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Investigation of Mechanical Properties of Different Fiber Reinforced Engineered Cement Composites

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Abstract **-** Engineered cementitious composite (ECC) is a fiber reinforced cementitious material with multiple cracking qualities that induce pseudo-strain hardening prior to softening, which can reach up to a tensile strain of 3 to 8%. However, the production cost of ECC is high due to the high prices of synthetic fibers such as polyethylene (PE) and polyvinyl alcohol (PVA) fibers. So, the application of ECC is limited in the construction sector. The aim of the study is to evaluate the properties of a cheap fiber Polypropylene (PP) in an ECC and to check the effect of various fibers on the concrete matrix through non-destructive tests (NDTs). For this purpose, the ECC-M45 mix originally developed by Victor Li is followed. Firstly, oiled PVA (OPVA) fibers are used, to be later replaced by PE and PP fibers. The compressive & tensile strength of concrete mixes are compared followed by ultrasonic-pulse velocity (UPV) and rebound hammer (RH) tests. Results show that ECC-PE shows the highest tensile strength 5.87MPa followed by ECC-OPVA (3.74MPa) and ECC-PP (3.34MPa). ECC-PE also shows the highest ultimate strains 11.15% followed by ECC-PP (7.2%) and ECC-OPVA fibers (1.94%). ECC-PP shows continuous strain hardening indicating better multi-cracking than ECC-OPVA which shows a steep drop in stress beyond 3.74MPa, yielding 2MPa stress at ultimate strain. The compressive strength of ECC-OPVA is 57.85MPa which is 6.8% and 42% greater than ECC-PP and ECC-PE fibers, respectively. The non-destructive tests show both OPVA-ECC and PP-ECC as superior and a big quality difference between them and PE-ECC. Therefore, the NDTs familiarize more with the compressive strength test irrespective of the fiber type which shows that all fibers have good bonding ability.

Keywords**:** fiber-reinforced concrete, engineered cementitious composite, tensile strength, ultimate tensile strain, non-destructive tests

1. Introduction

In recent decades, significant advancements have been made in the development of different types of concrete for diverse technical applications. Scientists have conducted numerous experiments to study the durability, mechanical and fracture properties of these concrete materials. One notable concrete material, known as engineered cementitious composite (ECC), was introduced in 1992 [1]. ECC was specially designed to improve the ductility and toughness of concrete, making it an ideal material for structural components subjected to fatigue loading, like beam-column joints. Moreover, ECC proves to be an excellent alternative for structures like bridges which face bending and axial stresses, weather effects, and potential damage from cracks, expansion, or reinforcement corrosion [2]. Considering these factors is crucial to prevent costly repairs, component replacements, or even the complete failure of bridge structures. Though, ultra-high-performance concrete may be preferable in some cases, the use of ECC, High-Performance Concrete (HPC), or Ultra-High-Performance Concrete (UHPC) can vary depending upon the requirements. Since ECC is primarily designed for structural parts subjected to repeated and cyclic loads, ductility and toughness are its critical characteristics. However, the compressive strength of concrete is regarded as the most important aspect when assessing overall quality. As a result, researchers perform compressive strength tests on several types of concrete samples. An overemphasis on high compressive strength, on the other hand, can contribute to increased brittle failure, particularly in important parts of structures, such as composite steel structural joints prone to concrete fracture [3]–[5]. Fundamentally, ECC provides a significant benefit by successfully addressing both tensile and compressive strength through the incorporation of fibers into its dense structure. [6]. Because of this distinguishing feature, ECC may be employed in structural zones subjected to very repeated, cyclic, axial, and bending loads. [7].

The initial version of ECC, developed in the mid-1990s, utilized high-modulus polyethylene (PE) fiber [8], [9]. PE-ECC has an outstanding tensile strain capacity ranging from 4% to 7%, a tensile strength above 5.5 MPa, and a compressive strength surpassing 60 MPa by integrating 1.5% by volume of high-modulus PE fiber in the mix. The inclusion of PE fiber significantly enhances the mechanical properties of ECC, making it an exceptional material choice. PE-ECC has also been successfully prepared using seawater and sea sand, ensuring non-corrosion functionality [10]. Additionally, researchers have explored the use of artificial fine aggregates in PE-ECC, which reduces the environmental burden associated with traditional aggregate production [11]. Another noteworthy advancement is the development of PE-ECC with ultra-high ductility, serving as a novel and resilient fireproof coating [12]. This particular formulation demonstrates remarkable fire resistance properties while maintaining its structural integrity under extreme conditions. Furthermore, to cater to complex and severe service environments, PE/steel fiber-ECC has been engineered with a compressive strength surpassing 210 MPa. This high-strength variant of ECC provides enhanced performance and durability in demanding applications. Researchers [13] have also developed an ultra-high-performance ECC (UHP-ECC) utilizing PE fibers. This UHP-ECC was created in such a manner that it can achieve high tensile strain as well as high tensile and compressive strength along with better multiple cracking and strain hardening properties. The results showed average tensile strength and compressive strength values of 17.42 MPa and 121.5 MPa, respectively. In [14], researchers developed a multifunctional ultra-lightweight ECC (ULW-ECC) incorporating PE fibers and fly-ash cenospheres. This ULW-ECC achieved compressive strength of 36-58 MPa and flexural strength in range 10.72–14.41 MPa, and a 4-8% tensile strain capacity. However, from various studies, it was observed that PE-ECC has a large crack width due to the hydrophobic character of PE fiber. Also, PE fiber is costlier which makes PE-ECC uneconomical. Therefore, there is a need to look for an alternative to PE fibers that can make an economical ECC. In view of this, it was found that Polypropylene fibers are much cheaper than PE fibers. They also have a better crack-bridging quality.

The inclusion of polypropylene (PP) fibers into limestone calcined clay cement (LC3) based materials has been studied in [15] to generate innovative low-carbon Engineered Cementitious Composites (ECCs) in their study. The study required the creation of 24 sets of specimens, each with four different curing ages and six distinct mix ratios. Compressive load-displacement data was collected, and the compressive curve's properties were investigated. Researchers have also used methods like; XRD, SEM-EDS, and MIP to get insight into the compressive strength resulting from the inclusion of PP fibers and LC3 in ECC. The study's findings show that the compressive strength of LC3-PP-ECCs normally declines over a 28-day period as the number of PP fibers introduced into the mixture rises. The combined action of PP fibers and hydration products, in particular, results in a considerable decrease in the compressive strength of LC3-ECCs containing 0.5% PP fibers. Despite the decrease in compressive strength, the specimens demonstrated better toughness, ductility, and energy absorption properties. The compressive strength under static loading decreased as the inclusion of PP fibers generated additional internal faults and weaknesses inside the composites' microstructures. In [16], researchers investigated the mechanical properties of ECC consisting of PE and PP fibers. The results show that PP-ECC gained almost 22% higher compressive strength than PE-ECC. It was also observed that the incorporation of PP fibers decreased the porosity and increased the proportion of smaller pores of 0.5-0.01 diameters.

The mechanical properties of Engineered Cementitious Composites (ECCs) incorporated with ordinary PVA, oiled PVA (OPVA), and PP fibers have been investigated in [17]. The results showed that more than 1.5% of the volume of PVA fibers and 2.5% of PP fibers, preferably 3%, is required for good ductility. However, these fiber volume contents result in fewer cracks with larger crack widths and low tensile strain. Furthermore, the composites with 3% of PP fibers by volume exhibited a slower loss of tensile load carrying capacity beyond peak tensile load than those with 2% by volume of oiled and ordinary PVA fibers. In addition, ECC with oiled-PVA fiber has shown higher compressive and flexural strength than ECC incorporating PP fibers.

Kuang [18] investigated the effect of PP-ECC on the compressive strength, with a fiber volume rate of 1.5%. Compared to a fiberless cement composite (mean value: 32 MPa), including the fiber enhanced the ECC's compressive strength (mean value: 32.5-40 MPa). Yang [19] performed an experimental study on ECC having polypropylene fiber. The results revealed that compressive strength increased up to a certain fiber content. After a specific limit, compressive strength starts decreasing with increased fiber content. This decrease in strength is caused by the weak interfacial bond between the cement matrix and excess fiber content. In another study [20], researchers examined the influence of polypropylene fibers of various percentages, i.e., 0.5%, 1.5%, 2%, and 2.5%, on the compressive strength of ECC. The results show that the compressive strength of specimens increases linearly from 0.5 to 2% fiber content compared to the mix without fibers. Due to the significant increase in fiber content, ECC's strength decreased when 2.5% of fibers were used.

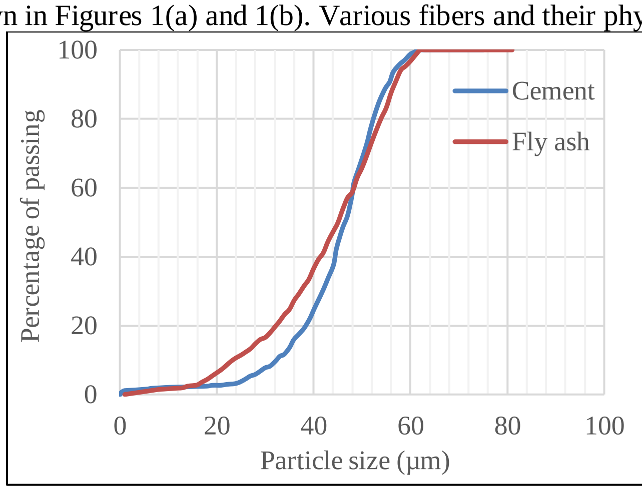
However, concrete is a heterogeneous material and so is expected for an ECC. In the case of ECC, this heterogeneity increases due to the addition of different fibers. It is important to study the behaviour of every ingredient with each other, which can be possible with the help of non-destructive tests (NDT) like ultrasonic pulse velocity (UPV). Generally, NDTs like rebound hammer (RH), and UPV are performed to predict the compressive strength of concrete, as it is difficult to use destructive methods in in-situ conditions. The non-destructive compressive strength test is used to monitor the development of compressive strength, assess the structure's integrity, or as a quality control method that replaces destructive testing methods. In a pilot study, where compressive and flexural strength are only evaluated, these non-destructive tests could bring an insight into the cracks and faults in the structure, thus indicating the effect of matrix morphology on the strength of the concrete as well as its tensile stress-strain capacity, rather than performing time-consuming microstructure analysis like SEM, XRD, etc.

This research aims to develop ECC mix (Engineered Cementitious Composite) with PVA, PP, and PE fibers, comprising approximately 2% of the binder's volume, and then evaluate the compressive strength of each mix through destructive and non-destructive tests. Also, the tensile stress-strain behaviour of these concretes will be analysed.

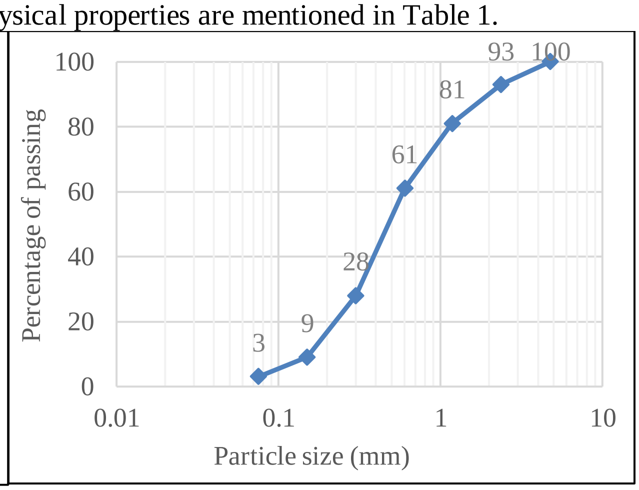
2. Materials and Methodology

2.1 Materials

This study adopted the mix M45 ECC originally developed by Victor Li [21]. The primary components of this mix include Portland cement, fly-ash, fine aggregate, water, and fibers. However, the current research used two different types of fibers: PE fiber and PP fiber. The Ordinary Portland cement of 43 grade with a specific gravity of 3.15 that conforms to IS 8112, class F fly-ash sourced from the Goindwal Sahib Power Plant with a specific gravity of 2.2, fine aggregate that conforms to zone III as per IS 383-1970 and has a specific gravity of 2.54, polycarboxylate (PCE) based super plasticizer, water, and different types of fibers were used in this study. The particle size distribution of cement, fly-ash, and fine aggregate is shown in Figures 1(a) and 1(b). Various fibers and their physical properties are mentioned in Table 1.



(a)



(b)

Figure 1: Particle size distribution (a) Cement, fly-ash (b) fine aggregate.

Table 1: Properties of Fibers

Type of Fibers	Length (mm)	Young's Mod. (GPa)	Density (kg/m^3)	Tensile Strength (MPa)	Elongation (%)
O-PVA	12	42.8	1300	1620	6.5
PP	12	7.1	910	530	26
PE	12	120	970	3000	5

2.2. Preparation of ECC

The mix proportions of ECC per cubic meter are mentioned in Table 2. To obtain a uniform mix of ECC, dry ingredients i.e., fine sand, cement, and fly-ash were added together in combination as shown in Fig.2. Then mixed in a Hobart mixer and rotated for 1 min at 140 rpm. Then water with super-plasticizer was slowly added to the mix and rotated for the next 5 min at 140 rpm. Then, while the mixer was being rotated, fibers were slowly added to it. After that, the mixer was rotated at 420 rpm for the next 2-3 min until the mixture became homogeneous.

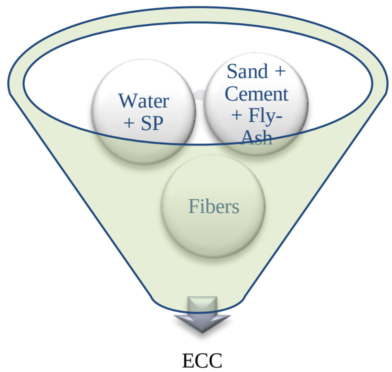


Fig. 2: Preparation of ECC

Table 2: Mix proportion of ECC per m^3

Mix	Cement	Fly-ash	Fine aggregate	Fiber	Water	Super-Plasticizer
OPVA-ECC	1	1.2	0.8	0.02	0.56	0.012
PP-ECC	1	1.2	0.8	0.02	0.56	0.012
PE-ECC	1	1.2	0.8	0.02	0.56	0.012

2.3. Tests conducted

2.3.1. Compressive Strength Test

The compressive strength tests were conducted according to the specifications outlined in IS: 516-1959, utilizing a Compression Testing Machine with a capacity of 2000 kN. The tests were performed on three cubes measuring 150 mm × 150 mm × 150 mm at 7 days and 28 days. During the test, the load applied to the specimen increased to 140 kg/(cm^2.min).

2.3.2. Uniaxial Tensile Test

The uniaxial tensile test is a direct tensile test in which the specimen is pulled apart at the ends. In this test, two YYU-25/80 extensometers are fixed on either side of the specimen to record the displacement of the middle part, whose length is 80mm. An MTS CMT5305 axial-pressure-leveraged stable testing system was employed with a 0.1 mm/min loading rate.

2.3.3. Ultrasonic Pulse Velocity (UPV) Test

The UPV test is used to assess the homogeneity, existence of fractures or other flaws, and quality of concrete without disturbing the samples. Two transducer-connected probes are placed on opposite faces of each other and used to transmit ultrasonic pulses through concrete samples of 100 mm×100 mm×100 mm of each ECC mix and examined at 7 & 28 days (Fig. 3a). The code specifies the following relationship between concrete quality and ultrasonic pulse velocity (Table 3):

Table. 3: Relation between Concrete Quality & Ultrasonic Pulse Velocity [IS:13311]

Quality of concrete	Pulse velocity (m/s)	Quality of concrete	Pulse velocity (m/s)
Doubtful	Below 3000	Good	3500-4500
Medium	3000-3500	Excellent	Above 4500

(a) (b)

Fig. 3. Set-up for non-destructive UPV test (a) and Rebound hammer test (b)

2.3.4. Rebound Hammer Test

A reasonable connection between the rebound index and the compressive strength may be utilized to determine the compressive strength using the non-destructive rebound hammer test to measure the compressive strength, uniformity, and quality of the components in concrete. In this study, 100x100x100 mm^3 cubes are tested for rebound hammer, and six rebound index measurements are obtained around each observation point (Fig. 3b). The rebound index for the point of observation is then calculated by averaging these readings after removing outliers following IS:8900-1978 and then correlated with the quality of the concrete (Table 4).

Table 4. Relation between quality of concrete and average rebound number

Avg. rebound Number	Quality of concrete	Avg. rebound Number	Quality of concrete
0	Delaminated	30 to 40	Good layer
<20	Poor concrete	>40	Very good layer
20 to 30	Fair		

3. Results and Discussion

3.1. Compressive Strength

The compressive strength of ECC mixes incorporated with 3 different types of fibers is shown in Fig. 5. It indicates that the compressive strength of ECC blended with OPVA fibers at 7 and 28 days has given higher strength than PP-ECC and PE-ECC. This OPVA-ECC at 28 days has given around 6.8% and 42% higher compressive strength than PP-ECC and PE-ECC, respectively.

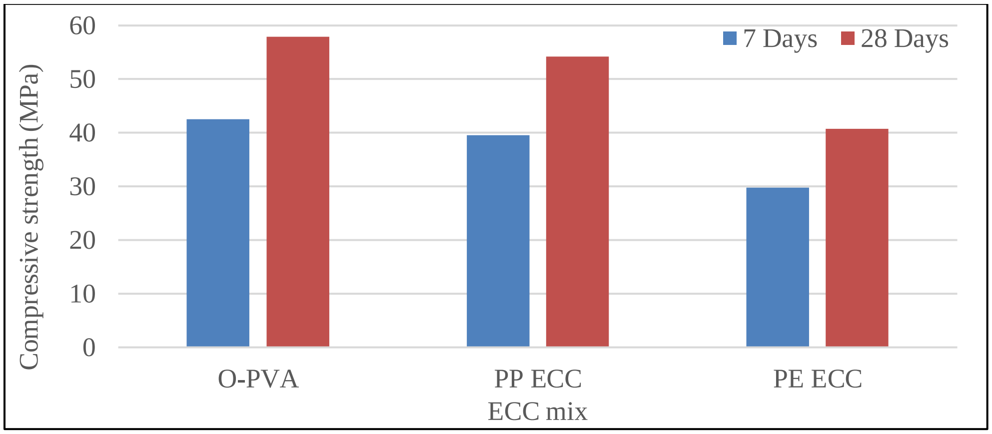


Fig. 5: Compressive strength of ECC incorporating 3 different fibers at 7 and 28 days

3.2. Tensile Stress-Strain Behaviour

Fig. 6 illustrates the tensile stress and tensile strain behaviour of ECC specimens containing OPVA, PE and PP fibers. The Figure indicates that PE-ECC exhibits significant strain hardening behaviour due to uniform dispersion and multiple-cracking/ fiber bridging properties of the PE fiber.

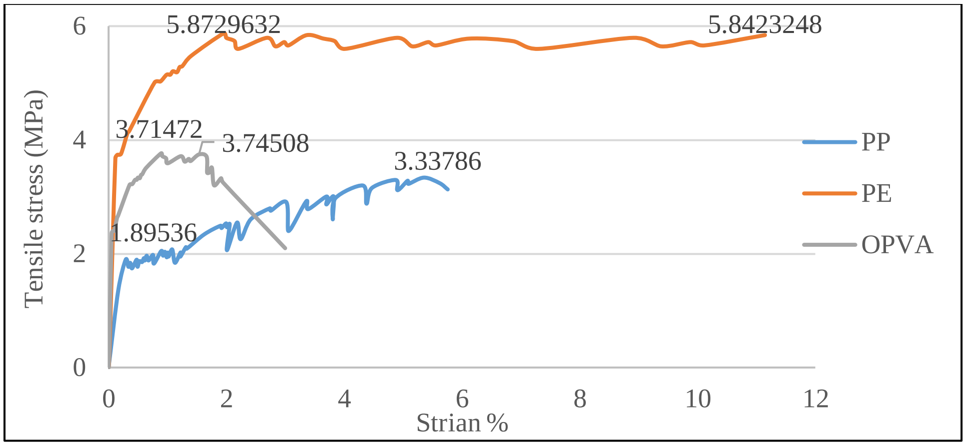


Fig. 6: Tensile stress-strain curve of ECC with OPVA, PE and PP fibers

3.3. Ultra Pulse Velocity (UPV)

Fig. 7 shows the UPV values for ECC mixes incorporating 2 different types of fibers. According to BIS 13311-1:1992 (BIS, 1992) and also mentioned in table 3, when the UPV values range between 3500 and 4500 m/s, the concrete is referred to as good concrete. When the values are above 4500 m/s, the concrete is considered excellent quality. At 28 days, UPV of ECC mixes incorporating PE and PP fibers has achieved more than 4000m/s due to less voids and water binder ratio, which comes under the good. Whereas OPVA fibers has given 4847 UPV value, which comes under excellent band. The minimum and maximum UPV values varied between 4028 m/s - 4847 m/s after 28 days of curing. Among these 3 mixes, PE-ECC has given lowest results.

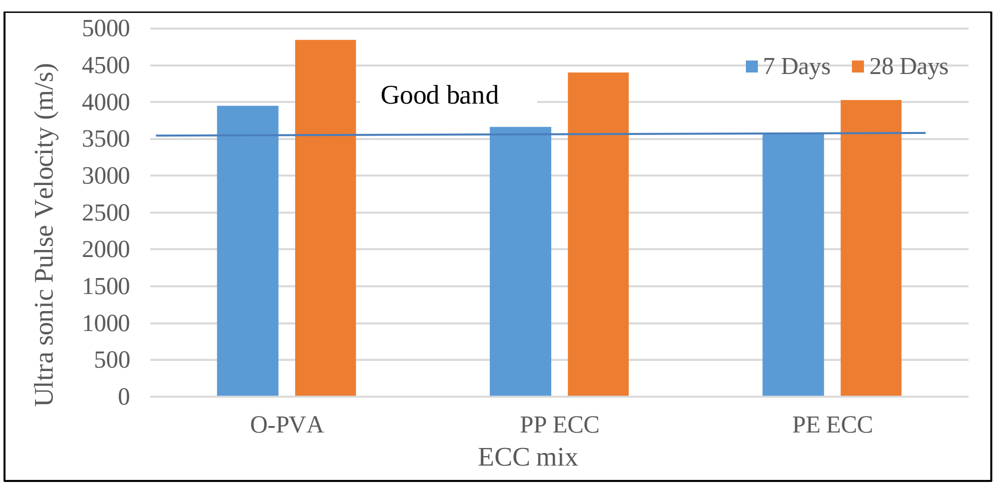


Fig. 7: Ultrasonic pulse velocity of ECC mixes at 7 and 28 days

3.4. Rebound Number (RN)

Fig. 8 shows the compressive strength of all three ECC mixes obtained from the rebound hammer. Rebound hammer test is a non-destructive test conducted per IS 13311:1992 part 2 on concrete samples after 7 and 28 days. This test is also performed to calculate the impact of fibers on the surface hardness of ECC. The measured surface hardness is also known as the rebound number. The rebound numbers obtained from the experimental study ranged from 37 to 47, indicating that the compressive strength for these three ECC mixes fell between 37 and 53 MPa. Among the ECC mixes, the one containing PE fibers displayed the lowest surface hardness value of 37 after 28 days of curing.

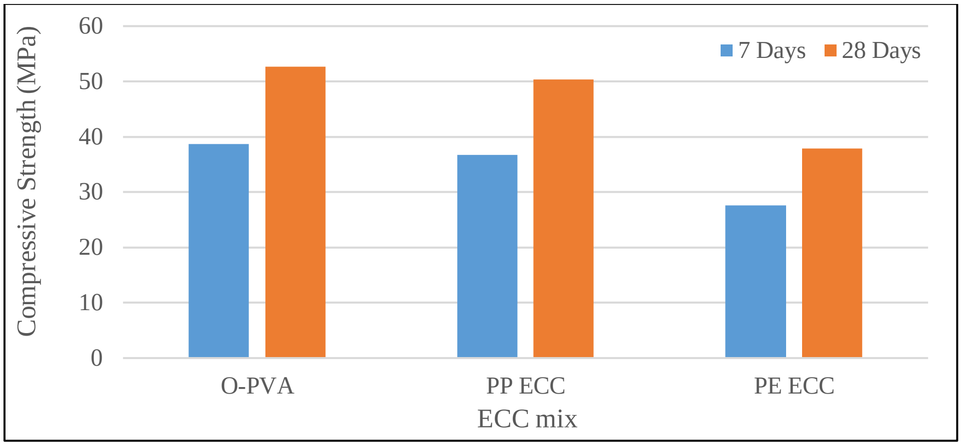


Fig. 8: The Compressive Strength obtained by rebound hammer test at 7 and 28 days

4. Conclusions

In this study, the compressive strength and tensile stress-strain behaviour of Engineered Cementitious Composites (ECC) with three different types of fibers was examined through experimental methods. The study evaluated the effectiveness of ECC with OPVA, PE and PP fibers by conducting destructive and non-destructive tests like rebound hammer and ultrasonic pulse velocity. Following conclusions are drawn based on the experimental investigation:

1. The uniaxial tensile strength of ECC incorporating PE fibers is very high, which means that PE fibers reinforced ECC has high resistance toward flexural fatigue. It can also help to withstand repetitive tensile loading without failure. Additionally, tensile strain carrying capacity of PE fibers are high compared to PP fibers. On the other hand, PE fibers makes ECC uneconomical.
2. The compressive strength of reference mix ECC-OPVA is 57.85MPa which is 6.8% and 42% greater than ECC-PP and ECC-PE fibers, respectively.
3. Tensile strength values of O-PVA fibers are moderate. The tensile strain capacity of ECC incorporating PP fibers is lower than PE fibers' incorporated ECC and its tensile strength (3.84MPa). Though it has lower tensile strength that what is required for pavements (4.5MPa), but its high ultimate strains (7.2%) make it suitable for high-volume overlays and concrete pavements. Also, this PP-ECC is cheaper than ECC incorporating PE fibers.
4. The variation in compressive strength by destructive method and rebound hammer of all mixes lies between 7% - 9%. The UPV values of all mixes varied from 4028 m/s and 4847 m/s after 28 days of curing which comes under excellent category.

References

[1] Z. Q. Zhao, R. J. Sun, Z. Q. Feng, S. S. Wei, and D. W. Huang, "Mechanical properties and applications of ECC," in *Applied Mechanics and Materials*, 2013, pp. 2889–2892.

[2] E. Booya, K. Gorospe, S. Das, and P. Loh, "The influence of utilizing slag in lieu of fly ash on the performance of engineered cementitious composites," *Construction and Building Materials*, vol. 256, 2020.

[3] S. H. Said and H. A. Razak, "The effect of synthetic polyethylene fiber on strain hardening behaviour of ECC," *Mater Des*, vol. 86, pp. 447–457, 2015.

[4] Z. Chen, Y. Yang, and Y. Yao, “Quasi-static and dynamic compressive mechanical properties of engineered cementitious composite incorporating ground granulated blast furnace slag,” *Mater Des*, vol. 44, pp. 500–508, 2013.
[5] M. A. E. M. Ali, A. M. Soliman, and M. L. Nehdi, “Hybrid-fiber reinforced engineered cementitious composite under tensile & impact loading,” *Mater Des*, vol.117, pp.139–149, 2017.
[6] S. Choucha, A. Benyahia, M. Ghrici, and M. S. Mansour, “Effect of natural pozzolan content on the properties of engineered cementitious composites as repair material,” *Frontiers of Structural and Civil Engineering*, vol. 12, no. 3, pp. 261–269, 2018.
[7] W. S. Alaloul, M.A. Musarat, B. A. Tayeh, S. Sivalingam, M. F. B. Rosli, S. Haruna, M. I. Khan, “Mechanical and deformation properties of rubberized engineered cementitious composite (ECC),” *Case Studies in Construction Materials*, vol. 13., 2020.
[8] V. C. Li, H. C. Wu, and Y. W. Chan, “Effect of plasma treatment of PE fibers on interface and cementitious composite properties,” *Journal of American Ceramic Soc.*, vol.79, pp700–704, 1996.
[9] V. C. Li, D. K. Mishra, and H.-C. Wu, “Matrix design for pseudo-strain-hardening fiber reinforced cementitious composites,” 1995.
[10] B. T. Huang, J. Q. Wu, J. Yu, J. G. Dai, C. K. Y. Leung, and V. C. Li, “Seawater sea-sand engineered/strain-hardening cementitious composites (ECC/SHCC): Assessment and modeling of crack characteristics,” *Cement Concrete Res*, vol. 140, 2021.
[11] L. Y. Xu, B. T. Huang, and J. G. Dai, “Development of engineered cementitious composites (ECC) using artificial fine aggregates,” *Constr Build Mater*, vol. 305, 2021.
[12] Z. Cai, F. Liu, J. Yu, K. Yu, and L. Tian, “Development of ultra-high ductility engineered cementitious composites as a novel and resilient fireproof coating,” *Constr Build Mater*, vol. 288, 2021.
[13] Ke-Quan Yu, Jiang-Tao Yu, Jian-Guo Dai, Zhou-Dao Lu, and Surendra P. Shah, “Development of ultra-high performance engineered cementitious composites using polyethylene (PE) fibers,” *Constr Build Mater*, vol.158, 217-227, 2018.
[14] H. Ran, M. Elchalakani, H. Liu, S. Yehia, and B. Yang, “Development and characteristics of multifunctional ultra-lightweight engineered cementitious composites incorporating cenospheres and PE fibre,” *Cement and Concrete Composites*, vol.140, 105084, 2023.
[15] J. Liu, W. Zhang, Z. Li, H. Jin, W. Liu, and L. Tang, “Investigation of using limestone calcined clay cement (LC3) in engineered cementitious composites: The effect of propylene fibers and the curing system,” *Journal of Materials Research and Technology*, vol.15, 2117-2144, 2021.
[16] Z. Feng, Y. Zhou, L. Sui, and Z. Zhu, “Optimal design of a low-cost high-performance hybrid fiber engineered cementitious composites,” *Constr Build Mater*, vol. 345, 2022.
[17] M. Lan, J. Zhou, and M. Xu, “Effect of Fiber Types on the Tensile Behaviour of Engineered Cementitious Composites,” *Front Mater*, vol. 8, 2021, doi: 10.3389/fmats.2021.775188.
[18] Y.-L. Kuang, “The Preparation and Optimization Design of High Performance Fiber Cement-Based Composites.,” Southwest University, Nanjing, China, 2015.
[19] L.-L. Yang, “Study on Properties of Hybrid Fiber Reinforced Cement-Based Materials,” Southwest University, Chongqing, China, 2020.
[20] P. Yan, B. Chen, S. Afgan, M. Aminul Haque, M. Wu, and J. Han, “Experimental research on ductility enhancement of ultra-high performance concrete incorporation with basalt fiber, polypropylene fiber and glass fiber,” *Constr Build Mater*, vol. 279, 2021.
[21] Michael D. Lepech and Victor C. Li, “Large-Scale-Processing-of-Engineered-Cementitious-Composites,” *ACI Mater J*, vol. 105, no. 4, pp. 358–366, 2008.