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IMPROVING MECHANICAL PROPERTIES OF RECYCLED AGGREGATE PERVIOUS CONCRETE USING TAGUCHI METHOD

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Abstract

The construction demolition is non-degradable. Recycled aggregates were utilized to create sustainable products in pervious concrete manufacture. Adding fibers enhances pervious concrete mechanical properties. High absorption of Recycled aggregate (RA) and polyethylene-glycol are used to ensure internal curing. The purpose of this study was to statistically improve the mechanical properties of pervious concrete based on an experimental investigation. Taguchi method was employed to present DOE (Design of Experiment). Five factors in four levels designed by Taguchi provide sixteen mixes (L16 array). The factors were the replacement of coarse aggregates by recycled aggregates, W/C ratio, synthetic macro-fiber, steel fiber and polyethylene-glycol. Designed mixes were prepared. Taguchi's analysis concluded; that macro-fiber addition has no impact on mechanical properties. Using a ratio of 10% recycled aggregates replacement was the optimum ratio. Taguchi prediction of optimum mixes was experimented with using mixes. Confirmation test results agree with the predicted values within ±10%.

Keywords:

Total Quality;
Pervious concrete;
Self-curing;
Recycling;
Fibers;
Taguchi Method;
ANOVA.

1.1. Introduction

Floodwaters are inundating major cities around the world at an alarming rate. Fueled by climate change, increased rainfall, and reduced permeable surfaces, storms are overwhelming drainage systems and crippling transportation [1]. Pervious concrete is defined as a concrete with little or no fine aggregate. It is a high void content concrete ranging from 13% to 42%. This makes it porous, allowing water to drain through it and replenish groundwater supplies. Manufacturing pervious concrete as road pavement became a tool to store rainwater in underground reservoirs on roadsides [2]. Pervious concrete or porous concrete gives flow water paths through the matrix. Gap grading of coarse aggregates is used to manufacture this concrete. Also, eliminating or reducing the fine aggregates creates a network of interconnected pores [3].

Pervious concrete offers a revolutionary approach to stormwater management. Unlike traditional concrete, which is impermeable, pervious concrete allows rainwater to infiltrate into the ground, mitigating flooding and replenishing groundwater resources. Although high porosity is crucial for pervious concrete's functionality, it can compromise its pore structure and mechanical properties. This trade-off highlights the need for ongoing research to optimize the design and performance of pervious concrete pavements [4][5].

Fibers are the pivotal ingredient to stronger cement-based and resin-based composite materials. They delay and hinder cracks, enhancing the matrix's strength and durability. They present interconnection bridging, which transfers stress. Steel fibers prevents complete crushing, especially with high steel fiber content. They becomes predominant after failure, as they binder cracks. High fiber content decreases ultimate strains values [6]. Steel fibers inhibit autogenously shrinkage and reduce shrinkage cracks during the conservation process. They also take on developed stress, preventing mechanical cracks from forming and growing, which increases the compressive strength [7]. After the initial crack developed, fibers increased the toughness and residual strength of the concrete. The ultimate compressive strength also increased, due to crack growth arresting, which depends on bond strength. [8]. Fibrous concrete reduces crack width, which improve the overall performance [9].

After concrete casting, moisture content is an essential need in the curing process, which supplements cement hydration till desired hardened concrete properties. Water scarcity obstacle conventional curing method [3]. Self-curing provides internal moisture distributed throughout the concrete volume ensuring continuity of cement hydration. Polyethylene-glycol polymer was used recently in concrete self-curing, which depends on solvent pressure according to Raoult's Law[10]. PEG enhanced hydration process[11].Hydrophilic molecules motivate hydrogen bonds in polymeric chains. Hydrogen positive charge attracts soluble polymers, which minimize concrete desiccation[11]. Studies have shown that concrete cured with PEG can achieve up to 30% higher compressive strength and 15% higher flexural strength than conventionally cured concrete. Furthermore, PEG-cured concrete has increased resistance to cracking and freeze-thaw degradation[10].

Construction waste, including demolished materials, is non-degradable and contributes significantly to landfill waste. In the European Union, over 900 million tons of construction waste are generated annually, accounting for a substantial portion of total waste. Recycling old concrete as aggregate in new concrete can significantly reduce landfill waste and conserve natural resources. By reusing demolition waste in construction projects, we can extend the lifespan of natural materials and minimize the environmental impact of the construction industry [12].

Due to the vast number of variables and percentages of variation, numerous experimental mixtures can be created to optimize the ideal composition. Design of Experiments (DOE) determines the pivotal experiments in the suggested array. Genichi Taguchi employed (DOE) in manufacturing. Taguchi's approach and DOE (design of experiments) are tools that democratizes quality engineering. It is used to develop robust products and processes that are insensitive to variation [13].

2. Research Significance

Pervious concrete may be suffering from low mechanical properties which need to be improved. This research aims to study the feasibility of enhancing recycled aggregate pervious concrete main mechanical properties through the study of the effect of using recycled aggregate, PEG 400, and fibers to improve its properties based on the Taguchi method to choose the main effective parameters based on previous research. Taguchi's approach curtails numerous experimental mixtures to optimize sustainable pervious concrete properties. This research provides researchers and engineers interested in using pervious concrete with recommendations for using improved pervious self-curing concrete cast using recycled aggregates.

3. Materials and Methods

3.1 Materials

Cement Ordinary Portland cement (CEMI 42.5N) locally produced is and manufactured by Elsewedy Cement according to the E.S.S. 4756-1/2013 requirement. Constant content (338 kg/m3) was used for all mixes.

Coarse Aggregate Natural and recycled aggregate were utilized. Aggregate complies with the requirement of the RC Egyptian code of practice (203-2020) with a max nominal size of 10 mm .Constant content (1530 kg/m3) was used for all mixes.

A-Crushed Dolomite Natural crashed dolomite from the Suez zone was used as a coarse aggregate. The particles have rough surface texture with irregular shapes.

B-Crushed Recycled Concrete: Crushed concrete from buildings demolition was used as irregular rough surface coarse aggregate Fig. (1). Replacement of coarse aggregates by Recycle aggregates (0 %, 10%, 30% and 50%).

Fig. (1) Natural crushed dolomite - Crushed concrete (10 mm)

Fine Aggregate specific gravity was 2.64 of local siliceous sand. Constant content (10% by weight of limestone) for all mixes.

The Water W/C ratio was variable from 0.30 to 0.36 for fresh tap water.

Fiber Additives.

Steel fiber was (Harx steel fibers) Fig. (2) Of 0.7850 kg/m3 density and a length of 5 mm, 1 mm equivalent diameter and made by Chemical for modern Building Company, Egypt. Addition of steel fiber in proportions (0%, 0.05%, 0.1% and 0.15%).

Synthetic macro – fibers (Sika fiber T-48 SL) Type Color 100% polyolefin, Length of fiber 48 mm, Diameter 0.9 mm, Compact density 0,91 kg/dm³. Macro-fiber was obtained from sika chemical company, Egypt Fig. (2). Addition of Synthetic macro-fiber in proportions (added by 0, 2.5, 5 and 7.5 kg).

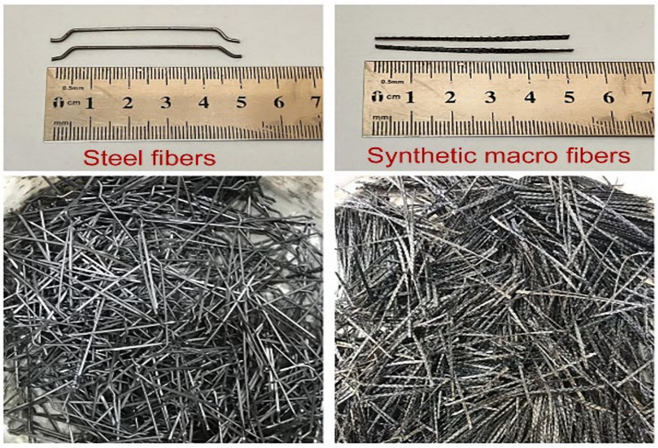

Fig. (2). Steel fibers and Synthetic macro – fibers

Reinforcing Steel Bars: The steel used in this experimental work is mild steel (ST.37) of 8mm diameter. Yield Stress 2400 (Kg/cm2), Tensile Strength 3600 (Kg/cm2), and Elongation equal to (20%), mechanical properties of reinforcing steel bars according to ECP 203-2020.

Polyethylene Glycol (PEG 400) is a versatile polymer with a wide range of applications, from pharmaceuticals to cosmetics. It is characterized by its water-soluble nature, which is indicated by its numeric suffix. The average molecular weight of PEG-400 is 400 g/mol and is highly soluble in water. PEG 400 was obtained from Global Chemical Company, Egypt, it was used as a ratio of cement (1.8, 2.0, 2.2, and 2.4%).

Super plasticizer: water reducer (Sikament – 163M) was used, which complies with ASTM-C- 494 Types G and F requirements for superplasticizers. It was used as a ratio of cement (2.0%).

4. Design Methodology

Taguchi method, as a tool for optimization, was employed to improve the mechanical properties of pervious concrete. It reduces uncontrollable factors (S/N) the Sensitivity to Noise that affects the quality characteristic. Table (1) shows the four levels of the five control factors that were selected for this study[14][15][13]. Experimental factors were chosen based on the Taguchi Method.

Table (1). Experimental Factors (Taguchi Method) .

Level	Factors				
	A	B	C	D	E
	Recycled aggregate Replacement.	W/C	Addition of Synthetic macro-fiber /cement	Polyethylene glycol 400 / cement	Steel Fiber Addition
1	0 %	0.30	0 Kg	1.8 %	0 %
2	10 %	0.32	2.5 Kg	2.0 %	0.05 %
3	30 %	0.34	5 Kg	2.2 %	0.1 %
4	50 %	0.36	7.5 Kg	2.4 %	0.15 %

4.1 Design of Experiment

Orthogonal array design (OAD) is a powerful tool for conducting experiments efficiently and effectively. OADs use a fractional design, which means that only a subset of all possible combinations of factors and levels are tested. This can significantly reduce the number of experiments needed, while still providing enough information to estimate the main effects of the factors. Array L16 with 16 rows and 5 columns was presented in Table (1). Each row represents an experimental trial condition. Each column indicates used factors levels of (A, B, C, and D).

4.2 Taguchi's Orthogonal Array

Taguchi's experimental design method aims to develop products that consistently achieve their target value, minimizing variation and maximizing quality. Table (1) shows the experimental factors and levels used. Mixes are given in Table (2).

Table (2): Experimental Design of Experiment and Detailed Factor Levels.

Exp. No.	Factors				
	Recycled aggregate Replacement	w/c	Addition of Steel Fiber	Addition of Synthetic macro-fiber	Polyethylene glycol 400Addition / cement
1	0%	30%	0%	0kg	1.8%
2	0%	32%	.5%	2.5kg	2%
3	0%	34%	1%	5kg	2.2%
4	0%	36%	1.5%	7.5kg	2.4%
5	10%	34%	.5%	0kg	2.4%
6	10%	36%	0%	2.5kg	2.2%
7	10%	30%	1.5%	5kg	2%
8	10%	32%	1%	7.5kg	1.8%
9	30%	36%	1%	0kg	2%
10	30%	34%	1.5%	2.5kg	1.8%
11	30%	32%	0%	5kg	2.4%
12	30%	30%	.5%	7.5kg	2.2%
13	50%	32%	1.5%	0kg	2.2%
14	50%	30%	1%	2.5kg	2.4%
15	50%	36%	.5%	5kg	1.8%
16	50%	34%	0%	7.5kg	2%

5. Concrete Mixes

Table (3) shows the mix proportions of all mixes.

Table (3). Concrete mix proportions for concrete mixes used [Kg/m^3]

Exp. No.	Factors								
	Coarse aggregates [kg]	Recycle aggregates [kg]	Fine aggregates [kg]	Cement [kg]	w/c	Steel fiber by volume of concrete [Kg/m3]	Addition of Synthetic macro-fiber [kg]	Polyethylene glycol 400 Addition [% wt. of cement]	Super plasticizer [% wt. of cement]
1	1530	0	153	338	30%	0	0	1.8%	2%
2	1530	0	153	338	32%	11.5	2.5	2%	2%
3	1530	0	153	338	34%	23	5	2.2%	2%
4	1530	0	153	338	36%	34.5	7.5	2.4%	2%
5	1377	153	153	338	34%	11.5	0	2.4%	2%
6	1377	153	153	338	36%	0	2.5	2.2%	2%
7	1377	153	153	338	30%	34.5	5	2%	2%
8	1377	153	153	338	32%	23	7.5	1.8%	2%
9	1071	459	153	338	36%	23	0	2%	2%
10	1071	459	153	338	34%	34.5	2.5	1.8%	2%
11	1071	459	153	338	32%	0	5	2.4%	2%
12	1071	459	153	338	30%	11.5	7.5	2.2%	2%
13	765	765	153	338	32%	34.5	0	2.2%	2%
14	765	765	153	338	30%	23	2.5	2.4%	2%
15	765	765	153	338	36%	11.5	5	1.8%	2%
16	765	765	153	338	34%	0	7.5	2%	2%

Mixing Procedure

There was dry mixing for 2 min. Then, 75% of (water + Super plasticizer + PEG400) was added and mixed for 2 min. Finally, mixing took 4min after adding remained amount of (Water + Super plasticizer + PEG400 + Fibers). Concrete samples were cast. Specimens were taken of molds after 24h.

6. Tests

All considered tests were performed on hardened concrete as follows:

1) Compressive Strength tests: Three concrete cubes were prepared with dimensions of 10x10x10 cm. Compressive strength tests were then conducted on these samples according to ISO 4012 and BS 1881: Part 115 standards. A 2000 KN hydraulic machine was used to apply a compressive load until failure. The maximum load recorded was used to calculate the compressive strength of the concrete as shown in Fig. (3).

2) Splitting tensile strength: Three concrete cylinders were prepared with dimensions of 10 cm diameter and 20 cm length. Splitting tensile strength tests were then conducted on these samples following BS 1881: Part 117 standards. A compressive load was applied along the length of the cylinder until failure. The maximum load recorded was used to calculate the splitting tensile strength as shown in Fig. (4).

3) Flexural strength tests: Three concrete prisms were prepared with dimensions of 50x10x10 cm. Flexural strength tests were then conducted on these samples following ISO 4013 guidelines. A 10-ton flexural testing machine was used to apply a load until the specimen failed. The maximum load recorded was used to calculate the flexural strength as shown in Fig. (5).

4) Bond strength tests: were carried out on 15*15*15cm cubes with a vertical embedded rounded high tensile steel bar of 12 mm diameter and 160mm height on a hydraulic compression test machine of 2000KN capacity as shown in Fig. (6). for the implanted bars in the concrete sample, a direct push-down test was performed. The bonding strength between concrete and rebar is calculated according to BS 8105: Part 113.

5) Slab flexure test: A three-point load system was applied to a one-way slab using a 100 KN flexural testing machine. Deflection measurements were taken at the midpoint of the slab's bottom surface using a dial gauge. The collected deflection data will be used to calculate the flexural strength of the slab. This involves plotting a load-deflection curve and determining the maximum load before failure. Details and reinforcement of slab dimensions 100mm*500mm*4mm illustrated in Fig. (7).

Fig. (3). Compressive strength test

Fig. (4). Indirect tensile strength test


Fig. (5). Flexure strength for prism

Fig. (6). Bond strength test

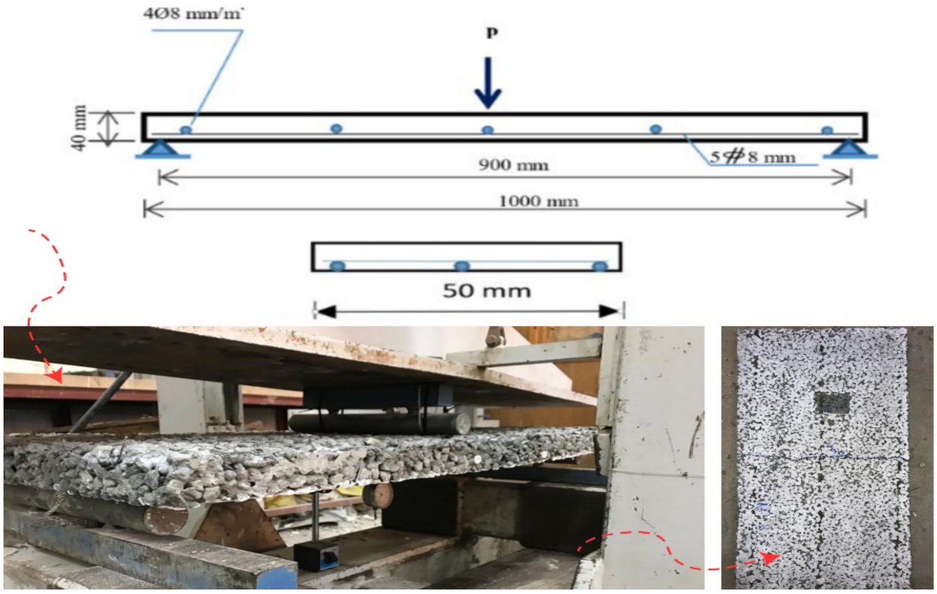

Fig. (7). Flexure strength and the loading frame of slab samples.

Details and reinforcement of tested slab samples.

7. Test Results

7.1 Main Mechanical Properties

The mechanical parameters that were examined and the behavior of the slab are assessed in terms of deflection values, ultimate loads, and initial cracking loads.

Compressive strength test results (7, 28 days), Splitting tensile (28 days), Flexural strength, and Bond strength at 28 days are shown in Table (4). For 16 mixes (array of Taguchi).

Table (4). Mechanical Properties of Hardened Concrete.

Mix. No.	Compressive strength [MPa]		Splitting tensile strength [MPa]	Flexural [MPa]	Bond strength [N]
	7 days	28 days	28 days	28 days	28 days
1	10.1	12.0	2.1	3.5	9.3
2	12.4	16.2	2.3	3.2	10.7
3	10.6	12.9	2.0	2.9	21.0
4	9.8	11.5	1.6	2.2	28.3
5	13.2	17.8	2.4	3.3	21.3
6	12.1	13.7	1.9	3.6	34.0
7	10.1	12.4	2.0	3.0	18.3
8	9.7	12.5	1.8	3.7	22.3
9	15.4	19.6	2.5	4.8	44.0
10	5.8	8.0	1.7	1.9	23.3
11	7.4	10.0	1.8	2.1	22.0
12	9.4	10.9	1.6	3.2	20.3
13	6.3	8.0	1.1	2.9	20.3
14	5.9	7.9	1.5	2.5	20.7
15	8.0	9.9	1.2	2.8	12.3
16	9.5	11.2	1.3	3.0	13.7

7.2 Slab Behavior

Table (5) presents the experimental results for 16 slabs, including first crack load, ultimate load, and displacements/deflection at first and ultimate load, ductility ratio, and energy absorption. The area under the load-deflection curve is used to calculate energy absorption, and the ratio of vertical displacements at ultimate load to vertical displacements at first crack load is known as the ductility ratio. Fig. (8-a) shows the load-displacement curve at measured points. Fig. (8-b) shows cracking patterns of tested slabs.

Fig. (8), in conjunction with Table (5), provides a comprehensive analysis of the structural behavior of the 16 tested slabs. Table (5) presents the quantitative data on key performance indicators, including first crack load, ultimate load, displacements at these critical points, ductility ratio, and energy absorption capacity. These numerical values offer a precise understanding of each slab's response to applied loads. Fig. (8-a) visually complements the tabular data by illustrating the load-displacement curves for each slab. These curves provide a graphical representation of the load-deformation relationship, allowing for a detailed observation of the different stages of the loading process, from initial loading to cracking and ultimate failure. Furthermore, Figure (8-b) offers qualitative insights into the failure modes and crack patterns exhibited by the slabs. By correlating the visual observations from Fig. (8-b) with the quantitative data in Table (5).

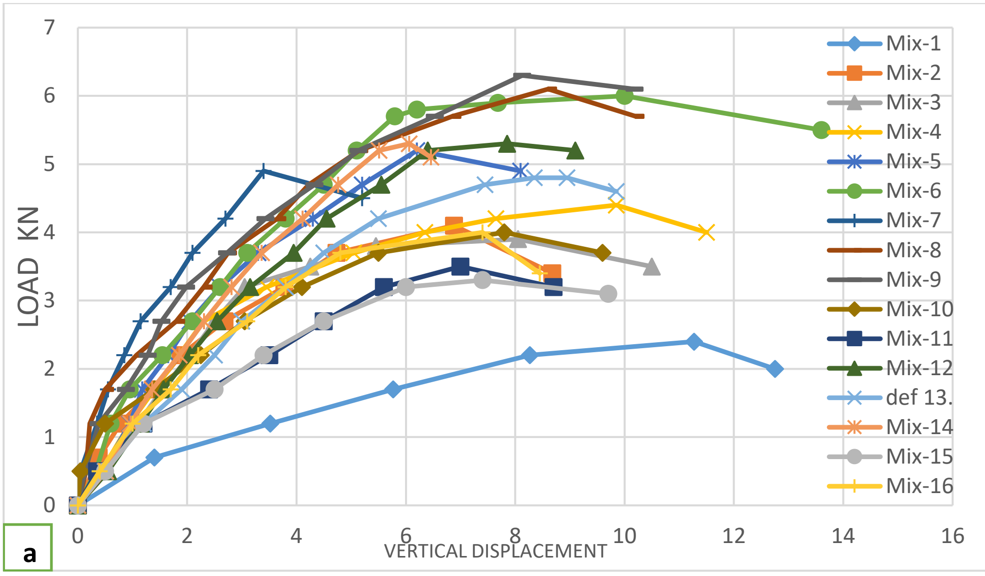

Fig (8). A- Experimental Load-Vertical Displacement Curve. B- Cracking Patterns

Table (5). Test Results for Slabs

Samples ID	First crack load, [KN]	Ultimate load, [KN]	Displacement at first crack load, [0.01 mm]	Displacement at ultimate load, [0.01 mm]	Ductility index	Energy absorption [kN.mm]
1	1.2	2.40	3.52	11.27	3.20	17.553
2	2.7	4.1	2.68	6.88	2.56	19.21
3	3.2	3.9	3.05	8.05	2.63	23.43
4	3.2	4.4	3.45	9.85	2.85	31.88
5	2.7	5.2	2.05	6.2	3.02	19.71
6	2.7	6.0	2.1	10	4.76	43.428
7	3.2	5.8	1.65	5.9	3.575	10.437
8	3.7	6.1	2.75	8.6	3.12	37.076
9	3.7	6.3	2.73	8.13	2.97	34.367
10	2.7	4.0	3.05	7.8	2.55	22.024
11	2.2	3.5	3.5	7	2	15.531

12	2.7	5.0	4.05	11.25	2.77	26.577
13	3.2	5.3	2.5	6.1	2.44	28.691
14	3.2	5.3	2.81	6.06	2.15	18.998
15	2.2	3.3	3.4	7.4	2.17	15.848
16	2.7	4.0	3.1	7.4	2.38	20.336

8. Analysis by Taguchi

Taguchi method optimized the mix proportion levels of concrete. The results, shown in Table (4), indicate that the best possible mix parameter combinations can be determined from the main effect plots in Figs (9-12). The S/N ratio is a measure of the signal (mean) to the noise (standard deviation). For strength characteristics, the "larger the better" objective function is used as in formula:

$$\left(\frac{S}{N}\right)_i = -10\log\left[\frac{1}{n}\sum_{j=1}^{n}\frac{1}{Y_{ij}^2}\right] \quad (1)$$

where number of a trial ‘i’; measured value ‘Y_{ij}’ for trial i^{th} and experiment j^{th}. Number of repetitions is ‘n’ experimental combination.

Equation 1 was used to calculate signal-to-noise (S/N) ratios for each experimental condition in order to compare the effects of various process factors on compressive, splitting tensile, flexural, and bond strength.

9. Discussion of Test Results

9.1. Mechanical Properties

9.1.1. Compressive Strength:

The results of the response of Signal-to Noise Ratios showed that the recycled aggregate and PEG400 have the most effect on compressive strength as shown in Table (6). Results also indicated that 10%, followed by 0%, is the best ratio for recycled aggregates replacement. It was not efficient to use macro-fiber. Additionally, adding steel fiber works best when mixed at a ratio of 0.5% or 1%. Also, a water-to-cement W/C ratio of 0.36 is the ideal ratio. The optimum level to add PEG400 was 2% as shown in Fig. (9-a). ANOVA (Analysis of Variance) can reveal the percentage contribution of individual parameters to strength. Table (6) shows the results of ANOVA. By examining the contribution percentage of each factor, one gains insights into their relative significance.

As a summary, it was observed that the two elements that have the largest compressive strength are recycled aggregate content and PEG 400 by 30.50 and 24.18% contribution, respectively as shown in Fig. (9-b). The concrete compressive strength depends mainly on the curing method, and porous concrete is difficult to use traditional curing methods. Factors Recycled aggregate content and PEG 400 act as internal reservoirs for water that supply the non-hydrogenated cement granules with water when needed to complete the hydration process, which helps in increasing concrete compressive strength [16].

Table 6: A -Response of Signal to Noise Ratios for Compressive Strength of 7, 28 Days (Larger Is Better)
b- Analysis of Variance for 28 Days Compressive Strength, Using Adjusted SS for Tests

Level	Recycled aggregate	Macro-fiber	Steel fiber	w/c	PEG 400
(a) Response of Signal to Noise Ratios for Compressive Strength at 7and 28 days (larger is better)					
1	22.29	22.62	21.32	20.51	20.34
2	22.86	20.71	22.44	21.05	23.20
3	21.16	21.00	21.99	21.54	20.94
4	19.21	21.20	19.78	22.42	21.04
Delta	3.65	1.91	2.66	1.90	2.86

Rank	1	4	3	5	2
(b) Analysis of variance "ANOVA" for compressive strength at 28 days, using Adjusted SS for Tests					
DF	3	3	3	3	3
Seq SS	52.54	26.05	33.89	18.11	41.65
Contribution	30.50%	15.12%	19.68%	10.52%	24.18%

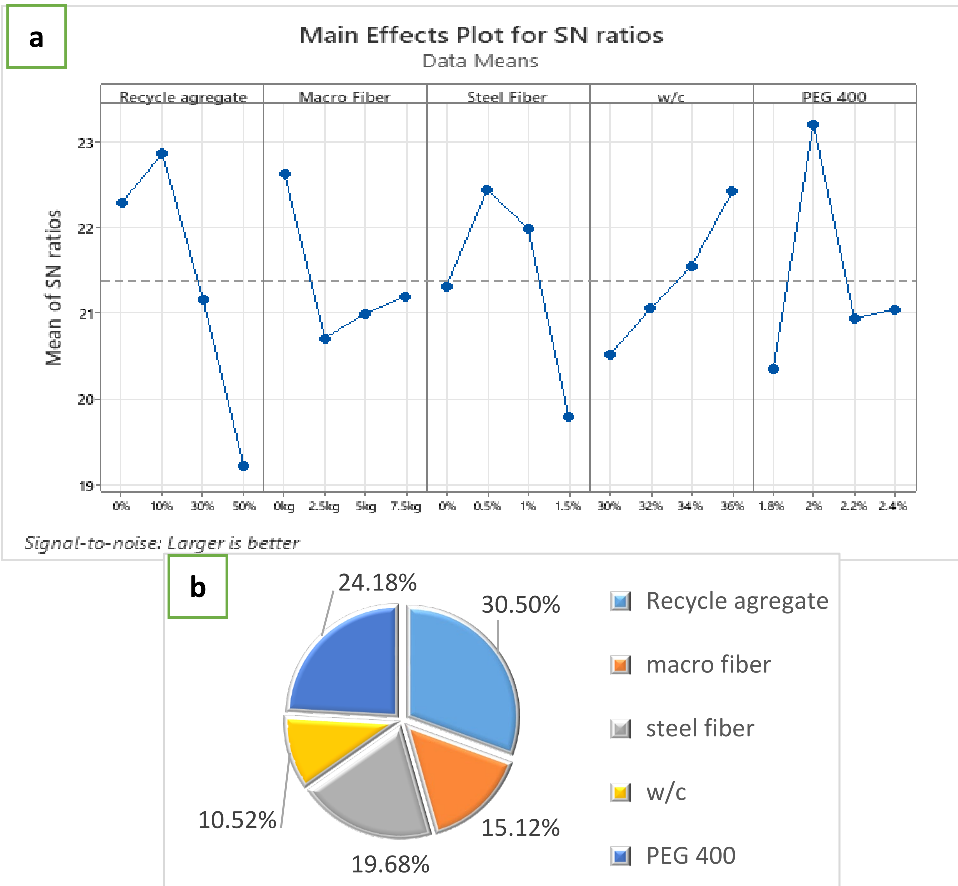

Fig. (9). (a) Main Effect Plot for Signal to Noise Ratio of Compressive Strength after7, 28 days (Larger is Better). (b) The contribution percentage of factors for compressive strength.

9.1.2. Splitting Tensile Strength:

The results of the response of signal-to-noise ratios showed that the recycled aggregate and Macro-fiber have the most effects on Tensile strength as shown in Table (7). Results also indicated that 10%, followed by 0%, is the ideal replacement rate for recycled aggregates. It was not efficient to use macro-fiber. Additionally, adding steel fiber works best when mixed at a ratio of 1%. Also the water-to-cement ratio of 0.34 the optimum one. The optimum level to add PEG400 was 2% as shown in Fig. (10). Referring to ANOVA Table (7), recycled aggregate content and macro-fiber have contribution of (58.73%) and (17.66%) respectively. They are the most influencing factors in splitting tensile strength.

Table (7). Response of signal-to-Noise ratios for Splitting Tensile Strength at 28 Days (Larger Is Better)

Level	Recycled aggregate	Macro-fiber	Steel fiber	w/c	PEG 400
(a) Response of signal-to-noise ratios for tensile strength at 28 days (larger is better)					
1	5.906	5.716	4.745	5.021	4.440
2	6.081	5.253	4.956	4.578	5.769

3	5.332	4.592	5.742	5.020	4.117
4	2.057	3.814	3.932	4.756	5.049
Delta	4.024	1.902	1.810	0.443	1.652
Rank	1	2	3	5	4
(b) Analysis of variance for tensile strength at 28 days, using adjusted SS for tests					
DF	3	3	3	3	3
Seq SS	1.46351	0.44004	0.27418	0.01400	0.30016
Contribution	58.73%	17.66%	11.00%	0.56%	12.05%

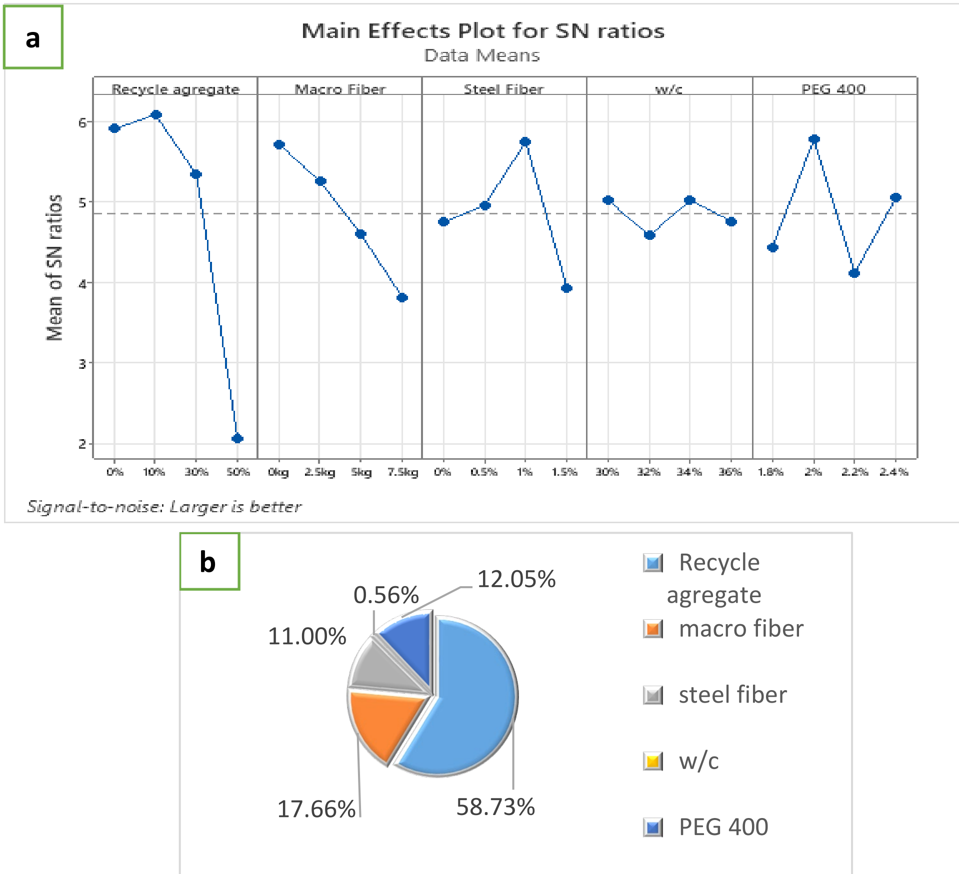

Fig 10: (a) Main Effect Plot for Signal to Noise Ratio of tensile Strength after 28 days (Larger is Better). (b) The contribution percentage of factors

9.1.3. Flexural Strength:

The results of the response of signal-to-noise ratios showed that the PEG400 and steel fiber has the most effect on Flexural strength as shown in Table (8). Results also indicated that 10%, followed by 0%, is the ideal replacement rate for recycled aggregates. It was not efficient to use Macro-fiber. Additionally, adding steel fiber works best when mixed at a ratio of 1%. Also, a water-to-cement ratio of 0.36 is ideal. The optimum level to add PEG400 was 2% as shown in Fig. (11). Referring to ANOVA in as shown in Table (8), macro fiber, PEG 400 and steel fiber have contribution of (28.40%), (26.64%) and (24.08%) respectively. They are the most influencing factors on flexural strength as shown in Fig. (11). the internal curing has a significant effect on flexural strength, by adding fiber. they strengthen the inter-linkages of the microstructure of the pervious concrete [17].

Table (8). A-Response of Signal to Noise Ratios for Flexural Strength of 28 days (larger is better). B-Analysis of Variance for 28 days Flexural Strength, using Adjusted SS for Tests.

Level	Recycled aggregate	Macro-fiber	Steel fiber	w/c	PEG 400
(a) Response of signal-to-noise ratios for flexural strength at 28 days (larger is better)					
1	9.280	11.067	9.437	9.640	9.140
2	10.636	8.722	9.937	9.255	10.724
3	8.903	8.459	10.475	8.637	9.942
4	8.864	9.435	7.834	10.150	7.878
Delta	1.773	2.609	2.641	1.512	2.846
Rank	4	3	2	5	1
(b) Analysis of variance for flexural strength at 28 days, using adjusted SS for tests					
DF	3	3	3	3	3
Seq SS	0.8616	2.1692	1.8392	0.7334	2.0353
Contribution	11.28%	28.40%	24.08%	9.60%	26.64%

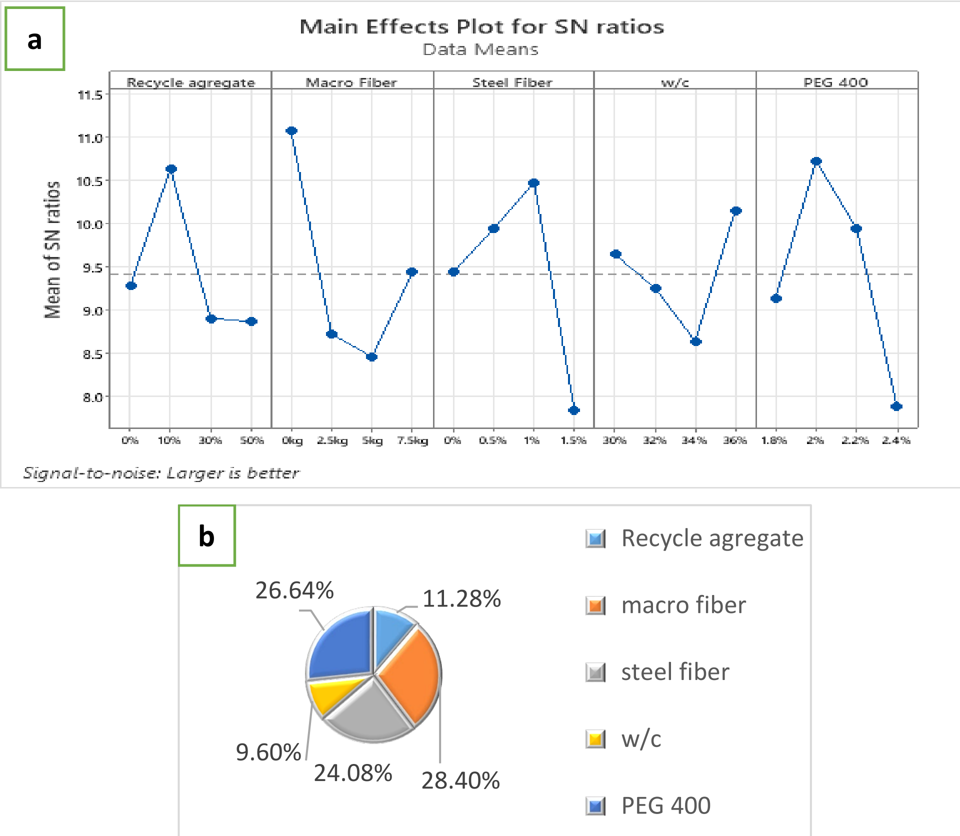

Fig (11): (a) Main Effect Plot for Signal to Noise Ratio of Flexural Strength after 28 days (Larger is Better). **(b)** The contribution percentage of factors

9.1.4. Bond strength:

The results of the response of signal-to-noise ratios showed that the recycled aggregate and steel fiber have a largesse effect on Bond strength as shown in Table (9). Results also indicated that 30%, followed by 10%, is the ideal replacement rate for recycled aggregates. Adding steel fiber works best when mixed at a ratio of 1%. Also the water-to-cement ratio of 0.36 is the ideal. The optimum level to add PEG400 was 2.2% as shown in Fig. (12). Referring to ANOVA in Table (9). Water-cement ratio and Recycle aggregate have contribution of 33.49% and 28.43% as shown Fig. (12).

Table [9]. Response of Signal to Noise Ratios for Bond Strength of 28 Days (Larger Is Better)

Level	Recycled aggregate	Macro-fiber	Steel fiber	w/c	PEG 400
(a) Response of signal-to-noise ratios for bond strength at 28 days (larger is better)					
1	23.86	26.25	24.90	24.28	23.89
2	27.36	26.21	23.78	25.14	25.35
3	28.31	25.09	28.15	25.77	27.35
4	24.25	26.23	26.96	28.59	27.20
Delta	4.45	1.16	4.37	4.31	3.46
Rank	1	5	2	3	4
(b) Analysis of variance for bond strength at 28 days, using adjusted SS for tests					
DF	3	3	3	3	3
Seq SS	323.41	60.25	251.85	380.92	121.14
Contribution	28.43%	5.30%	22.14%	33.49%	10.65%

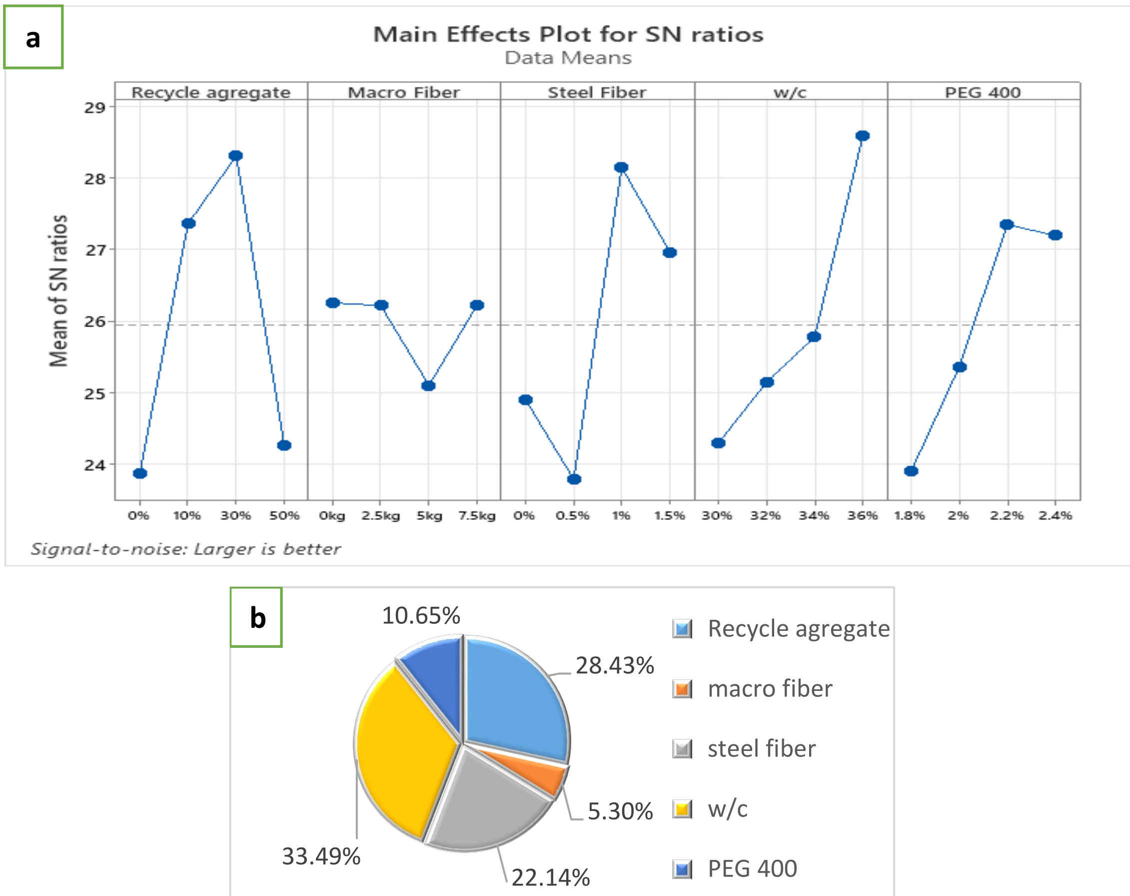

Fig (12): (a) Main Effect Plot for Signal to Noise Ratio of Bond Strength after 28 days (Larger is Better). (b)The contribution percentage of factors

9.2. Slab Analysis:

From the experimental results indicated in Table (5) and Fig. (8), specimen slabs (6, 8,and 9) have the highest ultimate loads of (6.0,6.10, and 6.30) KN, Energy absorption (43.428, 37.076, and 34.367) KN /mm and Ductility index (4.76,3.12 , and 2.97), While the results of the samples showed (1, 2, and 15) Weak values of the ultimate load (2.40,4.10, and 3.30) KN, Energy absorption (17.553, 19.21, 15.848) KN/mm and Ductility index, , (3.20,2.56 , and 2.17) respectively.

9.3. Evaluation of Factor Effects.

9.3.1. Effect of Recycle Aggregates.

Generally, The use of recycled aggregates affects investigated concrete properties, which diminishes as the replacement ratios rise [18]. However, when using recycled aggregates as internal reservoirs to make concrete, replacing 10% of the recycled aggregates mechanical properties improved it slightly. As Increasing the replacement rates to 30% and 50%, the compressive and tensile strengths decreased Figs. (9-12) following Zaetang et al., 2017 [19]. It can be concluded that recycled aggregates such as (crushed concrete) can store a high amount of water. So, each grain of RA may be considered as an internal water supplier in the concrete[16]. Mechanical properties reduction was observed with recycled aggregate content increase [20].

9.3.2. Effect of Using Steel Fiber.

1% steel fiber content increases mechanical properties significantly, while 1.5% addition resulted in a decrease in mechanical properties which satisfied previous research [21] and [22]. The ability of fibers add cohesion between the components of the mixture, which aids decreasing cracks and give additional resistance to concrete under loading. The fibers act as bridges in the crack region, which provides additional resistance and decreases crack propagation [6][7]. Fibers are the ingredient that gives concrete strength. After the concrete matrix fractures, fibers work together to distribute the load and prevent the structure from collapsing. The performance of fibers depends on their placement, orientation, and embedment length, including the concrete composition, fiber type, rheological properties, casting method, and consolidation in agreement with previous researches [23] [17] [24][21].

9.3.3. Effect of Using Synthetic Macro-Fiber.

As shown in Figs. (9-12), 2.5-7.5kg synthetic fiber addition led to a decrease in mechanical properties. The study findings were broadly consistent with those of previous studies [25][26]. Synthetic fibers have smooth surfaces that provide poor bond to a poor cement paste. The cement paste does not completely envelop the fibers, which weakens the fibers' effectiveness for load transfer. Bond strength can be modified by fiber surface coating [27].

9.3.4. Effect of Using Chemical Curing Agent "PEG 400"

As shown in Figs. (9-12), the results indicated that 2% of polyethylene glycol 400 is the ideal dose. The study findings were broadly consistent with those of previous studies [28] [29]. PEG 400, a curing agent for mixing water, is uniformly dispersed throughout the matrix. The curing agent moisture remains dormant until a humidity gradient forms during hydration, triggering a chemical reaction. [30]. Water is moved to dry zones of the matrix by capillary suction for continuous hydration[31]. PEG 400 is a revolutionary admixture that can transform concrete into a self-curing base. It works by reducing water evaporation, which helps to retain moisture and improve hydration. This results in stronger, more durable concrete with fewer cracks and defects. [16].

9.2.1 Effect of Ratio of Water to Cement.

Chemical reaction bonding developed concrete strength through cement hydration. Cement hydration produces a compound that binds the ingredients together and gives concrete strength and durability. The volume of the hydrated concrete is greater than the volume of the cement and water used. The W/C ratio is 0.42 for complete hydration[32]. Paste content, void ratio, and pervious concrete typically have a greater impact on strength than w/c ratio. [33]–[35].

10. Prediction of Properties Characteristic

Quality characteristic predicted means of the compressive strength, Splitting tensile strength is computed using the following equation (2):

$$Smp = \bar{Y} + (\bar{A}_O - \bar{Y}) + \overline{(B_O} - \bar{Y}) + (\overline{C_O} - \bar{Y}) + (\overline{D_O} - \bar{Y}) + (\overline{E_O} - \bar{Y}) \tag{2}$$

Which is the performance characteristic average. $A0 - Y$, $B\ 0 - Y$, $C0 - Y$, $D\ 0 - Y\ and\ E\ 0 - Y$ The factors values were chosen: Mix (1) (A=10%, B=0%, C=0.05%, D=0.36% , E=2.0%) and Mix (2) (A=0%, B=0%, C=0%, D=0.30% , E=2.0%) and Mix (3) (A=0%, B=0%, C=1%, D=0.30% , E=2.0%) and Mix (4) (A=0%, B=5kg, C=0%, D=0.30% , E=2.0%) From the analysis, the mean values of the study were predicted as shown in Table (10). Factor A is coarse aggregates Replacement by Recycle aggregates. Factor B is the Ratio of water to cement .Factor C is the addition of Synthetic macro-fiber in proportions. Factor D is the addition of steel fiber. Factor E is Polyethylene glycol 400.

Table (10). Taguchi predicted values and actual values for SCRC.

	Mix [1]		**Mix [2]**		**Mix [3]**		**Mix [4]**	
Test	**Comp. strength [MPa]**	**Splitting tensile strength [MPa]**	**Comp. strength [MPa]**	**Splitting tensile strength [MPa]**	**Comp. strength [MPa]**	**Splitting tensile strength [MPa]**	**Comp. strength [MPa]**	**Splitting tensile strength [MPa]**
Experimental results of the confirmation mix	20.45	2.05	15.0	2.2	18.4	2.5	12.2	2.0
Taguchi predicted value	22.23	2.13	16.2	2.4	17.75	2.6	13.17	2.1
Ratio of predicted value and actual value	92%	96%	93%	92.8%	103%	94%	92.8%	95.5%

Some factors ratios were selected to experiment with confirmation performance Mix (1-4) illustrated in Table (10). Confirmation experiment results were compared to predicted values obtained from Minitab program as in Table (10). Actual values to predicted values ratio are in the range of ±10% difference. This confirms experimental results. The number of mixtures was $4^5 = 1024$ (5 factors in 4 levels) using the traditional method, and statistically using the Taguchi method it became 16 mixtures Table (2). Also, Taguchi's method provides a prediction of the non-experimental results.

11. CONCLUSION

Self-curing pervious concrete parameters were experimented. The following statistical and experimental statements are concluded:

- The incorporation of recycled aggregates in self-curing pervious concrete negatively impacts compressive strength. An optimal Polyethylene Glycol (PEG) dosage of 2% was determined to enhance overall performance.
- Compressive strength exhibited a maximum value when the mixture contained 10% recycled aggregates, no synthetic macro-fibers, 0.05% steel fiber, a water-cement ratio of 0.36, and 2% PEG400. Recycled aggregate content and PEG dosage were identified as the most influential factors affecting compressive strength.
- Regarding S/N ratio results, Optimal splitting tensile and flexural strength were achieved in specimens with 10% recycled aggregates, no synthetic macro-fibers, 0.1% steel fiber, a water-cement ratio of 0.30, and 2% PEG400. Synthetic macro-fibers and steel fibers significantly influenced flexural strength.
- ANOVA analysis confirmed that recycled aggregate content and PEG dosage had the most substantial impact on compressive strength, contributing 30.50% and 24.18% respectively. Recycled aggregate content (58.73%) and macro-fibers (17.66%) were the primary factors affecting splitting tensile strength.

Generally, recycled aggregate type and content affect the main mechanical properties of recycled aggregate pervious concrete. Using PEG 400 enhances the recycled aggregate pervious concrete to be self-cured. Researchers can use the Taguchi method to help in choosing the most effective parameters based on previous research to reduce the experiments and costs.

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