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Performance Evaluation of Quaternary Concrete Incorporating Locally Sourced Bagasse Ash, Eggshell Powder and Copper Slag

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***Abstract*— This study explores the mechanical and durability properties of quaternary concrete. Quaternary concrete is mix of concrete of Ordinary Portland Cement (OPC) replaced with Sugarcane Bagasse Ash (SCBA), Eggshell Powder (ESP), Copper Slag (CS). All the materials are locally available in Central India. Various mix combinations (SCBA6-15 %, ESP 2-5 %, CS 2-10%) were prepared and tested for compressive strength, flexural strength, ultrasonic pulse velocity (UPV), rebound hammer test and permeability test at 7 and 28 days. The results shown that the mix M-80-12-3-5 achieved the great performance with a 28-days compressive strength of 50.98 MPa, flexural strength of 5.01 MPa, UPV of 6.51 km/s, rebound number of 49, and permeability of 1.5×10^{-12} m/s (18 mm depth of penetration) exceeding conventional concrete. This enhancement is mainly due to the SCBA's pozzolanic silica, ESP's calcium and densifying property of CS. After optimum levels, strength is reduced due to cement dilution. The study confirms that locally available Supplementary Cementitious Materials can be cost effective, eco-friendly and high performance concrete suitable for sustainable civil infrastructures.**

***Keywords*— Sugarcane Bagasse Ash (SCBA), Eggshell Powder (ESP), Copper Slag (CS), Quaternary Concrete, Mechanical Properties, Sustainability.**

I. INTRODUCTION

Concrete remains the backbone of global infrastructure. It contains nearly 8% of anthropogenic carbon dioxide emissions, mainly from cement production. The need for ecofriendly binders has driven research towards Supplementary Cementitious Materials (SCMs) and it derived from industrial and agricultural waste. When conventional concrete mixed with multiple SCMs, it produces as a low effect carbon alternative that enhance the strength and durability. Reduces environmental impact.

Egg shell powder (ESP) is rich in calcium carbonate. It provides lime for calcination. SCBA is an agro-waste it contains silica and alumina. It shows strong pozzolanic activity. Copper Slag (CS) is a metallurgical waste of copper industries. It improves packing density and abrasion resistance. By combining these three materials can reduce waste management, improve microstructure and promote sustainability in construction.

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II. REVIEW OF LITERATURE

A. Sugarcane Bagasse Ash (SCBA)

SCBA has high silica content and it has pozzolanic property. Burning temperature, fineness, and carbon content has a significant effect on the mechanical and durability advantages of SCBA. By increasing pozzolanic content, high-volume SCBA and silica fume can increase long-term strength and durability [1]. Using finely ground SCBA to replace up to 20–25% of cement shown in a increase in late-age strength [2]. The studies are the importance of preprocessing and the variability of SCBA. Because of unburned carbon and irregular particle size, the untreated SCBA can increase porosity and decrease strength [3]. On the other side, optimised SCBA mixes improved sulphate resistance, pore structure, and decreased permeability [4] [5]. By addition and by treated SCBA to high-strength concrete improved to chloride penetration [6]. The use of SCBA in special important for the concrete has grown as well. Developed the sugarcane filter cake waste for lightweight foamed concrete [7], Integration of the SCBA into self-compacting concrete [8]. SCBA is a has partial cement and partial substitute with significant improvement [9].

B. Eggshell Powder (ESP)

The main component of eggshell powder is CaCO3, which, calcined, provides filler effects, nucleation sites, and possible cementitious reactions. ESP is a viable partial cement replacement, at the low percentages (2–10%), where it increases density without sacrifice the strength [10]. Chong et al.'s thorough meta-analysis from 2021 revealed that variations is and the in-calcination temperature, particle size, and replacement the technique were responsible for performance between studies [11]. The higher the reactive of nano-processed ESP has interest. The nano-ESP was with other SCMs, improved hydration of the kinetics, denser the microstructure, and increased early strength [12] [13]. Superior mechanical performance was demonstrated by ultra-high-performance concrete that contained nano-ESP [14]. The environment has the advantages of ESP in lightweight foamed concrete [10]. In a more recent study, observed the carbonation treatment of ESP concrete & discovered that is it enhanced stability and mechanical characteristics, suggesting the possibility of carbon-curing technologies [15].

C. Copper Slag (CS)

The high density, angularity, and glassy structure, copper slag is used as an option for fine aggregates. Better packing and mechanical and interlock, substituting it 30–50% CS for natural sand improve the compressive and flexural strengths [16]. Higher replacement ratios, however, its increased bleeding and decreased workability, and admixture adjustments. There have also been reports that the durability gains from CS. The study of bacterial and copper slag concrete found improvements the in durability indices and the strength driven by the bacterially induced calcite precipitation [17]. And has High-performance concrete has demonstrated synergistic benefits when CS and SCMs are combined, which is consistent with more general sustainability goals.

D. Combined System

The component has the binder systems that use SCBA, ESP, CS, and other SCMs are receiving more attention. In the study of quaternary concrete blends, found that when property has been are optimised, complex interactions among SCMs that can greatly important and improve the mechanical performance, decrease permeability, and refine microstructure [18]. In a similar vein, binary, ternary, and blends the quaternary of fly ash, copper slag, and silica fume and showed that combine the several SCMs improves strength and durability as compared to single-additive systems [19]. Quaternary concretes can greatly lower CO_2 emissions while keeping structural performance [20]. Fibre-reinforced quaternary concrete can notably improve toughness and post-crack behaviour [21]. The empirical review combines research on SCBA, CS, and ESP, pointing out that synergistic effects are possible but very sensitive to how materials are processed and the mix design variables [22].

III. METHODS AND MATERIALS

A. Materials

- Cement - OPC 53 Grade
- Fine Aggregate - Sand from river
- Coarse Aggregate - 20 mm angular stone
- SCBA - Collected from agro industries
- ESP - Waste of Eggshell
- CS - Industrial by-product from copper industries

B. Mix Design

Concrete of grade M40 was proportional as per IS 10262:2019. OPC was replaced by 6-15% of SCBA, 2-5% Of ESP, and 2-10% of CS.
The optimal combination of M-80-12-3-5 it represents 80% cement, 12% SCBA, 3% ESP, and 5% CS. water cement ratio is 0.40.
The detailed mix proportions for all combinations are presented in Table I.

TABLE I. MIX DESIGN

Sr. No.	Combination	Cement	SCBA	ESP	CS	Fine Aggregate	Coarse Aggregate	Mix Design Ratio
1	Conventional	450 kg	-	-	-	658 kg	1142 kg	1: 1.46:2.53
2	M-90-6-2-2	432 kg	29 kg	10 kg	10 kg	518 kg	900 kg	1: 1.19:2.08
3	M-80-12-3-5	383 kg	57 kg	14 kg	24 kg	387 kg	673 kg	1: 1.10:1.75
4	M-80-10-2-8	383 kg	48 kg	10 kg	38 kg	423 kg	735 kg	1: 1.10:1.91
5	M-80-10-4-6	383 kg	48 kg	19 kg	29 kg	424 kg	736 kg	1: 1.10:1.92
6	M-75-10-5-10	359 kg	48 kg	24 kg	48 kg	413 kg	717 kg	1: 1.15:1.99
7	M-70-15-5-10	335 kg	72 kg	24 kg	48 kg	312 kg	541 kg	1: 0.92:1.61

C. Testing Methods

All mixes were tested for:

- Compressive Strength Testing
- Flexural Strength Testing
- Ultrasonic Pulse Velocity
- Rebound Hammer Testing
- Permeability Testing

The materials used and practical procedures are shown in Figure 1-6 material matrix, mould preparation, mixing process, hardened concrete samples, testing procedures, and specimen types.

Figure 1. Material Matrix

Figure 2. Moulds

Figure 3. Material Mixing

Figure 4. Harden Concrete

Figure 5. Testing on Harden Concrete

Figure 6. Concrete Cubes, Beam, Cylinders

IV. Results and Discussion

A. Constituents of Materials

TABLE II. CONSTITUENTS OF MATERIALS AS PER XRF

Oxide	Cement (OPC)	SCBA	CS	ESP	Contribution in Concrete
CaO (Lime)	63%	8%	5%	90%	CaO is key element for hydration & strength. It is high in ESP. It supports cement replacement
SiO_2 (Silica)	21%	60%	32%	3%	SiO2 contributes to pozzolanic activity. It forms C–S–H for strength. It is high in SCBA
Al_2O_3 (Alumina)	6%	7%	7%	1%	Al_2O_3 accelerates setting time. It supports early strength.
Fe_2O_3 (Iron Oxide)	3%	3%	40%	1%	Fe_2O_3 improves colour and thermal stability. Excessive Fe_2O_3 is inert to hydration.
MgO (Magnesium Oxide)	2%	2%	3%	1%	MgO controls expansion in cement. In small amounts it enhances durability.
SO_3 (Sulphur Trioxide)	2.50%	1.50%	1.50%	1%	SO_3 regulates setting time (via gypsum).. Too much in amount may cause sulfate attack
K_2O (Potassium Oxide)	1.50%	7%	1%	1%	K_2O increases alkali content. It affects alkali-silica reaction (ASR) risk.
Na_2O (Sodium Oxide)	1%	1%	0.50%	1%	Na_2O affects durability (can increase ASR).
Other Oxides	0%	0%	10% (ZnO)	1% (trace)	It may impact setting, coloration, or durability. It is usually inert.
Total	100%	100%	100%	100%	

The XRF results shown in Table II shows that every material contributes in different ways to cementitious content. OPC has high lime content (63%) and silica (21%). It is important for hydration and strength. SCBA is high in silica about 60%.

It acts as strong pozzolanic material and it also forms additional C-S-H gel. ESP is high in lime content about 90%. It increases early hydration and gains strength. CS contains high amount of iron oxide (40%) and silica (32%). It increases packing and microstructure.

B. Mechanical Properties

The compressive strength results for different mixes are shown in Table III.

TABLE III. COMPRESSIVE STRENGTH

Sr. No.	Combination	Compressive Strength (MPa)	
		7 days	28 days
1	Conventional	26.02	46.33
2	M-90-6-2-2	28.63	47.06
3	M-80-12-3-5	30.20	50.98
4	M-80-10-2-8	26.56	49.62
5	M-80-10-4-6	24.98	48.74
6	M-75-10-5-10	25.75	40.65
7	M-70-15-5-10	23.42	38.87

The flexural strength results are in Table IV.

TABLE IV: FLEXURAL STRENGTH

Sr. No.	Combination	Flexural Strength MPa (28 days)
1	Conventional	4.76
2	M-90-6-2-2	4.81
3	M-80-12-3-5	5.01
4	M-80-10-2-8	4.93
5	M-80-10-4-6	4.87
6	M-75-10-5-10	4.52
7	M-70-15-5-10	4.46

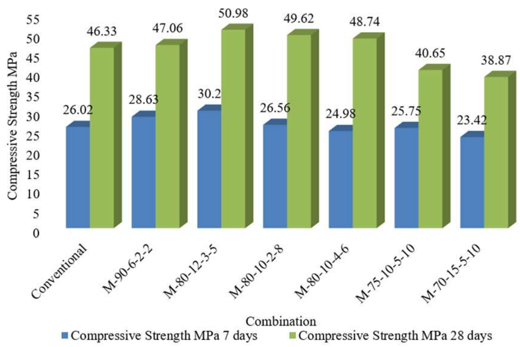

Figure 7. Compressive Strength of Samples (7 and 28 days)

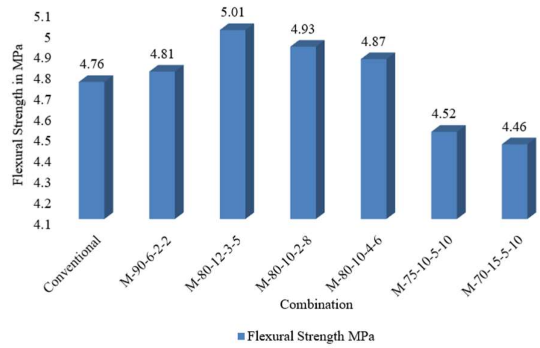

Figure 8. Flexural Strength (28 days)

The Compressive strength presented in Table III and illustrated in Figure 7 shows that, it is peaked up at 50.98 MPa for M-80-12-3-5. It is about 10% above the control (46.33 MPa). The improvement is about to SCBA's pozzolanic C-S-H gel formation and ESP, CaO contribution. If higher replacement (>20%) lowered strength due to reduced cementitious content. Flexural strength follows the same procedure as shown in Table IV and Figure 8: 5.01 MPa for M-80-12-3-5 versus 4.76 MPa for control. The energy among SCMs refined the matrix and improved load transfer.

C. Non-Destructive Testing:

The UPV results are shown in Table V and Figure 9.

TABLE V: ULTRASONIC PULSE VELOCITY

Sr. No.	Combination	Velocity in km/s	Remark
		28 days	
1	Conventional	5.49	Good
2	M-90-6-2-2	5.96	Excellent
3	M-80-12-3-5	6.51	Excellent
4	M-80-10-2-8	5.79	Excellent
5	M-80-10-4-6	4.78	Excellent
6	M-75-10-5-10	4.81	Good
7	M-70-15-5-10	4.9	Good

The Rebound Hammer Test results are shown in Table VI and Figure 10.

TABLE VI. REBOUND HAMMER TEST

Sr. No.	Combination	Rebound Number
1	Conventional	44
2	M-90-6-2-2	45
3	M-80-12-3-5	49
4	M-80-10-2-8	47
5	M-80-10-4-6	44
6	M-75-10-5-10	43
7	M-70-15-5-10	42

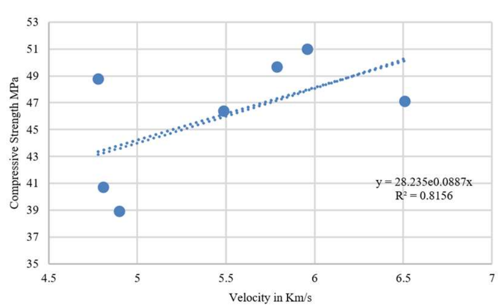

Figure 9. Relation of UPV and Compressive Strength

UPV values (6.51 km/s) classified M-80-12-3-5 as "excellent quality," and it signifying a dense, homogeneous matrix as shown in Table V and Figure 9.

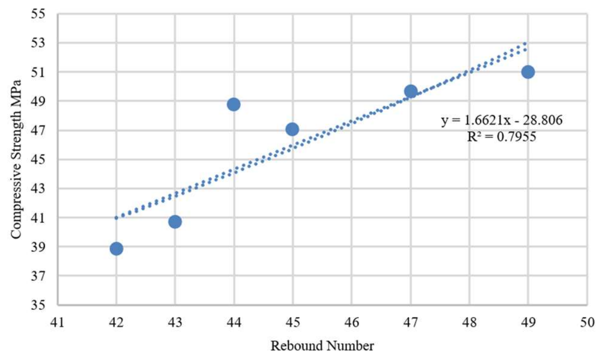

Figure 10. Relation of Rebound Number and Compressive Strength

Rebound hammer results are correlated strongly with the compressive strength ($R^2 \approx 0.79$) as per Figure 10

D. Durability Performance

The permeability test results are as shown in Table VII and Figure 11.

TABLE VII. PERMEABILITY TEST

Sr. No.	Combination	Depth of Penetration (mm)	k (m/s)	Permeability Class
1	Conventional	22 mm	2.5×10^{-12}	Very Low
2	M-90-6-2-2	21 mm	2.3×10^{-12}	Very Low
3	M-80-12-3-5	18 mm	1.5×10^{-12}	Very Low
4	M-80-10-2-8	19 mm	1.8×10^{-12}	Very Low
5	M-80-10-4-6	20 mm	2.0×10^{-12}	Very Low
6	M-75-10-5-10	28 mm	4.5×10^{-12}	Low
7	M-70-15-5-10	31 mm	5.5×10^{-12}	Low

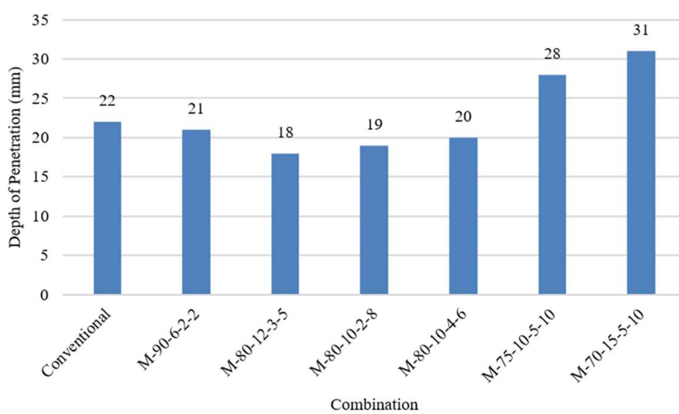

Figure 11. Permeability

Permeability dropped from 2.5×10^{-12} m/s for (control) to 1.5×10^{-12} m/s (M-80-12-3-5) as shown in Table VII and Figure 11, it is indicating the enhanced resistance to the chloride. The reduction is because of the pore filling by SCBA and ESP particles.

D. Optimal Mix

Above all parameters, the M-80-12-3-5 offered the best balance between strength, density, and permeability. The mix achieved 20 % binder replacement without compromising mechanical properties—it translating into ≈15 % CO_2 reduction and ≈12 % material cost savings as compared to conventional OPC concrete.

V. CONCLUSIONS

- The combined use of SCBA, ESP, and CS increased the strength and durability as compared to base concrete.
- The highest strength resulted from 12 % SCBA, 3 % ESP, 5 % CS replacement.
- Compressive and flexural strength are improved by ≈10 % and permeability decreased by ≈40 %.
- Use of these waste materials contributes to the circular economy, reduces landfill burden, and lowers CO_2 emissions.
- The quaternary system is suitable for structural concrete in sustainable construction where M40–M50 grade strength is required.

FUTURE SCOPE

- Long Term Durability Performance
- Microstructural Studies via XRD/SEM analysis

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