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Study on the Mechanical Properties of Concrete with Lightweight Coarse Aggregate

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ABSTRACT
Current advancements in the construction of cement and workability improving substitutes have made it simple for fabrication of concretes with high compressive strength. The scope of this study is to discuss the use of structural lightweight aggregate concrete and examine it potential utilizations. Lightweight concrete properties is discuss to have a prior knowledge about the structural lightweight concrete (LWC). The method of production, types, and characteristics of lightweight aggregates (LWA) used for structural purpose are presented. Production and main characteristic of concrete make from this aggregates were investigated.
Keywords: concrete, lightweight aggregate, lightweight concrete.

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دراسة الخواص الميكانيكية للخرسانة المحتوية على الركام الخشن خفيف الوزن

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الملخص

أدت التطورات الحالية في مجال تصنيع الأسمنت والبدائل المحسنة لقابلية للتشغيل إلي تسهيل تصنيع الخرسانة ذات قوة الضغط العالية، يهدف نطاق هذه الدراسة إلي مناقشة أستخدام الخرسانة الهيكلية الخفيفة الوزن ودراسة الأستخدامات المحتملة لها. تتم مناقشة خصائص الخرسانة الخفيفة الوزن للحصول علي معرفة . يتم عرض الأنتاج وأنواع وخصائص الركام الخفيف الوزن (LWC)مسبقة عن الخرسانة الخفيفة الوزن المستخدم للأغراض الهيكلية، ثم التحقيق في أنتاج وخصائص الخرسانة المصنوعة من هذا الركام (LWA)

الكلمات المفتاحية: الخرسانة، الركام الخفيف الوزن، الخرسانة الخفيفة.

1. Introduction

A rare credit of concrete that causes it really multipurpose is that it includes relatives of materials accompanied by a huge variety in density, strength and durability characteristics. Concretes of unit weight ranging from 1800-3000 kg /m3 are practically used for structural purpose [1]. Current advancements in the construction of cement and workability improving substitutes have made it simple to fabrication of concretes with high compressive strength. Such concretes, however, are proportionately heavy with high weights. Moreover, NWC is made with natural aggregates. Clearly, these systems are seriously destructive to the environment. Lightweight is becoming more important in the construction world now because it is essential more in energy conservation and also the raw material is use for the escape natural recourses. For example, the thermal resistance of such materials increases with decreasing the density which in turn leads to considerable energy savings [2]. Nevertheless,

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a concrete, including lightweight aggregate is simpler to mix and place than a normal weight concrete. In addition, Lightweight concretes (LWCs) in the strength range of 30–80 MPa can easily be made [1, 3]. Although Micro cracking at the interface will easily appear at early hydration due to higher absorption rate, pre-wetting the lightweight aggregate is one method of minimizing this effect and therefore, maintaining the consistency of the concrete mixes [4]. Approximately, there are 600 million tons of Fly ash (FA) are available in the world, whereas only 10% of FA is currently [5]. Since big amounts of the fly ash stay unutilized in most countries of the earth, the creation of lightweight fly ash aggregates is a suitable step to greatly increase its use, especially, through the manufacturing of lightweight aggregate by the process, namely, cold bonding and sintering. It was possible to fabricate lightweight concrete with density in the range of 1560–1960 kg/m3 and in the strength of medium range [5]. The increasing demand for lightweight concrete (LWC) has led to a growing interest in the development of artificial lightweight aggregates (LWA). These aggregates play a fundamental role in reducing the self-weight of concrete while maintaining satisfactory mechanical and durability properties. Lightweight aggregates can be produced from a wide range of raw materials, including natural resources and industrial by-products such as fly ash. The characteristics of LWA are strongly dependent on both the nature of the raw materials and the manufacturing techniques employed. Among the various production methods, cold-bonding has emerged as a sustainable and energy-efficient alternative to traditional high-temperature sintering processes. This technique is particularly advantageous due to its lower energy requirements and reduced environmental impact. In the cold-bonding process, fine particles—especially fly ash—are agglomerated into spherical granules through the addition of water, which acts as a binding agent. This process facilitates particle cohesion without the need for thermal treatment, thereby contributing to waste valorization and environmental protection. Consequently, the physical and mechanical properties of the resulting lightweight aggregates, such as density, porosity, and strength, have a direct influence on the performance of lightweight concrete. These properties govern key aspects of LWC behavior, including compressive strength, durability, and thermal insulation

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capacity [6–9]. Some experimental studies have been conducted to explore how the aggregate type influences the properties of LWCs [10, 11]. It is reported that the compressive strength of LWCs is strongly affected by the material and binder type of LWAs [10, 12]. However, it is not clear if LWC strength has advantage over the NWC, strength of LWC can be improved substantially by the reduction of water/cement ratio (w/c) and by the incorporation of silica fume [13]. According to Khokhrin [14], the permeability of LWC manufactured through porous LWA is lower than that of NWC. It was referred to a combination of the improved interfacial zone between the aggregate and mortar matrix. Similarly, Thomas [15] found that chloride penetrability of LWC made with blended cement and silica fume at a w/c of 0.30 were substantially lower than those of NWC. However, in the study of Behera et al. [16], concentration of chloride penetrated into the LWC was slightly higher than that in NWC of the same 28-day designed compressive strength of 50 MPa. As reported in most literature, the wide diversity of the lightweight aggregate source and manufacturing process result in distinctive behavior among the LWC.

2. Research Significance

The growing interest in lightweight concrete (LWC) has encouraged the exploration of alternative aggregates such as pumice to reduce the self-weight of structures while maintaining adequate mechanical performance. However, due to the variability in raw materials and manufacturing processes, lightweight concretes often exhibit different behaviors, making it necessary to investigate their properties individually.

Therefore, this study aims to evaluate the feasibility of using pumice as a lightweight aggregate by partially and fully replacing conventional coarse aggregate at replacement levels of 20%, 40%, 60%, 80%, and 100% in M30 concrete. The study also seeks to compare the characteristics of conventional concrete and pumice aggregate concrete through key mechanical tests, including compressive strength, split tensile strength, and flexural strength.

The findings of this research are expected to demonstrate the effectiveness of pumice aggregate in producing structural lightweight concrete and to highlight its potential as a sustainable alternative to conventional aggregates.

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3. Classification of Light Weight Concrete

In this Paper lightweight concrete produced by the use of LWAs will be studied. There are many types of LWA and their properties cover wide ranges. Depending on the required properties of concrete, such as density and strength, particular aggregates can be chosen.

4. Classification of Lightweight Aggregates

Lightweight aggregates are naturally found or the others are manufactured. It is a granular material with a bulk density not exceeding 1200 kg/m^3 or with a particle density not exceeding 2000 kg/m3 [17].

There are many type of aggregates which are considered to be lightweight. These aggregates maybe sub divided into three group.

- **Naturally Occuring Materials**: examples of these are pumice scoria, volcanic tuff etc.
- **Naturally occurring materials that require further processing (artificial lightweight aggregates):** Examples include perlite, vermiculite, and expanded clay, shale, and slate. The first two materials (perlite and vermiculite) are generally classified as non-structural lightweight aggregates and are mainly used for insulation purposes due to their low strength. In contrast, expanded clay, shale, and slate are produced through thermal treatment and are suitable for structural applications because of their relatively higher strength and durability.
- **Processed industial waste materials**: examples of theses are sintered pulverised-fuel ash, expanded blas furnace slag, sintered colliery waste, plastic particles, and clayed blended sludge ash,. Some of these e.g. plastic particle, are also non structural materials.
-

5. Methodology

The behavior and properties of pumice stone as a coarse aggregate were systematically investigated. Raw materials—including cement, fine aggregate, conventional coarse aggregate, and pumice stone—were obtained from well-documented sources. To provide insight into the expected performance of the concrete, a chemical composition analysis was performed for each material (TABLE 1).

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TABLE 1. Chemical Composition of Materials (% by weight)

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	LOI*
Cement	21.5	5.1	3.2	64.0	2.5	0.8	0.2	3.0
Fine Aggregate	65.0	15.0	5.0	8.0	2.0	1.0	0.5	3.5
Coarse Aggregate	70.0	12.0	4.0	6.0	2.0	1.0	0.5	4.5
Pumice Stone	75.0	13.0	2.5	3.0	1.5	1.0	0.5	3.5

*LOI = Loss on Ignition

Conventional M30 grade concrete mix proportions were determined first. For pumice aggregate concrete, partial and full replacement of natural coarse aggregate was carried out at levels of 20%, 40%, 60%, 80%, and 100%. The replacement was weight-based, calculated as a percentage of the total weight of coarse aggregate in the mix. Concrete samples were cast in cubic moulds of 150 mm × 150 mm × 150 mm and cylindrical moulds of 100 mm × 200 mm. To ensure statistical reliability, three specimens per replacement level per test were prepared. All specimens were cured under standard conditions for 7 and 28 days. Mechanical properties were evaluated through Compressive Strength and Split Tensile Strength

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tests, conducted according to standard procedures. The average values of all specimens were reported for each replacement level. The results were analyzed to assess the feasibility of using pumice as a structural lightweight aggregate and its effect on the mechanical performance of M30 concrete (Fig 1 and 2).

Fig. 1. Filled up Concrete Cubes

Fig. 2. Compressive strength test

6. Materials

- **Characterizations of constituent Materials**

Most of the materials used in this study are materials obtained from the local markets. The detailed properties of the materials used are as follows:

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- **Cement:**

Ordinary Portland cement is the most common type of cement in general utilize around the world because it is a basic component of concrete, mortar, stucco. The cement that was used was PC 42.5N, should be free from lumps and any foreign matters before it is used. The cement should be stored under the dry condition and used for this short duration

- **Chemical Composition of Cement:**
-

TABLE 2. Chemical composition of the cement

Features		Analysis Results
Chemical	Insoluble Residue (%)	0.18
	Loss on Ignition (%)	2.54
	SO3 (%)	2.98
	SiO2 (%)	22.45
	CaO (%)	55.00
	CaO free (%)	1.10
	MgO (%)	2.34
	Al2O3 (%)	6.00
	Fe2O3 (%)	4.70
	Cl (%)	0.00

- **Physical Properties of Cement**

The physical properties of the cement used is tabulated below, as provided by manufacturers' certificate. See TABLE 3.

TABLE 3. Physical properties of the cement

Features		Analysis Results
Physical	Specific Gravity (g/cm3)	3.15
	Specific Surface Blaine (cm2/ g)	3567
	90 Micron Sieve (%)	0.13
	W/C Ratio (%)	29.2

- **Fine Aggregates:**

Sieve Analysis of (0mm – 4mm) fine aggregates: The sieve analysis of the fine aggregates were booked down and calculated. See TABLE 4 and Fig 3 illustrating the sieve analysis for fine aggregate

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TABLE 4. Sieve Analysis of (0mm – 4mm) fine aggregates

S/No	Sieve Size (mm)	Weight Retained (g)	%Weight Retained	% Cumulative Weight Retained	% Weight Passing
1	4.75	0	0	0	100
2	2.36	44	2.9	2.9	97.1
3	1.18	486	32.4	35.3	64.7
4	0.60	362	24.1	59.4	40.6
5	0.30	328	21.9	81.3	18.7
6	0.15	183	12.2	93.5	6.5
7	0.075	97	6.5	100	0
Total		1,500			

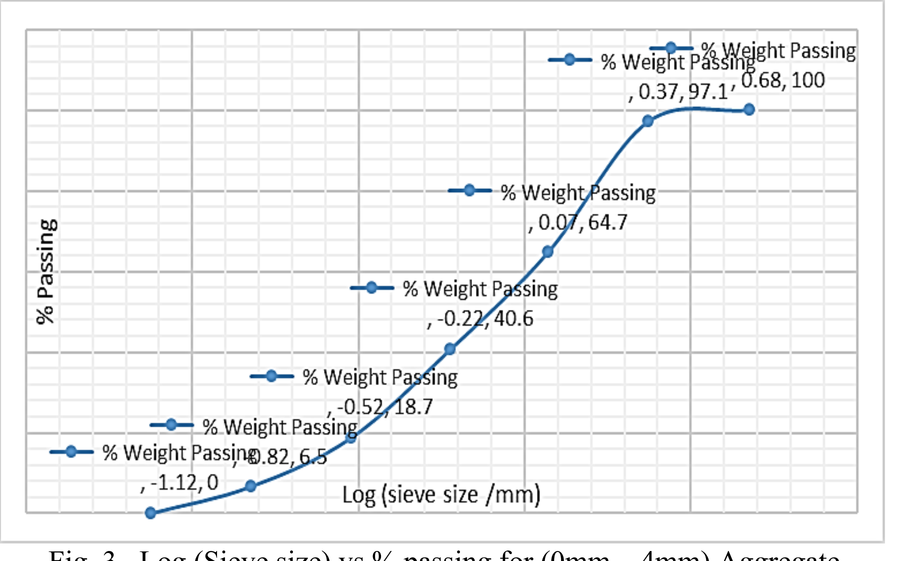

Fig. 3. Log (Sieve size) vs % passing for (0mm – 4mm) Aggregate

❖ **Coarse Aggregates:**

Sieve Analysis of (4mm – 8mm) coarse aggregates:

The sieve analyses were tabulated. See TABLE 5 and Fig 4 for the calculations and results.

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TABLE 5. Sieve Analysis of (4mm – 8mm) coarse aggregates

S/No	Sieve Size (mm)	Weight Retained (g)	%Weight Retained	% Cumulative Weight Retained	% Weight Passing
1	9.5	0	0	0	100
2	4.75	690	69	69	31
3	2.36	240	24	93	7
4	Pan	70	7	100	0
Total		1,000			

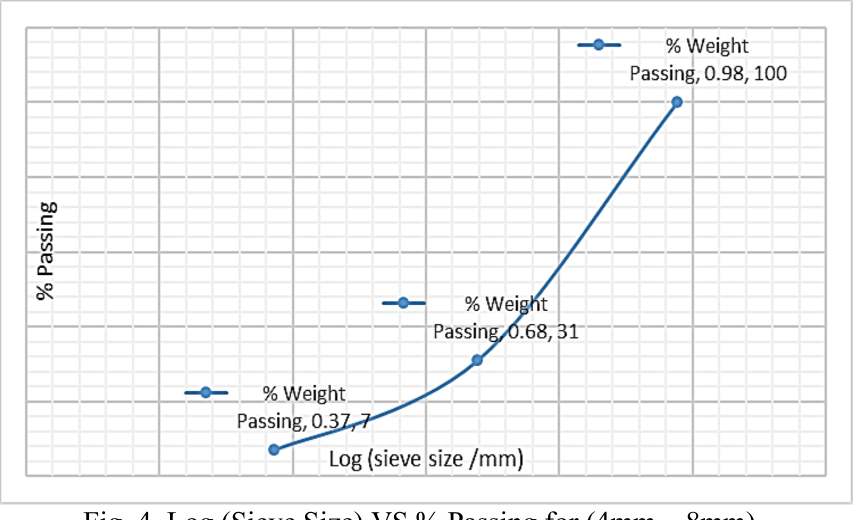

Fig. 4. Log (Sieve Size) VS % Passing for (4mm – 8mm) .

❖ **Sieve Analysis of (8mm – 19mm) coarse aggregates**:

The sieve analysis for the coarse aggregates were tabulated down, and calculated shown in TABLE 6 and Fig 5.

TABLE 6. Sieve Analysis of (8mm – 19mm) coarse aggregates

S/No	Sieve Size (mm)	Weight Retained (g)	%Weight Retained	% Cumulative Weight Retained	% Weight Passing
1	19	44	2.9	2.9	97.1
2	14	337	22.5	25.4	74.6
3	12.5	323	21.5	46.9	53.1
4	9.5	546	36.4	83.3	16.7
5	4.75	244	16.3	99.6	0.4
6	pan	06	0.4	100	0
Total		1,500			

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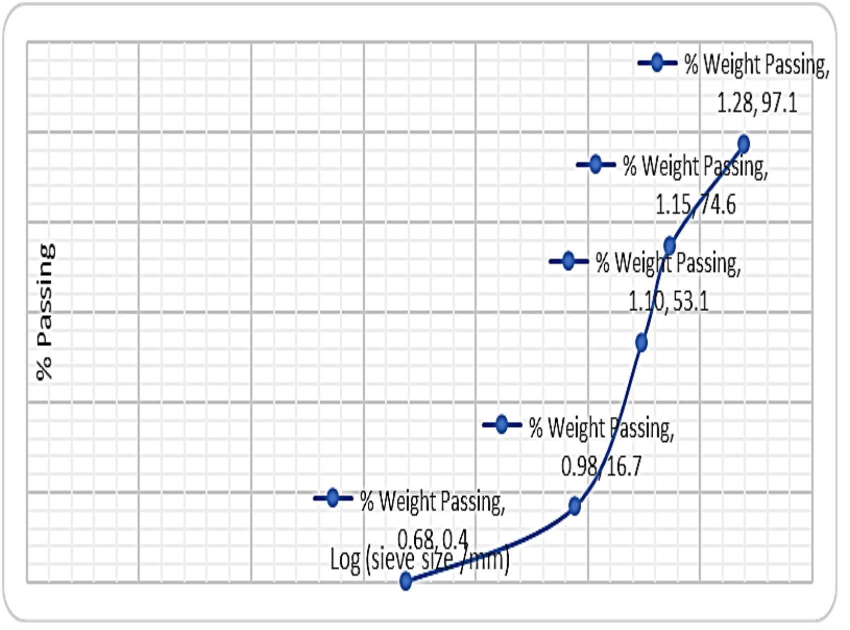

Fig. 5. Log (Sieve Size) vs % passing for (8mm – 19mm) Aggregates

❖ **Sieve Analysis of (Light weight aggregates)**

TABLE 7. Sieve Analysis of (Light weight aggregates)

S/No	Sieve Size (mm)	Weight Retained (g)	%Weight Retained	% Cumulative Weight Retained	% Weight Passing
1	10	0	0	0	100
2	8	39.5	7.9	7.9	92.1
3	4	193.5	38.7	46.6	53.4
4	2	208.5	41.7	88.3	11.7
5	1	17.5	3.5	91.8	8.2
6	0.5	3	0.6	92.4	7.6
7	0.25	3.5	0.7	93.1	6.9
8	pan	34.5	6.9	100	0
Total		500			

❖ **Water Absorption of Lightweight Aggregate**

Tap water was used in all concrete mixtures and in the curing of all the tests specimens which is considered safe to drink. The principal concept of using water in concrete is "If you can drink it, you can make concrete with it".

Most of the lightweight aggregates are porous and the water absorption rate is higher than normal weight aggregate. Specific Gravity and Water Absorption of Lightweight Aggregates. The specific gravity and water absorption were calculated and booked down in TABLE 8.

Abbreviation Symbols:

Oven Weight of Lightweight Aggregates – *OWA*

Saturated Surface Dry Weight of Lightweight Aggregates – *SSDWA*

Water + Lightweight Aggregate + Glass mould – *WAM*

Water + Mould – *WM*

Formulas used in Calculating

- **Bulk (*S.G*) dry = (*OW(LWA)*) / [(*SSDW(LWA)*) + (*WM*) - (*W(LWA)M*)]**
- **Bulk Saturated Surface Dry Specific Density (S.*S.G*) dry = (*SSDW(LWA)*) /[(*SSDW(LWA)*)+ (*WM*) -(*W(LWA)M*)]**
- **Apparent Surface Dry (S.D) = (OW(LWA)) / [(OW(LWA)) + (*WM*) - (*W(LWA)M*)]**
- **% Water Absorption = [(*SSDW(LWA)*) - (OW(LWA))] / (OW(LWA)) x 100**

TABLE 8. Specific gravity and water absorption for Lightweight aggregates

Lightweight aggregates	OW (LWA) (g)	SSDW (LWA) (g)	W(LWA)M (g)	WM (g)	S.G Dry	S.G S.S.D	S.G Apparent	% Water Absorption
0-8mm	98.7	105	1415	1395	1.16	1.24	1.25	6.38%

- **Mix Design**

In this study, M30 grade of concrete, then the coarse aggregate was replaced by respective amount of Lightweight aggregates (20%,40%, 60%,80%,100%) The mix proportion for normal

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concrete and various percentage of replacement of pumice aggregate concrete is given in TABLE 9.

TABLE 9. Mix Proportion

Mix id	Proportion	Cement (kg/m3)	Fine Aggregate (kg/m3)	Coarse Aggregate (kg/m3)	Lightweight Aggregate (kg/m3)
P0%	1 :1.7 :3.11 :0	400	680	1244	0
P20%	1 :1.7 :2.49 :0.29	400	680	995.2	117
P40%	1 :1.7 :1.87 :0.55	400	680	746.4	220
P60%	1 :1.7 :1.24 :0.78	400	680	497.6	310.7
P80%	1 :1.7 :0.62 :0.96	400	680	248.8	384
P100%	1 :1.7 :0 :1.2	400	680	0	481

7. Results and Discussions

- **Compressive Strength:**

The compressive strength for concrete specimens is found to be maximum for P0% (conventional concrete), i.e., 0% replacement of coarse aggregate by pumice. The value is found to decrease for P20%, decrease for P40%, decrease subsequently for P60%, 80% and P100% as shown in TABLE 10 and Fig 6.

TABLE 10. compressive strength valuse

Type of concrete	Compressive strength after 7 days	Compressive strength afte28 days
P0%	25.1	37.9
P20%	19.23	32.2
P40%	9.12	24.01
P60%	8.45	17.44
P80%	6.11	13.25
P100%	4.22	11.24

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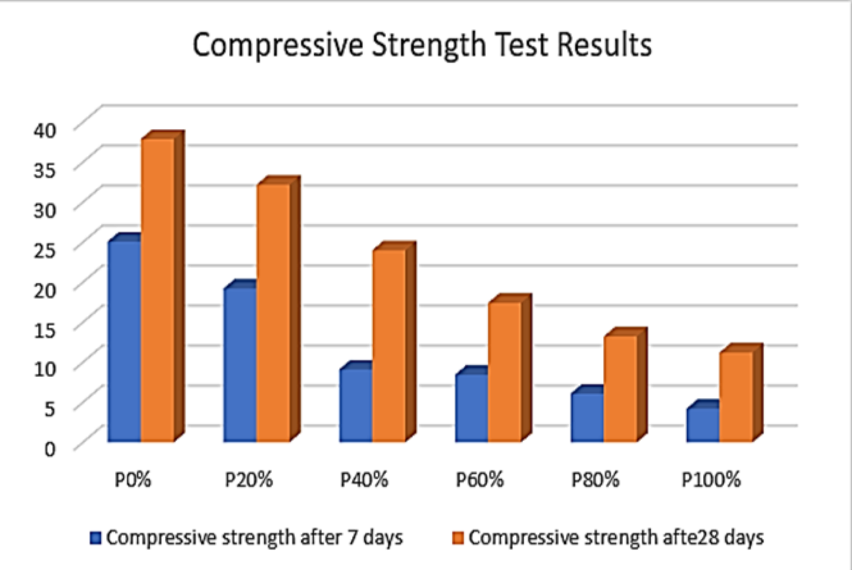

Fig. 6. Compressive Strength at 7 and 28 days

- **Split Tensile Strength:**

The Split Tensile Strength (STS) of concrete was measured using cylindrical specimens of 100 mm diameter × 200 mm height, following the standard ASTM C496 / BS EN 12390-6 procedure. In this test, a cylinder is placed horizontally between the loading platens of a compression testing machine. A line load is applied along the vertical diameter of the cylinder until failure occurs, producing a tensile stress perpendicular to the applied load, which causes the cylinder to split along its vertical plane.

The split tensile strength is calculated using the formula:

$$fst=2P/\pi LD$$

where:

- fst = split tensile strength (N/mm²)
- P = maximum applied load at failure (N)
- L = length of the cylinder (mm)
- D = diameter of the cylinder (mm)

In this study, each replacement level of coarse aggregate by pumice (0%, 20%, 40%, 60%, 80%, 100%) was tested using three

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specimens, and the average values after 7 and 28 days of curing were reported in TABLE 11 and Fig 7.

Observation from TABLE 11: The trend of STS follows that of compressive strength. The STS decreases gradually as the proportion of pumice aggregate increases, indicating that higher replacement levels reduce the tensile capacity of the concrete. For example:

- **P0% (conventional concrete):** 2.4 N/mm² after 7 days, 4.1 N/mm² after 28 days
- **P100%:** 1.3 N/mm² after 7 days, 1.92 N/mm² after 28 days

This method ensures that the measured tensile stress reflects the actual influence of pumice replacement on concrete performance.

TABLE 11. Split Tensile strength valuse

Type of concrete	Average split tensile strength after 7 days (N/mm2)	Average split tensile strength after 28 days (N/mm2)
P0%	2.4	4.1
P20%	2.1	3.9
P40%	1.88	3.1
P60%	1.6	2.6
P80%	1.34	2.1
P100%	1.3	1.92

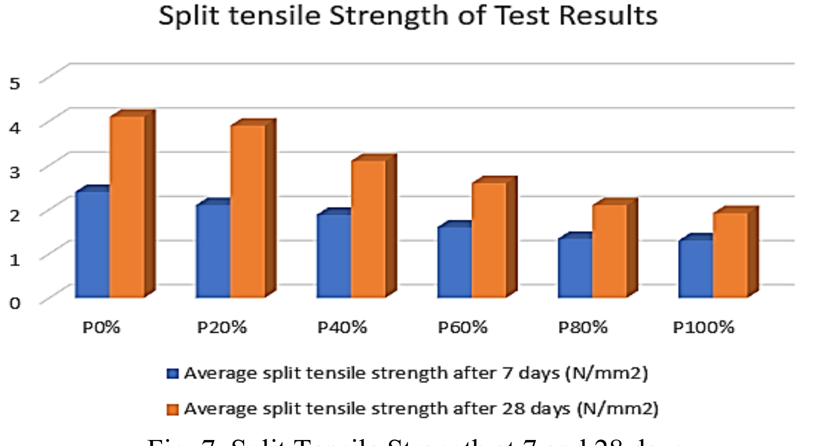

Fig. 7. Split Tensile Strength at 7 and 28 days

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- **Flexural strength test:**

Flexural test is performed to determine the flexural strength of the concrete flexure test. The specimen is tested at the age of 28 days curing, using 40-ton Universal testing machine. Flexural test strength for concrete specimens is found to be maximum for P0% (conventional concrete), i.e., 0% replacement of coarse aggregate. The value is found to decrease for P20%, P40% P60%, 80% and P100% as shown in TABLE 12 and Fig 8.

TABLE 12: Flexural strength test valuse

Type of concrete	Average flexural strength (N/mm2)
P0%	**4.11**
P20%	**3.88**
P40%	**3.71**
P60%	**3.52**
P80%	**3.27**
P100%	2.91

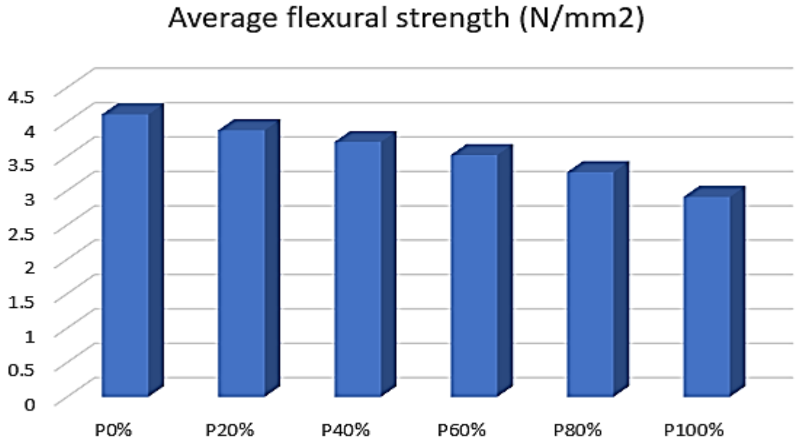

Fig. 8. Flexural strength at 28 days

Conclusion

- Structural Lightweight aggregate concrte has satistactiry performance and is no less durable than concrte made with natural sand and gravel. It can be employed anywhere instead of normal weight concrte if the necessary prcautions are taken. Concrte of considerable strength can be readily produced with proper structural lightweight aggregates.

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- Structural Lightweight aggregate concrete is most economical when the dead weight is large compare with the total load. By employing it in the superstructure, the bulk of the foundations can be reduced. The saving of foundation costs is most pronounced with tall buildings and with bad soil conditions. In any structure, when the spans get larger, lightweight aggreagte concrete becomes more economical. Time and cost for erection and handling of prefabricated componets can be saved. The increases heat, frost, and fire resistance have favorabe effect on the indirect building and maintenace cost.
- Reduced weight can be availed in highly seismic zones. Here column behaiour which is critical during earthquakes should not be problem since tests show that properly detailed columns made of structural lightweight aggregate concrete perform as well as those made of normal weight concrete under seismic loading.
- The most approprite type of structural lightweight aggregate for most countries are those produced from industrial watse materials, especially pulverised-fuel ash. Use of clay, shale, and slate should only be considered as a later measure.

Recommendation

At this end of this study, it is recoommended that more study should be made on the properties of LWAC on the economic and finacial aspect of the concrete.

Other type of concrete should also be investigated on to be able to compare with this type. This will help to compare and contrast between different type of concrete.

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