceous earth powder by 4.86%, 4.81%, 4.66%, 3.92%, 3.89%, and 4.31% compared to the conventional concrete mix at 28 days, as displayed in Figure 12 (a) - (c). The E-waste fibre and diatomaceous earth powder resisted cracks and enhanced the TS of the concrete. According to the experimental study, the optimum mix groups were groups I and VI. Additionally, the samples failed with minor cracks compared to the remaining group samples.



(a) Groups 1– 2 (b) Groups 3– 4

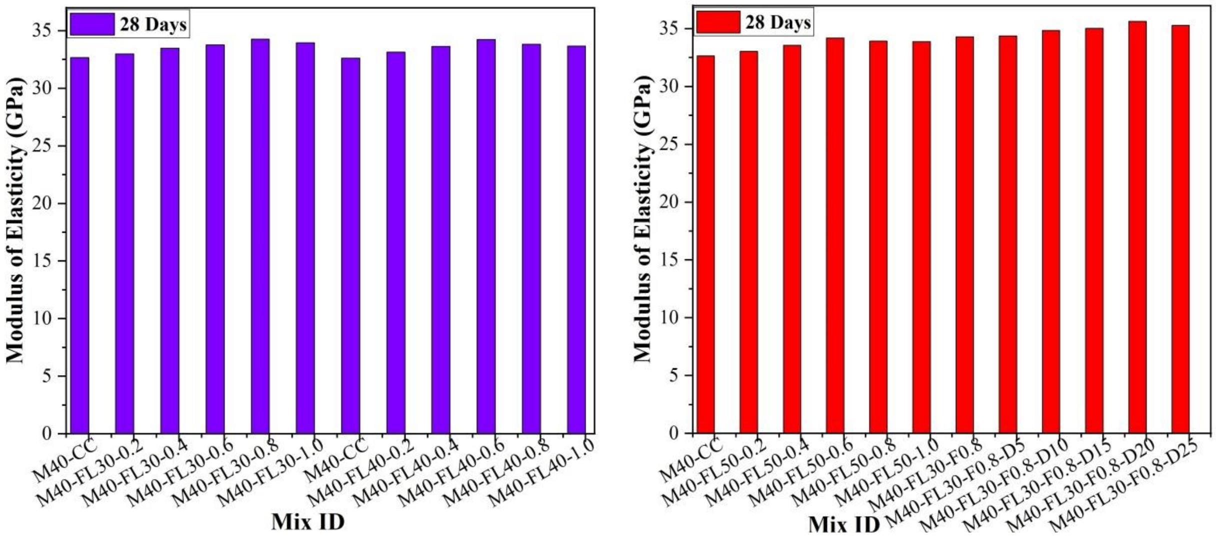


(c) Groups 5– 6

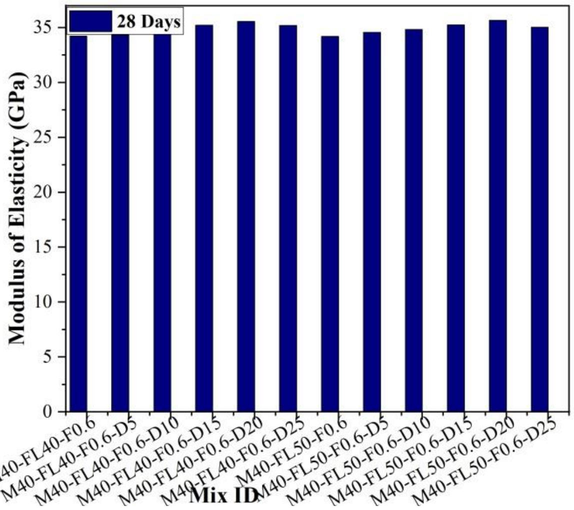
Figure 12. Flexural strength of FRC at 28 days.

3.5. Modulus of elasticity of FRC

The modulus of elasticity (ME) of concrete is a crucial property that measures the relationship between stress and strain in concrete when an external force is applied. It is also known as the elastic modulus and plays a significant role in structural design. Factors influencing the modulus of elasticity of concrete include concrete composition, concrete strength, aggregate properties, and age of the concrete. The present study determined the ME of fibre-reinforced concrete at twenty eight days of hardened concrete using a compresso extenso meter (IS: 516-1959). The calculated ME of the FRC is presented in Table 9. With the addition of diatomaceous earth powder in concrete mix groups I-III, the modulus of elasticity increased compared to Group I-III, as illustrated in Figure 13 (a) – (c).



(a) Groups 1– 2 (b) Groups 3 – 4



(c) Groups 5– 6

Figure 13. Modulus of elasticity of FRC at 28 days.

4. Statistical analysis

4.1. Comparison between compressive and split tensile strength of FRC

The statistical analysis involved linear regression analysis and various codes used in this study. The relationship between the CS and STS of the FRC was analysed, and the STS results were predicted using Equation (1). The predicted STS results are reported in Table 10. The regression coefficient (R^2) is 0.95, indicating that CS explains 95% of the variability in STS. The correlation coefficient (R) is also 0.95, suggesting a strong direct relationship between CS and STS, as shown in Figure 14. The experimental and predicted STS results are compared and illustrated in Figure 15. Additionally, the STS were predicted using various codes (ACI - 318 - 08; Iravani, 2010; GB – 500100 – 2010) and the results are reported in Table 11. Among the three codes, code 26 exhibits a stronger correlation than the remaining two codes.

$$f_{sp} = 1.7856 + 0.0495 * \mathrm{CS} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Table 10. Prediction of strength properties of FRC at 28 days.

		Predicted STS (MPa)				Predicted FS (MPa)				Predicted ME (GPa)		
Mix Group	Mix ID	Eq.(1)	(ACI)	(Iravani)	(GB)	Eq.2	(ACI)	(DU)	([IS)	Eq.3	(ACI)	(IS)
I	M40-CC	3.90	3.59	2.99	3.17	6.03	4.05	5.29	4.57	32.68	30.71	32.66
	M40-FL30-0.2	3.94	3.63	3.02	3.22	6.09	4.09	5.34	4.62	32.99	31.01	32.98
	M40-FL30-0.4	4.01	3.68	3.09	3.29	6.19	4.15	5.43	4.69	33.48	31.48	33.49
	M40-FL30-0.6	4.04	3.71	3.12	3.34	6.24	4.19	5.47	4.73	33.76	31.75	33.77
	M40-FL30-0.8	4.11	3.77	3.18	3.40	6.33	4.25	5.55	4.79	34.22	32.18	34.24
	M40-FL30-1.0	4.07	3.74	3.14	3.37	6.28	4.21	5.50	4.76	33.96	31.94	33.97
II	M40-CC	3.90	3.59	2.99	3.17	6.03	4.05	5.29	4.57	32.68	30.71	32.66
	M40-FL40-0.2	3.96	3.64	3.04	3.24	6.12	4.11	5.37	4.64	33.13	31.14	33.12
	M40-FL40-0.4	4.02	3.70	3.10	3.31	6.22	4.17	5.45	4.71	33.61	31.61	33.63
	M40-FL40-0.6	4.10	3.76	3.17	3.40	6.33	4.24	5.54	4.79	34.20	32.17	34.22
	M40-FL40-0.8	4.06	3.73	3.13	3.35	6.27	4.20	5.49	4.75	33.88	31.86	33.90
	M40-FL40-1.0	4.03	3.70	3.11	3.32	6.23	4.18	5.46	4.72	33.67	31.66	33.68
	M40-CC	3.90	3.59	2.99	3.17	6.03	4.05	5.29	4.57	32.68	30.71	32.66
III	M40-FL50-0.2	3.94	3.63	3.03	3.22	6.10	4.09	5.35	4.62	33.01	31.02	33.00
	M40-FL50-0.4	4.01	3.69	3.09	3.30	6.20	4.16	5.43	4.69	33.52	31.52	33.53
	M40-FL50-0.6	4.10	3.76	3.17	3.40	6.32	4.24	5.54	4.78	34.16	32.13	34.18
	M40-FL50-0.8	4.06	3.73	3.14	3.36	6.27	4.21	5.50	4.75	33.91	31.89	33.92
	M40-FL50-1.0	4.05	3.72	3.13	3.34	6.26	4.19	5.48	4.74	33.81	31.80	33.83
IV	M40-FL30-F0.8	4.11	3.77	3.18	3.40	6.33	4.25	5.55	4.79	34.22	32.18	34.24
	M40-FL30-F0.8-D5	4.13	3.78	3.20	3.43	6.37	4.27	5.57	4.82	34.39	32.34	34.41
	M40-FL30-F0.8-D10	4.20	3.84	3.25	3.50	6.46	4.33	5.65	4.88	34.87	32.79	34.89
	M40-FL30-F0.8-D15	4.22	3.86	3.28	3.53	6.50	4.35	5.68	4.91	35.08	32.98	35.09
	M40-FL30-F0.8-D20	4.30	3.92	3.35	3.62	6.62	4.42	5.78	4.99	35.67	33.52	35.66
	M40-FL30-F0.8-D25	4.24	3.87	3.29	3.55	6.53	4.37	5.71	4.93	35.22	33.11	35.22
V	M40-FL40-F0.6	4.10	3.76	3.17	3.40	6.33	4.24	5.54	4.79	34.20	32.17	34.22
	M40-FL40-F0.6-D5	4.13	3.79	3.20	3.43	6.37	4.27	5.57	4.82	34.39	32.34	34.41
	M40-FL40-F0.6-D10	4.20	3.84	3.25	3.50	6.46	4.33	5.65	4.88	34.88	32.80	34.89
	M40-FL40-F0.6-D15	4.24	3.87	3.29	3.55	6.52	4.37	5.70	4.93	35.20	33.09	35.20
	M40-FL40-F0.6-D20	4.29	3.91	3.34	3.61	6.60	4.41	5.76	4.98	35.58	33.44	35.57
	M40-FL40-F0.6-D25	4.23	3.86	3.28	3.54	6.51	4.36	5.69	4.92	35.12	33.02	35.13
VI	M40-FL50-F0.6	4.10	3.76	3.17	3.40	6.32	4.24	5.54	4.78	34.16	32.13	34.18
	M40-FL50-F0.6-D5	4.15	3.80	3.22	3.46	6.40	4.29	5.60	4.84	34.57	32.51	34.58
	M40-FL50-F0.6-D10	4.19	3.83	3.25	3.50	6.45	4.32	5.64	4.88	34.83	32.75	34.84
	M40-FL50-F0.6-D15	4.25	3.88	3.30	3.56	6.54	4.37	5.71	4.94	35.25	33.14	35.26
	M40-FL50-F0.6-D20	4.30	3.92	3.35	3.62	6.61	4.42	5.78	4.99	35.66	33.51	35.65
	M40-FL50-F0.6-D25	4.22	3.86	3.27	3.53	6.50	4.35	5.68	4.91	35.05	32.95	35.06

Table 11. Split tensile strength of FRC was estimated using the existing empirical formulas.

Type of concrete	STS (MPa)
PCC	$f_{sp} = 0.55x(f_c)^{0.5}$ (ACI - 318 - 08)
	$f_{sp} = 0.301x(0.8xf_c)^{0.65}$ (Iravani, 2010)
	$f_{sp} = 0.19x(f_c)^{0.75}$ (GB - 500100 - 2010)

Note: PCC – Plain cement concrete.

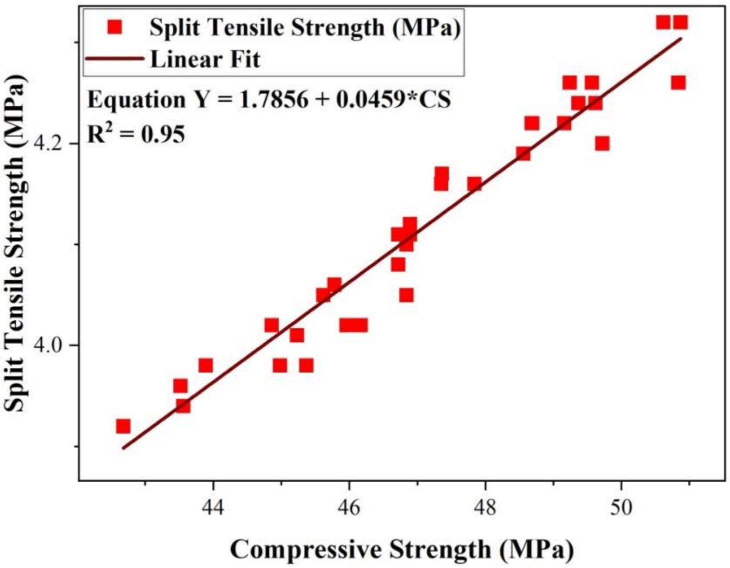


Figure 14. Relationship between the compressive and split tensile strength of FRC.

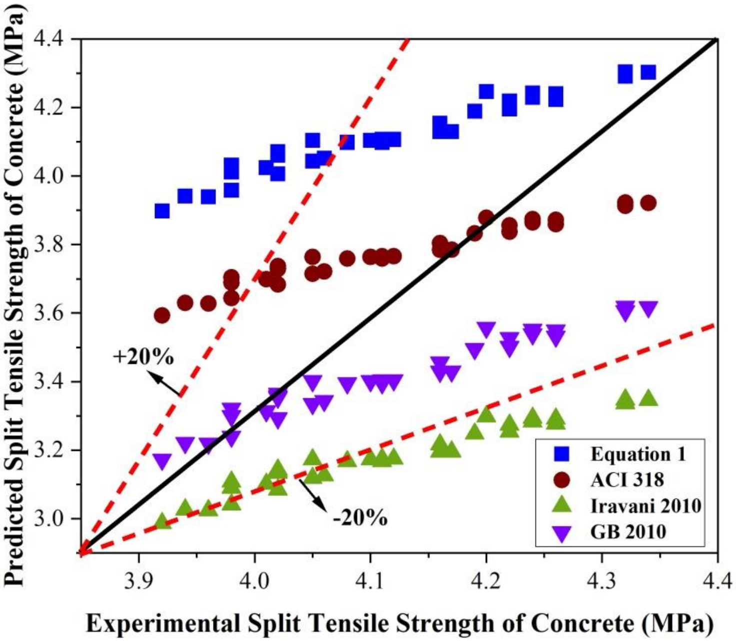


Figure 15. Comparison between experimental and predicted split tensile strength of FRC.

4.2. Comparison between compressive and flexural strength of FRC

The FS of the FRC was examined, and the predicted results are presented in Table 10. The predicted results are compared to the experimental results, which agree with experimental results using Equation (2) and code (Du, 2010), displayed in Figure 16. Also, the FS was predicted using the different types of codes Table 12. Since FS (or whatever it represents) has a regression coefficient (R2) of 0.98, CS can account for 98% of FS variability, as illustrated in Figure 17. Additionally, there is a high direct association between CS and FS, as indicated by the correlation coefficient (R) of 0.98.

$$f_b = 3.0021 + 0.07106*CS\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

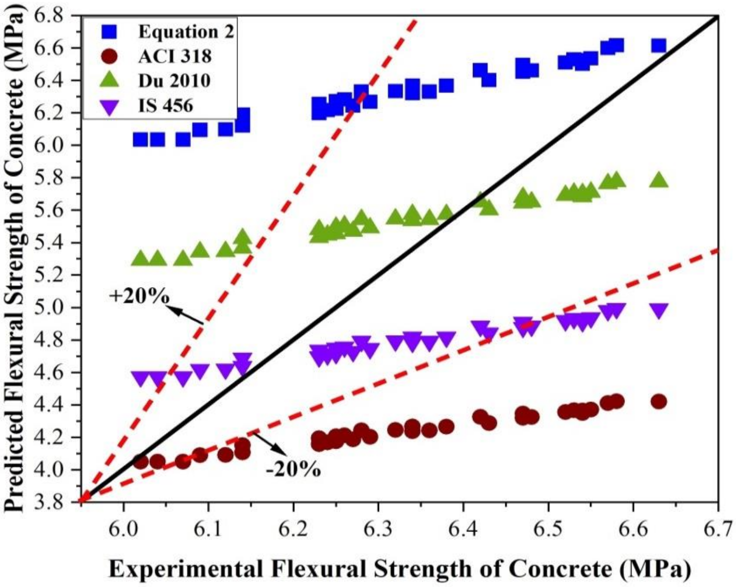


Figure 16. Comparison between experimental and predicted flexural strength of FRC.

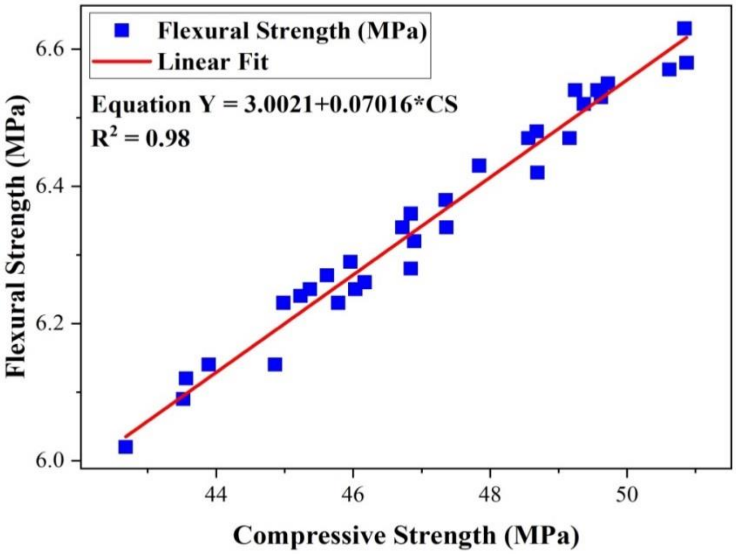


Figure 17. Relationship between compressive and flexural strength of FRC.

Table 12. Flexural strength of FRC was estimated using the existing empirical formulas.

Type of concrete	FS (MPa)
PCC	$f_b = 0.62x(fc)^{0.5}$ (ACI – 318-08)
	$f_b = 0.81x(fc)^{0.5}$ (Du – 2010)
	$f_b = 0.70x(fc)^{0.5}$ (IS 456: 2000)

4.3. Comparison between compressive and modulus of elasticity of FRC

The relationship between CS and ME of the FRC was evaluated using regression analysis Equation (3), and the calculated results are reported in Table 10. Also, the ME was calculated using the various codes (ACI - 318 - 08; IS - 456: 2000) given in Table 13. Given that CS explains 99% of the variability in ME, the regression coefficient (R^2) is 0.99. Additionally, a strong direct relationship exists between CS and ME, as evidenced by the correlation coefficient (R) of 0.99 displayed in Figure 18. The ME was predicted using Equation 3 and code (IS – 456:2000). The experimental and predicted modulus of elasticity of the concrete was compared, and its good agreement with the experimental results (Candassamy et al., 2024) is illustrated in Figure 19.

$$E_C = 17.1188 + 0.3647*CS \qquad (3)$$

Table 13. Modulus of elasticity of FRC was estimated using the existing empirical formulas.

Type of concrete	ME (GPa)
PCC	$E_C = 4700x(f_c)^{0.5}$ (ACI - 318 - 08)
	$E_C = 5000x(f_c)^{0.5}$ (IS – 456: 2000)

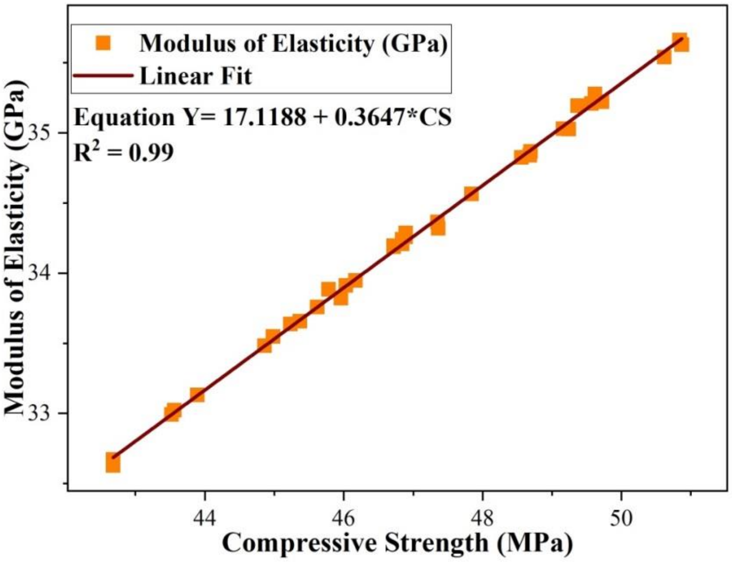


Figure 18. Relationship between CS and modulus of elasticity of FRC.

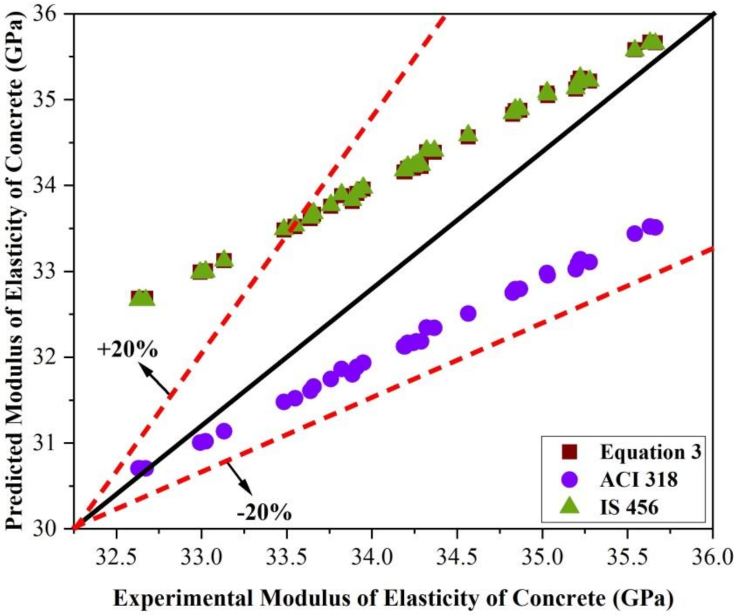


Figure 19. Comparison between experimental and predicted modulus of elasticity of FRC.

5. Conclusions and comments

The present research work has investigated the mechanical properties of FRC, including E-waste fibres of various lengths (30mm, 40mm & 50mm) and diatomaceous earth powder. Based on the experimental study, the following conclusion can be drawn.

1. The experimental study investigated the strength properties of FRC with the addition of E-waste fibres (0.2%, 0.4%, 0.6%, 0.8%, and 1.0%) and diatomaceous earth powder (5%, 10%, 15%, 20%, and 25%).
2. The impact of adding E-waste fibres to the concrete mix on the workability of fresh concrete properties was examined. Slump values decreased with increasing fibre content. The simultaneous partial replacement of diatomaceous earth powder led to increased slump values.
3. The CS of Fiber-Reinforced Concrete (FRC) was enhanced by adding E-waste fibre by 4.85%, 3.32%, and 4.08%. Additionally, the diatomaceous earth powder was partially replaced by cement. This replacement increased the CS of the concrete by 4.85%, 5.37%, and 5.60% compared to the control concrete mix at 28 days.
4. The STS was improved by 4.92%, 5.65%, 5.32%, 4.11%, 4.62%, and 4.57% compared to the conventional concrete mix at 28 days.
5. Similarly, the flexural strength increased by adding E-waste fibre and diatomaceous earth powder by 4.86%, 4.81%, 4.66%, 3.92%, 3.89%, and 4.31% compared to the traditional concrete mix at 28 days. Moreover, the modulus of elasticity of the concrete also improved with the addition of E-waste fibre and diatomaceous earth powder.
6. According to the experimental study, the mechanical properties of FRC were significantly increased in groups I & VI compared to the remaining mix groups.
7. The strength properties of FRC were predicted using linear regression analysis and various codes. The predicted results were compared to the experimental results. The regression (R^2) values for STS, FS, and ME were 0.95, 0.98, and 0.99, respectively. The linear regression analysis and various codes effectively helped predict the experimental results, and the predicted results showed a high correlation with the experimental results.
8. Finally, the main application of diatomaceous earth powder in concrete is to provide green pervious concrete and sustainable building materials and enhance its strength and durability.

Furthermore, the flexural behaviour of Reinforced Concrete (RC) beams with various loading conditions can be studied using the optimum strength mixes.

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