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Laboratory Study on the Water-Soluble Polymer as a Self-Curing Compound for Cement Concrete Roads in Ethiopia

Makendran Chandrakasu [1], Karunanidhi Suthandhiram [1], Shiferaw Garoma [1], Bekesha Merea [1] and Balaguru Sethuraman [2,*]

[1] Department of Civil Engineering, College of Engineering & Technology, Wollega University, Nekemte P.O. Box 395, Ethiopia; makendran@wollegauniversity.edu.et (M.C.); karunabalasingam@wollegauniversity.edu.et (K.S.); shiferawgaroma@gmail.com (S.G.); bekesha.m@gmail.com (B.M.)

[2] School of Mechanical Engineering, VIT Bhopal University, Sehore 466114, India

* Correspondence: iitmguru239@gmail.com or balaguruiitm@gmail.com

Abstract: In this paper, the self-curing process was considered and found to be a better alternative to the conventional curing process for concrete structures in Ethiopia. It is well known that water plays a significant role in the curing process of preparing concrete in the construction industry. A good quality water is required for the conventional curing process, but that is scarce in Ethiopia. Curing concrete for bridges and roads is difficult in Ethiopia due to the poor quality and scarcity of water. In this study, Polyethylene Glycol (PEG) 600, a self-curing process, is considered as an alternative. Using the M40 Grade mix, four different percentages of PEG-600, 0.0, 0.5, 1.0, and 1.5 of cement weight, were studied, and the specimens were tested. Here, M40 grade stands for “a concrete mix with a characteristic compressive strength of 40 N/mm^2, i.e., 40 Newton per square millimeter”. Additionally, the mechanical strengths and properties of both conventional and self-cured processed concretes were calculated and compared. The present investigation concludes that PEG 600 offers significant results for self-curing concrete. The study procedure, results, and recommendations are presented in the text of the paper.

Keywords: bridges; polyethylene glycol 600; self-curing concrete; cost analysis; road pavements

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1. Introduction

Ethiopia is presently prioritizing the construction of new roads because it is a landlocked country in the African continent. A good road network provides the door-to-door delivery of every service. In Ethiopia, highway networks are used for transporting goods such as agricultural products, passengers, cattle, etc. A highway network is the most communicative–economic infrastructure and is a crucial and valuable asset for any nation. Roads provide the safe and comfortable transportation of passengers and goods. Ethiopia has more than 126,773 km of road networks, making it the 46th largest network in the world [1]. Roads are directly linked to the agricultural production sectors. Poverty is one of the persistent diseases in rural areas, and these roads play an important role in decreasing the poverty rate [2]. In comparison to construction, curing the concrete pavement is a difficult process for developing countries where water is a scarce resource [3–6]. The most critical element of highway construction is the pavement. Two types of pavements are being used for construction, flexible and rigid. Particularly, rigid pavements have been used for highways, drainages, bridges, culverts, canals, tunnels, bus terminals, parking places, narrow streets, and railway bridges. In the construction process, based on the global use of resources, concrete is placed in the second position after water. However, the majority of these bridges are built with cement concrete only. Curing the cement concrete pavements is a complicated process in Ethiopia due to the poor quality and unavailability of water. Presently, in Ethiopia, water quality is a great constraint in the construction sector.

In other words, water is a significant part of the manufacturing process of concrete and its curing. Curing is a mandatory process to strengthen concrete structures, including concrete roads and pavements [7]. However, potable water or groundwater is costly and scarce in African countries, including Ethiopia, and hence, an alternate solution is needed. The water used for the curing process should not be acidic with a pH not less than 6, and it should also satisfy other standards. Thus, alternative methods and materials must be explored to reduce water use and bring down the cost of construction.

Due to water shortages, carrying good water long distances for curing increases the project cost. For the curing process alone, 1 cubic meter of conventional concrete requires 3000 L of water [8]. Ethiopia is suffering from a severe water crisis, and thus, a sufficient amount of quality water is not available. Therefore, there is a strong need for a novel approach, especially for an alternative solution for water in the construction sector. This study proposes an alternative solution for the conservation of water for today and tomorrow. In this regard, the central idea of this paper is to find an alternate solution for the water constraint of ordinary concrete instead of self-curing concrete for construction sectors.

Generally, concrete curing procedures are classified as either water adding or water holding. Internal curing is a water retention treatment. The internal curing process of concrete can be conducted following two different approaches. The first approach uses saturated lightweight porous aggregate that replenishes the water consumption by chemical shrinkage during cement hydration. The second approach uses hydrophilic elements in concrete to prevent evaporation and retain water. In the present investigation, the second strategy is considered for conducting laboratory experiments and analysis. This study introduces Polyethylene Glycol (PEG-600) as an alternative to water used in the self-curing process of concrete. Self-curing is one of the novel techniques used to improve concrete's strength properties in road and bridge constructions. It increases all these mechanical properties or parameters and reduces early age shrinkage failures. The present study reveals that the self-curing technique reduces the cost of the curing process significantly, i.e., around ETB 1142 for one cubic meter of concrete.

In the literature, Ruhal Pervez Memon et al. (2018) [9] discussed self-curing concrete and its functioning, mechanism, and properties. Conventional curing is a challenging technique to use and monitor in hilly areas. Reviews have also found that self-curing chemicals are environmentally eco-friendly. Self-curing chemicals are used to replace aggregates and bonding agents. The study examined the mechanical, durability, and microstructure properties of self-curing concrete. The findings suggest that employing self-curing concrete increases the properties of the material. It is utilized in strong concrete to prevent shrinkage due to a low water–cement ratio. John Cleary and Norbert Delatte (2008) [10] conducted a study on implementing internal curing in concrete at the transportation department in Columbus, Ohio, USA. Here, the self-curing technique was used to construct road pavements. At 7 and 28 days, the compressive strength of the mixes increased by an average of 6% when lightweight aggregate (LWA) was utilized. After a period of 56 and 90 days, the average increase was 14. The use of LWA was shown to boost compressive strength, and this study backed up this finding. Additionally, the specimens demonstrated a 15% improvement in overall splitting tensile strength. The study concluded that the self-curing technique reduced early-age cracks in concrete pavements [10].

Lopez et al. (2010) conducted a study on self-curing concrete and concluded that the compressive strength of the pavement increased by 31%, and its shrinkage was substantially reduced. Additionally, the study concludes that the concrete pavements have better performance and elastic modulus [11]. Desalegn (2015) conducted a study to estimate water availability in Ethiopia. The study concluded that service, coverage, quantity, quality, and reliability are insufficient. The demand and supply of water are not balanced in Ethiopia, i.e., the demand is much higher than the supply [12].

Weber and Reinhardt (1998) considered the self-curing technique with improved hydration of cementation materials, smaller water–cement ratio, and increased mechanical properties. It has been established that partially substituting prewetted lightweight aggregates for normal-weight aggregates results in an internal water supply for constant cement hydration. Despite water loss due to evaporation, there is a constant increase in strength of up to 25% after one year when compared to normal compressive testing [13]. Nduka et al. (2018) [14] conducted a self-curing concrete study in Nigeria and its aids. This particular technique was capable of reducing early-stage shrinkage cracking for bridge constructions. Finally, the study concludes that the self-curing method results in low permeability and evaporation, reduced coefficients of thermal expansion, and that it mechanically improved the high-performance concrete HPC strength and impact resistance [14]. Dhir et al. (1994) considered using self-curing concrete to replace the conventional curing process entirely. That means water is exempted in the curing process. As a result, it is observed that the strength of the concrete was found to be improved significantly [15]. Weber and Reinhardt (1997) have shown that self-curing concrete decreases the porosity and permeability of the structure. Additionally, the study reveals that the self-curing technique is excellent and improves the splitting tensile and flexural strength of concrete [16]. Sastry and Kumar (2018) have conducted a study on self-curing concrete, C25 grade mix using three chemicals viz., PEG, poly vinyl alcohol (PVA), and super absorbent polymer (SAP). Overall, compressive strength improved 10% over conventional concrete using PEG 400 [17]. Udhanyan R. and Rajamane N. P. have shown that self-curing concrete techniques offer several outstanding advantages, including excellent hydration, better strength, significant reduction in early shrinkage cracks, improvements in durability, and low permeability. At various temperatures both inside and outside the lab, the test results were examined for air curing. The best dose of PEG-400 was found to be 1%, which gave 10% strength [18]. Wen-Chen Jau (2007) also conducted a study on self-curing concrete. This technique is proved to significantly improve the hydration of cement and attracts water from the moistures [19]. El-Dieb et al. (2013) have shown that self-curing concrete directly results in the preservation of water from the construction process [20]. Naresh et al. (2017) conducted a study on M40 grade PEG 400 mixes and discovered that compressive strength increased by 6% when compared to conventional curing method [21]. Here, M40 grade stands for "a concrete mix with a characteristic compressive strength of 40 N/mm^2, i.e., 40 Newton per square milli meter". Udayabanu et al. (2020) have investigated the advantages of self-curing concrete, which is composed of PEG-400 with M20-grade mix. Finally, the study concludes that the strength of the concrete structure is 10% improved because of the self-curing concrete [22].

Based on the previous research, studies, and observations found in the literature, it is clear that self-curing is the new process, and it requires minimal water quantity. In the present study, polyethylene glycol (PEG-600) has been introduced for the internal curing of concrete. It is thus advisable to implement the self-curing technique for the construction of roads and bridges. This study aims to verify and confirm the following specific objectives: (i) to introduce polyethylene glycol (PEG-600) as self-curing agent and to examine its effectiveness, (ii) to investigate the properties and strengths of both conventional and self-curing concretes and to compare them, (iii) to investigate the workability mixer of polyethylene glycol (PEG 600) in concrete, and (iv) to compare the cost–benefit parameters of conventional and self-curing concretes.

Here, in what follows, the significance of the present research has been elaborated. Water quality is one of the challenges that societies have been facing in this century. However, not only the quality but also the supplied amount of water directly affects human health, wealth, agricultural produces, production, and the construction industry. Ethiopia is facing a significant water crisis. Hence, it is necessary to find alternative methods to reduce water consumption. That is, water is to be saved for the next generations. In this connection, Wollega University, College of Engineering and Technology, Nekemte, Ethiopia, has sponsored a laboratory study of self-curing concrete using polyethylene glycol (PEG-600) in Ethiopian climatic conditions. The important task of this present work is to use self-curing concrete in road and construction sectors as an alternate for conventional concrete. This study introduces polyethylene glycol (PEG-600) for the self-curing of concrete. In this novel technique of self-curing concrete, less water is used, and hence the problem of the water crisis in Ethiopia will be solved.

The present study on self-curing concrete uses polyethylene glycol (PEG-600), consists of six phases. These phases and the corresponding procedures are as follows.

The first phase of the study is the collection of materials for the test purpose. During the collection, there will be no compromise in the quality of materials. All basic tests will be conducted so as to confirm the qualities. The materials to be collected include: OPC 53 Grade of cement, fine and coarse aggregates, potable water, and Polyethylene Glycol (PEG-600). Further, the coarse, fine aggregates, and cement material properties and investigations considered are (i) specific gravity (Sp.gr) and (ii) water absorption. The chemical properties considered are (i) solubility, (ii) density, (iii) odor, (iv) mean molecular weight and (v) appearance for polyethylene glycol PEG-600.

The second phase aimed to test what percentage of PEG is the best to be added to self-curing concrete. For that purpose, in M40 mixes, PEGs with 0.0, 0.5, 1.0, and 1.5 percentages of weights of cement quantity have been considered. The third phase comprises the evaluation of both strength parameters and properties of conventional and self-curing concretes. The fourth phase determines the optimum dosage and percentage of polyethylene glycol PEG-600. Similarly, the fifth phase comprises conducting a scanning electron microscopy (SEM) test for bonding the concrete and analyzing the cost benefits for self-curing concretes. Finally, the study ends in the sixth phase, which contains an analysis, conclusions and recommendations.

2. Material and Methodology

2.1. Material

2.1.1. Cement

In this study, self-curing M40-grade concrete uses OPC 53-grade cement. Basic property tests on the cement were carried out, and the results have been incorporated in Table 1.

Table 1. Tests conducted on cement.

No.	Name of the Test	Result Obtained	Remarks/Standards
1	Fineness range of cement	1.5–10 microns	Acceptable as per ASTM C786 17 standards [23]
2	Normal consistency	31%	ASTM C187-11E1 [24]
3	Initial and final setting time of cement	27 min and 8 h	Acceptable as per ASTM C-191 standards [25].
4	Specific gravity (Sp.gr)	3.15	Acceptable as per ASTM C128-15 [26].
5	Soundness	3 mm	ASTM C151 [27]
6	Compressive strength	43 N/mm^2	ASTM C109/C109M-02 [28]

Table 1 shows that the test results of cement satisfy the standards.

2.1.2. Aggregates

This study has obtained coarse and fine aggregates from Nekemte, the East Wollega Zone of the Oromia Region, Ethiopia. Natural stone aggregates of the highest quality are used. A well-graded aggregate with a maximum size of 25 mm and properties meeting ASTM C136/C136M–19 standards is used [29]. The aggregate parameters such as flakiness ratio, elongation ratio, sphericity, shape factors, and its values are presented in Table 2. The equation that determines the sphericity is given as follows:

$$\textbf{Sphericity} = \sqrt[3]{\left(\frac{\text{Thickness} * \text{Breath}}{\text{Length}^2}\right)} \quad (1)$$

Table 2. Properties of sand and stones.

No.	Properties of Aggregate	Fine Aggregate	Coarse Aggregate	Test Followed
1	Average flakiness ratio		0.62	
2	Flakiness index		7.3%	
3	Elongation index		12%	
4	Elongation ratio		1.3	ASTM 4791-10 [30]
5	Impact value		12%	
6	Crushing value		16%	IS: 2386 (Part IV)–1963 [31]
7	Sphericity		0.65	ASTM D5821-01, 2017 [32]
8	Shape factor		0.64	ASTM D 3398-97 [33]
9	Bulk density	1618 kg/m^3	1625 kg/m^3	ASTM C29 / C29M-17a [34] ASTM C1252-17 [35]
10	Water absorption test	1.35%	2.0%	ASTM C127–15 [36]
11	Specific gravity	2.625	2.710	ASTM C127–15 [36]

2.1.3. Fine Aggregate

Fine aggregates are collected from dry river sand around Nekemte town and are 100% clean and free of clays. Fine aggregates pass through a sieve of 4.75 mm, confirming the standards of ASTM C136/C136M-19. Table 2 shows both fine and coarse aggregates [28].

2.1.4. Potable Water

Water is one of the prime and major research materials in making the concrete in this project, and it laboriously participates in neutralization reactions with cement [37]. Potable and fresh water is used, and it is 100% free from mud. The PH value is 7, and it confirms the standard ASTM E2542-08(2014) [38].

2.1.5. Polyethylene Glycol PEG-600

This study introduces the environmentally sustainable water-soluble polymer as a self-curing compound PEG-600 for cement concrete pavements of Ethiopian roads. Polyethylene glycol (PEG-600) with a low-molecular-weight grade is used. The physical and chemical properties and details of PEG-600 have been described in Table 3.

Table 3. Properties of polyethylene glycol (PEG-600).

No.	Properties of PEG-600	Result
1	Molecular weight	570–630 g/mol.
2	Color	Clear Fluid
3	Hydroxyl value, mg KOH/g	178.0–197.0
4	Density	1.13 kg/cm^3
5	Water (Karl Fischer)	0.5% max
6	pH at 5%	4.5–7.5
7	Solubility	Soluble in water
8	Free EO (ethylene oxide),	10.0 ppm max.
9	Specific gravity	1.12
10	Ethylene glycol and diethylene glycol	0.2% max
11	Odor	Mild odor
12	Viscosity @ 20 °F	9.9–11.3
13	Flashpoint	4 °C to 8 °C
14	Heavy metals	5 ppm.
15	Dioxane 1,4	10.0 ppm.
16	Molecular weight	570–630 g/mol
17	Ash	0.1% max

2.2. Mix Design

The mix design M40 was carried out as per the method of the American Concrete Institute (ACI) described in [39–41]. The following procedures were followed and material selection for mix design details presented in Table 4.

Table 4. Material Selection for Mix Design.

Test	Values	Standards
Maximum size of aggregate	25 mm	ACI 211.1-91 [39]
Slump	50 mm, 25 mm	ACI 211.1-91 [39]
Water content	180 kg/m^3	ACI 308R-01 [7]
Air content	1.5%	ACI 308R-01 [7]

- Mean design strength of concrete (f_m) = f_{min} + K.S
- Mean design strength of concrete (f_m) = 40 + (1.65 × 5.6) = 49.25 N/mm^2
- Water cement ratio (W/C) = 0.40 non-air-entrained concrete for road pavement
- Cement content (W/0.40) = (180/0.40) = 450 kg per one m^3 of concrete

2.2.1. Determination of the Coarse Aggregates (C.A.)

For 25 mm, the maximum size of aggregate and fineness modulus of Fine Aggregate (F.A.) value is 3.0. The bulk density of C.A. is 1700 kg/ m^3 of concrete. Consequently, the bulk volume of dry rodded C.A. value is 0.69.

$$\text{Weight of C.A.} = (\text{Bulk volume of dry rodded C.A. of fineness modulus}) \times (\text{Bulk density of C.A.}) \tag{2}$$

- Weight of C.A. = (0.69 × 1700) kg per one m^3 of concrete
- Weight of C.A. = 1173 kg per one m^3 of concrete

2.2.2. Determination of the Fine Aggregates (F.A.)

For the fresh concrete density of 25 mm maximum size, the fine aggregate is 2395 kg per one m^3 of concrete for non-air-entrained concrete. The mix proportion details are presented in Table 5.

$$\text{Weight of F.A.} = \text{Weight of F.A.} - (\text{Wt. of Water} + \text{Wt. of cement} + \text{Wt. of C.A.}) \tag{3}$$

Table 5. Mix of M40 grade concrete for cement concrete road pavement.

Materials	Unit	Quantity	Cement Concrete Ratio
Cement	kg	450	1.0
Fine Aggregate	kg	590	1.31
Coarse Aggregate	kg	1173	2.60
Water	Liters	180	0.40

Weight of F.A. = 2395 − (180 + 450 + 1173) = 590 Kg per one m^3 of concrete.
Hence, as shown in Table 5, the cement concrete ratio is given as

Cement:fine aggregate:coarse aggregate = 1.00:1.31:2.60

2.2.3. Calculation of PEG Weights

The conventional concrete as well as the self-curing concrete with 0.0%, 0.5%, 1%, and 1.5% of polyethylene glycol (PEG-600) is designed, PEG-600 weights with various percentages are calculated and the results are presented in Table 6.

$$\text{Weights of PEG} - 600 = (\% \text{ of PEG} - 600 \times \text{Wt. of Cement}) \tag{4}$$

Table 6. Quantity of polyethylene glycol (PEG-600) in various percentages.

% of PEG	Cement in (kg/m^3)	Weight of PEG in (kg/m^3)	Total Wt. of Concrete in (kg/m^3) (Cement + PEG + F.A. + C.A. + Water)
0%	450	0.00	450 + 0.00 + 590 + 1173 + 180 = **2393.00**
0.5	450	2.25	450 + 2.25 + 590 + 1173 + 180 = **2395.25**
1.0	450	4.5	450 + 4.50 + 590 + 1173 + 180 = **2397.50**
1.5	450	6.75	450 + 6.75 + 590 + 1173 + 180 = **2399.75**

2.2.4. Preparation of Test Specimens

The following steps were followed in order to prepare specimens for both conventional and self-curing concretes [29,30]. Concrete mix samples were made ready for M_{40} grade with sustainable water-soluble polymer PEG 600. The mix was prepared for M_{40} concrete for compressive strength, tensile and split cast for the testing purpose. The three shape types selected for performing various tests were as follows: (i) cubes of $150 \times 150 \times 150$ mm^3 for compressive strength; (ii) cylinders of 150mm diameter $\times$ 300mm height for tensile strength; and (iii) prism molds of $100 \times 100 \times 500$ mm^3 for a split test. Specimens were prepared and tests were conducted on compressive, flexural, and split tensile strength for both conventional and self-curing polyethylene glycol (PEG-600) concretes.

Test Procedures

Samples were prepared for M40-grade concrete mix with sustainable water-soluble polymer (PEG-600). Compressive strength test cubes with size $150 \times 150 \times 150$ mm^3 were prepared as the samples. A compressive testing machine with a capacity of 2000 kN and with a load rate of 140 $kg/cm^2/min$ was utilized and was applied to the sample. The compressive strength experimental setup is shown in Figure 1. The load was applied gradually on the test specimen and continued until the dial gauge needle was reversed. The reversal motion of needle indicated a failed specimen. At that time, the ultimate load on the dial gauge was marked. The compressive strength was calculated as per the equation given below:

$$\textbf{Compressive strength}\left(\frac{\mathbf{N}}{\mathbf{mm^2}}\right) = \frac{\textbf{Ultimate load }(\mathbf{N})}{\textbf{Area of cross section }(\mathbf{mm^2})} \quad (5)$$

Figure 1. Compressive Strength Test setup.

The beam mold with size $100 \times 100 \times 500$ mm^3 was casted and considered the specimen. The bed of the testing equipment was equipped with two steel rollers 38 mm in diameter and was used to support the specimen. Figure 2 shows the experimental setup for flexural strength.

Figure 2. Flexural strength testing setup.

These rollers were set in such a way that the spacing between them was 400 mm. The load was applied at a 180 kg/min rate via two identical rollers positioned at the third points of the supporting span, which were 133 mm apart from center to center. The flexural strength was calculated as per the given equation:

$$\textbf{Flexural strength} \quad \left(\mathbf{N/mm^2}\right) = \mathbf{PL}/\boldsymbol{BD}^{\mathbf{2}} \tag{6}$$

The concrete tensile strength was determined using "Split tensile test" on a concrete cylinder. Due to the brittle nature of concrete, its tension is extremely weak. Thus, the concrete was not expected to withstand direct tension. Concrete develops cracks whenever it is exposed to tensile pressures. The split tensile test was conducted on a 300 mm-long concrete cylinder of 150 mm diameter. The experimental setup of split tensile test is shown Figure 3.

Figure 3. Split tensile test setup.

In the test as shown in Figure 3, a load was applied continuously without interruption at the rate of roughly 14–21 kg/cm^2/min. The total load remained in the range from 9900 kg/min to 14,850 kg/min. The split tensile strength was calculated using the equation given below:

$$\textbf{Split tensile strength} \ \left(\mathbf{N/mm^2}\right) = \mathbf{2P}/\boldsymbol{\pi DL} \tag{7}$$

3. Result and Discussion

Test specimens were prepared and tested for on compressive, flexural, and split tensile strength for both conventional and self-curing polyethylene glycol (PEG-600) concretes. In these laboratory tests, self-curing concrete utilized in polyethylene glycol was successfully performed on compressive, flexure, and tensile strengths. The results are investigated and are presented in the subsequent sections. The outcomes of self-curing concrete and workability tests such as slump and compaction factor test are carried out and are presented in Table 7. It was found that polyethylene glycol 600 self-curing agent improved workability.

Table 7. Workability for conventional and polyethylene glycol (PEG-600) concretes.

Test	Conventional Concrete	Self-Curing PEG-600 Concrete		
Workability M_{40}	Without PEG- 600	PEG-600: 0.5%	PEG-600: 1%	PEG-600: 1.5%
Slump in (mm)	62	78	99	121
Compaction factor	0.83	0.86	0.89	0.92

3.1. Compressive Strength

The compressive strength of the concrete is decided by hydration and is subsequently determined by the water holding capacity of the specific concrete. In comparison, the curing process is an ideal environment. This study has tested self-curing polyethylene glycol (PEG-600) with percentages 0.0, 0.5, 1.0, and 1.5.

Figure 4 shows the comparative statement of compressive values of both conventional and self-curing PEG-600 concretes recorded on 7th, 14th, and 28th days, respectively. Additionally, it shows that the compressive strength of 1% polyethylene glycol (PEG-600) is more when compared to other percentages. The maximum strength is achieved with the addition 1% of polyethylene glycol (PEG-600) and attained a compressive strength of 45.40 N/mm^2. However, the compressive strength was significantly improved by 10.73% in self-curing concrete.

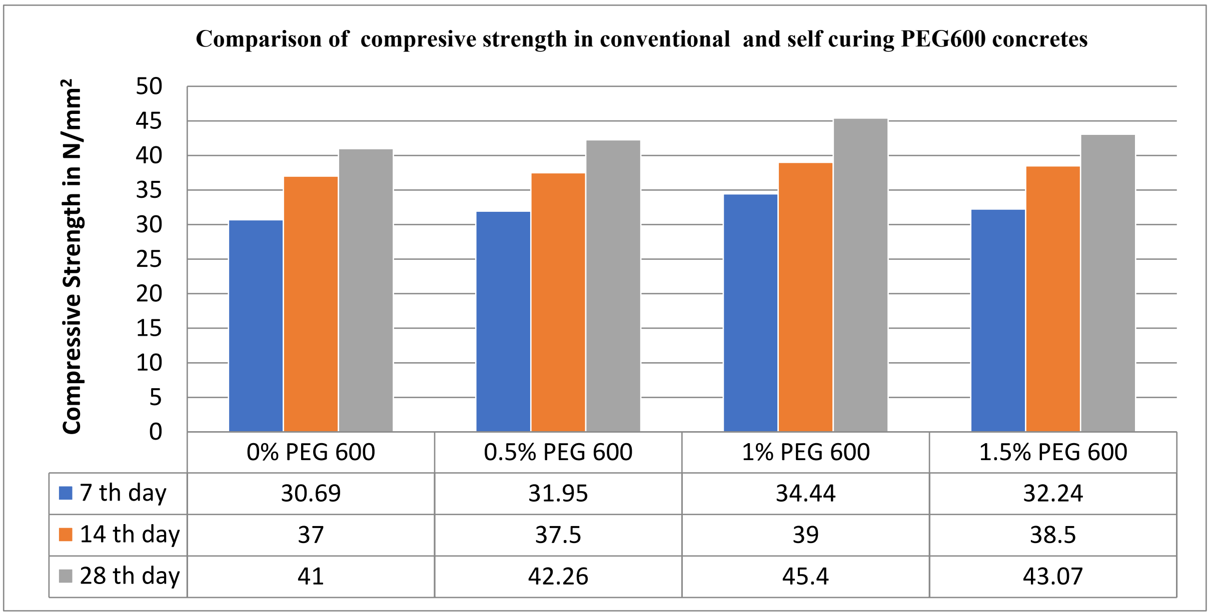


Figure 4. Comparison of compressive strength in conventional and PEG-600 concretes.

3.2. Flexural Strength

Self-curing polyethylene glycol (PEG-600) concrete with percentages of 0.0, 0.5, 1.0, and 1.5 were used, and test results are as shown in Figure 5.

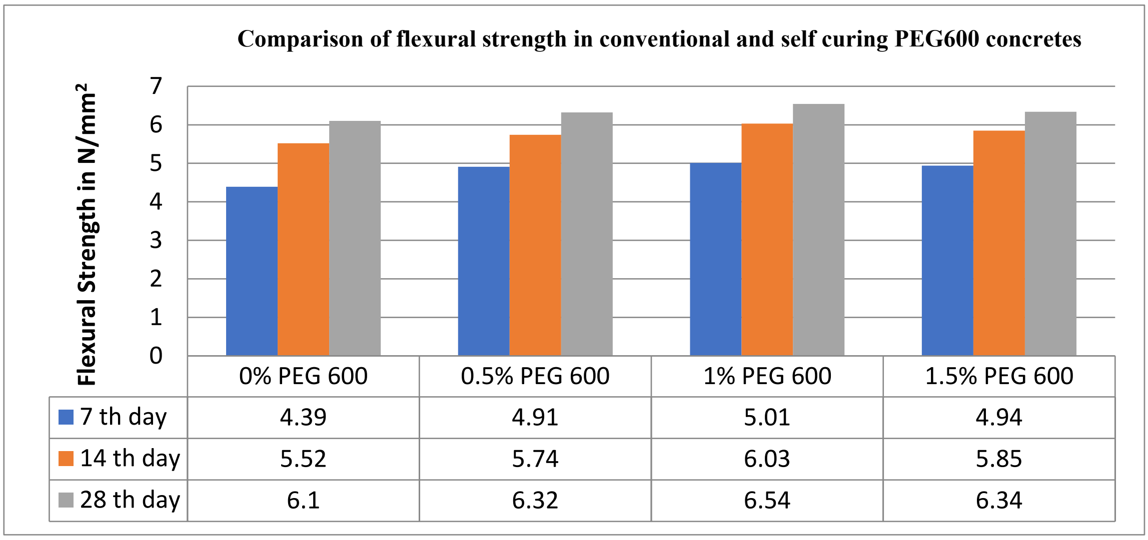


Figure 5. Comparison of flexural strengths of Conventional and PEG-600 concretes.

Figure 5 shows the comparative study of both conventional and self-curing polyethylene glycol (PEG-600) concretes. Flexural strength values recorded on the 7th, 14th, and 28th days are presented, respectively. It shows that the flexural strength of 1% polyethylene glycol (PEG-600) is more when compared to other percentages. It can be observed that the maximum flexural strength of 6.54 N/mm^2 achieved with the addition of 1% polyethylene glycol (PEG-600). The flexural strengths are increased by 7.2% when compared to conventional concretes.

3.3. Split Tensile Test

Self-curing PEG-600 with 0.0, 0.5, 1.0, and 1.5 percentages of cement were tested, and the results have been incorporated in Figure 6.

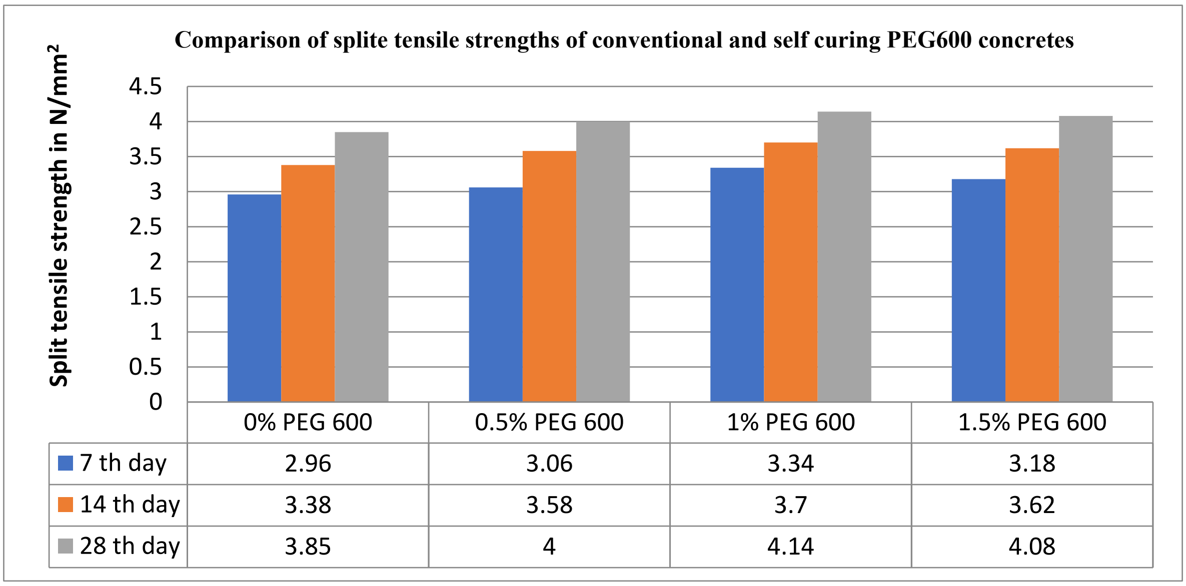


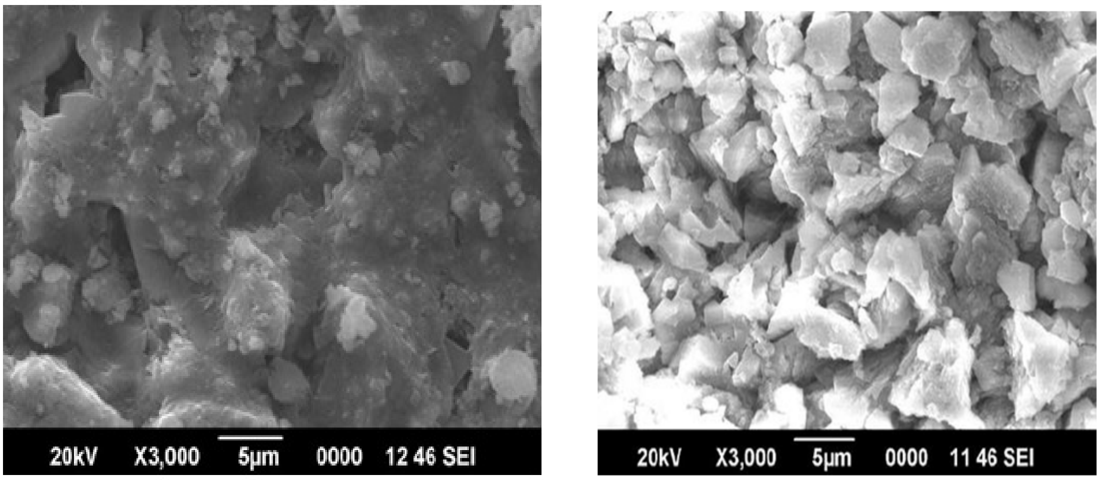
Figure 6. Comparison of split tensile strengths of Conventional and PEG-600 concretes.

For conventional and self-curing polyethylene glycol (PEG-600) concretes, the split tensile strength values recorded on 7th, 14th, and 28th days, respectively, are given in Figure 6. It can be observed that the split tensile strength of 1% polyethylene glycol (PEG-600) is more than that of other percentages. That is, the maximum strength is achieved with the addition of 1% polyethylene glycol (PEG-600), and this gained a split tensile strength of 4.14 N/mm^2. It can be observed that split tensile strength also increases by 7.5% in self-curing concrete. The PEG-600 of self-curing concrete yields significant compressive, flexural, and split tensile strengths. The PEG-600 of the self-curing process does not require the continuous availability of water in concrete. Additionally, the PEG-600 increases the cement hydration and it creates a good bond in low voids and pores.

3.3.1. Scanning Electron Microscopy (SEM) Test

The hydration process of concrete results in the development of empty pores and a decrease in the relative humidity of the concrete. This is caused by chemical shrinkage. This results in the concrete mixture drying up on its own and a lack of available moisture. Additionally, it causes the formation of porous structures and microscopic cracks, which are the weak points in the concrete. So, self-curing is used to keep the temperature and humidity stable and stop self-desiccation.

The microstructures of both conventional and self-curing polyethylene glycol (PEG-600) concretes are determined by SEM analysis. The results of SEM analysis conducted on conventional concrete and water-soluble polymer as self-curing concrete are shown in Figure 7a,b, respectively.



(**a**) (**b**)

Figure 7. (**a**) Conventional concrete, (**b**) self-curing concrete.

The microstructure of water-soluble polymer as self-curing concrete exhibits a denser microstructure with a smaller width of micro cracks and reduced crystalline hydration products when compared with conventional concrete. Thus, the water-soluble polymer PEG-600 has increased the cement hydration as expected.

The microstructure of conventional concrete indicates that the pore sizes are larger when compared to self-curing concrete, which may be due to fewer hydrogen bonds, as shown in Figure 7a. The microstructure of self-curing concrete indicates that the pore sizes are significantly smaller than conventional concrete, which may be due to the presence of hydrogen bonds as shown in Figure 7b. Thus, it can be concluded that the microstructure of self-curing concrete has fewer pore sizes, increasing durability and reducing cracks on concretes. Additionally, interfacial adhesion zones significantly improved.

3.3.2. Analysis of Cost–Benefits

The curing process is mandatory for conventional concrete. Normal curing processes need extra cost and time for carrying the water through vehicles and labor for road and bridge projects. However, self-curing concrete does not need any extra cost for the curing process.

The estimation and cost–benefit analysis for curing the conventional and self-curing polyethylene glycol (PEG-600) concrete is shown in Table 8. The comparison of cost–benefit analysis for both conventional and self-curing concretes is presented in Table 8. The costs are given in Ethiopian Birr (ETB) for 1 m^3 of concrete.

Table 8. Estimation for curing process of conventional and self-curing polyethylene glycol (PEG- 600) concrete.

Type of Concrete	Water Required for Curing Process of 1 m^3 Concrete	Cost of Water Per Liter (ETB)	Labor Cost for Conventional Curing Process of 1 m^3 (Number of Laborers × Labor Cost Per Day) (C = Labor Cost) or Self-Curing Polyethylene Glycol (PEG-600) Concrete-(Number of Liters × Cost) (C = Cost of PEG-600/L)	The Total Cost Required for 1 m^3 of Concrete (ETB)
	(A = Liters of water)	(B = Cost of water/liter)	(C = Labor cost)	X = (A × B) + (C)
Conventional concrete	3000	0.60	5 × 350	1800 + 1750 = 2850
Self-curing Polyethylene Glycol (PEG 600) concrete	180	0.60	3.20 × 500	108 + 1600 = 1708
The Cost saved by using self-curing PEG 600 for 1 m^3 of concrete (ETB) = **1142**				

4. Conclusions

In this study, the strength evaluations of an environmentally sustainable water-soluble polymer as a self-curing compound for cement concrete pavements have been conducted. Polyethylene glycol (PEG-600) is one of the best alternative techniques for the self-curing process and is a very useful technique for African countries such as Ethiopia due to water scarcity. Based on the previous research, studies, and observations, it was found that PEG 400 was more frequently utilized than PEG-600. Workability and compaction factor are increased in self-curing concrete compared to conventional concrete.

In this present study, the usage of self-curing concrete in PEG-600 has been tested as a successful one. It has been shown that self-curing concretes significantly improve compressive, flexural, and tensile strengths. The optimum dosage of polyethylene glycol (PEG 600) is found to be 1% in M40 grade of concrete. As a result, the compressive strength is increased by 10.73% in self-curing concrete. The flexural strengths are increased by 7.2% when compared to conventional concretes. Further, we compared the split tensile strengths of conventional and PEG-600 concretes. It can be observed that split tensile strength also increases by 7.5% in self-curing concrete. Hence, polyethylene glycol (PEG-600) can be considered a very suitable self-curing agent, as it is resolvable 100% in concrete.

In the scanning electron microscopy (SEM) test, the microstructure of self-curing concrete indicates that the pore sizes are significantly smaller than that of conventional concrete, which may be because of the presence of hydrogen bonds. Polyethylene glycol (PEG-600) has higher molecular weight than potable water. Thus, it can be concluded that the microstructure of self-curing concrete has fewer pore sizes, increasing durability and reducing cracks on concretes. Additionally, interfacial adhesion zones significantly improved.

It is shown that the self-curing technique has reduced the costs of the curing process by about 1142 ETB per 1 m^3 of concrete. Thus, this study recommends that polyethylene glycol (PEG-600) be used for internal curing concrete to construct road and bridge projects. Self-curing concrete is preferable for the mountain regions, hilly areas, remote locations, railway projects, and also for areas where water is scarce in Ethiopia.

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