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Experimental Investigations on the Physical and Mechanical Properties of a Lightweight Concrete Using Oil Palm Shell as Coarse Aggregate

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Abstract: Oil palm shell is an interesting organic material that can be used as aggregate for concrete. It can help mitigate the environmental problems caused by the concrete industry. We intend to contribute to the knowledge of OPS (oil palm shells) concrete studying the physical mechanic and thermal behavior. Then, this paper presents the results of investigations carried out on the effects of replacing by volume, CGA (crushed granite aggregate) in concrete with OPS. Then, the dry density, apparent porosity, water absorption, electrical resistivity, thermal parameters, flexural strength, compressive strength and static elastic modulus are investigated. Microscopic analysis with an SEM (scanning electron microscopic) is also conducted. The results show that replacing crushed granite aggregate by OPS, increases the apparent porosity of concrete. This makes the concrete lighter and the concrete mechanical strengths lower. SEM analysis indicates that these decreases may be the consequence of a bad bond existing between the cement paste and OPS aggregate. Though, the compressive strength of OPS concrete which is 28 days old is acceptable for structural concrete. OPS concrete is more ductile and has a better thermal behavior compared to CGA concrete.

Key words: Biosourced aggregate, lightweight concrete, physical-mechanical, thermal properties.

1. Introduction

Africa has currently the fastest rate of urbanization in the world. By 2050, his rate is intended to reach 60 percent [1]. To face this rapid urbanization, more houses, infrastructures, roads are needed. Many kinds of building materials are used for construction. Concrete is among the most widely used. This huge popularity is due to its numerous benefits such as low cost, general availability and its vast range of applications.

However, the use of concrete is negated by its environmental impact. Concrete is typically made of about 12% cement and 80% aggregate by mass [2]. The massive concrete quantities needed every year in turn, means that huge quantities of natural resources will be used. Thus, many environmental problems will occur. To preserve the earth's natural resources, waste or recycled materials are studied as potential construction material [3-5]. Researchers are interested in lightweight concrete. The most popular method for the lightweight concrete studied is the use of lightweight aggregates such as fly ash, expanded slag cinder, and bottom ash which are lighter than the conventional coarse aggregates [6-8]. In Africa, oil palm industry is

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developing. Oil palm production waste consists of empty fruit bunch, fibers and shell. The current waste disposal practice includes incineration within the industry or by blacksmith as fuel, which contributes to atmospheric pollution. Using OPSs (oil palm shells) as aggregate in concrete can help resolve the concomitant environmental problems. In addition, a substantial amount of cost can be reduced if the weight of the concrete structure is decreased. Olanipekun et al. [9] have compared the cost of concrete made of coconut shells and palm kernel shells as coarse aggregates. They have found that a cost reduction of 30% and 42% respectively for concrete produced from coconut shells and palm kernel shells is possible.

Many authors have compared the properties of OPS concrete to normal weight concrete [10-12]. For Mannan et al. [13], the mix design of ACI (America Concrete Institute) method for conventional concrete, is not appropriate for OPS lightweight concrete. They have found 13.5 MPa as the 28-day compressive strength although the strength of 28 MPa was planned. Besides, the mix design used, researchers have reported different grades of strength depending on the intrinsic properties of OPS or the curing conditions. For the same mix design (1:1:2) with a water/cement ratio of 0.5, Okpala et al. [13] and Olanipekun et al. [9] have obtained respectively 22.2 MPa and 15 MPa as concrete compressive strength at 28 days. Other studies have shown that OPS can be used to produce concrete up to 20 MPa, with a density of 1,725-2,050 kg/m^3 [14]. Recent researches show that up to 30 MPa concrete is achievable with the use of silica fume and class F fly ash [15]. It is also important to take into account the low value of elastic modulus (E). Only a few references are available on this important property. Teo et al. [16] showed the E-value of 5.31 GPa. Alengaram et al. [15] showed that this E-value of OPS concrete can be enhanced using 5% fly ash and 10% silica fume. Furthermore, the OPS content of Alengaram et al. was higher than that of Teo et al. Mahmud et al. [17] showed an E-values about twice the value reported by Teo et al. (10.90 GPa). All these differences concerning OPS properties or mix design make it difficult to compare all the properties of OPS concrete from an author to another.

A great number of studies about OPS lightweight aggregate concrete particularly for structure have been done. But, little information is available regarding other properties of OPS concrete such as thermal parameters. To examine how the locally available materials in western Africa can be used efficiently, this study concerns the influence of volume replacement of CGA (crushed granite aggregates) with OPS. Considering the same mix design, three mixes are made, by substituting 0%, 50% and 100% of the CGA by OPS aggregate. Then, the physical and mechanical properties of concrete such as dry density, apparent porosity, water absorption, electrical resistivity, thermal conductivity, volume-specific heat, flexural strength, compressive strength and static elastic modulus are investigated. SEM (scanning electron microscopic) analysis was also made.

2. Materials and Methods

2.1 Materials Used

2.1.1 Cement

The cement used was a CEM I-42.5 of the company CIMTOGO which was produced in accordance with standard EN 197-1. The cement had a specific density, a bulk density and a BET surface area that are 3.15 t/m^3, 1.06 t/m^3 and 2.96 m^2/g respectively.

2.1.2 OPS Aggregate

The OPS used, is a by-product from a palm oil industry (SIFCA), based in Ivory Coast. SIFCA (Societe Immobiliere et Financiere de la Cote Africaine) is an industrial group which operates throughout the chain of production of oil palm, from planting to marketing.

To obtain palm oil, the process often consists of 6 stages that are sterilization, threshing, pressing, depericarping, separation of kernel and shell and clarification [18]. Shell is one of the wastes produced during this process. The shells, shown in Fig. 1 are of different shapes and size, depending on the breaking pattern of the nut. The thickness varies and depends on the species of palm tree from which the palm nut is obtained and ranges from 0.15-8 mm [19].

In general, the OPSs were dirty, recovered with oil and other impurities. So, before the OPSs were used, they have been washed and then left under a roof for air drying. After that, they were sieved and only the aggregates with a size smaller than 8 mm have been used. Los Angeles abrasion testing machine has been used to obtain an abrasion value of the aggregate. The particle size distribution of the OPS aggregate can be seen in Fig. 2, whereas its properties are shown in Table 2.

OPSs are primarily organic compounds. Structurally, they are composed of lignin, hemicellulose and cellulose. From Table 2, it stands out that OPSs are 52.3% lignin, with only 25% hemicellulose and 9.1% cellulose. Lignin is difficult to degrade due to its complex structure. Its principle function in plant cell wall, is to provide rigidity and resistance from compression [20]. Therefore, OPSs are suitable as coarse aggregate for structural lightweight concrete.

2.1.3 CGA (Crushed Granite Aggregate)

OPSs were used to substitute granite aggregate obtained locally. The sieve analysis of this crushed granite aggregate has been performed based on NF EN 933-1. Los Angeles abrasion testing machine has been also used to obtain an abrasion value of the aggregates. The particle size distribution is shown in Fig. 2. The physical and mechanical properties of CGA are also shown in Table 2.

2.1.4 Sand

The sand used as fine aggregate, comes from a local river. It has a maximum aggregate size of 5 mm. The particle size distribution of sand shown in Fig. 2, presents a poorly graded sand with a coefficient of uniformity Cu = 3 and a coefficient of curvature Cc = 0.9. A sand equivalent value of 98 indicates that there is less clay-like material in the sand and it is appropriate for a concrete of high quality. The specific density, the bulk density and the fineness modulus of the sand were 2,680 kg/m^3, 1,530kg/m^3 and 2.90, respectively.

2.2 Concrete Mix Proportions and Manufacture

Theories on the mix design of OPS concrete are discussed in Refs. [12, 16, 21]. The mix design of this study is based on that of Teo et al. [22]. Trial mixes have been made to achieve a practical end result. The proportions used for the different concretes are presented in Table 3.

Three mixes were manufactured by replacing 0%, 50% and 100% CGA by OPSs. OPSs have a lower density than CGA. Therefore, the substitution has been

Fig. 1 Sample of OPS aggregate.

Table 1 Carbohydrates composition of OPS.

Parameter	Value
Hemicellulose (%)	25.0
Cellulose (%)	9.1
Lignin (%)	52.3

Table 2 Physical and mechanical properties of CGA and OPS aggregates.

Properties	OPS	CGA
Maximum size (mm)	8	8
Bulk density (kg/m^3)	560	1,510
Specific density (kg/m^3)	1,340	2,660
Los Angeles abrasion value (%)	13	42
Water absorption (24 h) (%)	23.3	0.7

Table 3 Concrete mix proportions (kg/m^3).

	Cement	Sand	CGA	OPS	Water	Sp
0%	550	913	655	0	220	4
50%	550	913	330	165	220	5.5
100%	550	913	0	330	220	7.15

performed in volume. A water/cement ratio of 0.4 has been considered. To allow the concrete to be manufactured with this low effective water/cement ratio, an Sp (superplasticizer) additive was added to the mixing. With the objective of maintaining a similar consistency of concrete (slump of 0-20 mm), the amount of Sp was modified for each mix.

For each mixture, coarse aggregate was introduced first with the sand and mixed for 2 min. Then, the cement is added, and they were all mixed for 2 more min. Later, the water with the Sp were added and mixed for 4 min. The concrete mixed is placed in moulds and vibrated. After 24 h, the samples were taken off the moulds and put into a water tank for curing.

2.3 Experimental Tests

2.3.1 Dry Density and Apparent Porosity Test

Dry density and apparent porosity of concrete were measured using the gravimetric method (ISO 5017). The sample is saturated with water. The saturated sample is first weighed suspended under a scale and immersed in water (M_w). Second, it is weighed in air (M_o). After that the sample is left to dry in an oven then weighed dry (M_d). The various weights read, and Eqs. (1) and (2) allow the dry density and apparent porosity to be found.

$$\rho_d = M_d * \rho_w/(M_o - M_w) \quad (1)$$

$$\varepsilon = M_d * \rho_w/(M_o - M_w) \quad (2)$$

where, ρ_d is the apparent density of the concrete sample; ρ_w is the density of water; and ε is the apparent porosity of the concrete sample.

2.3.2 Bulk Resistivity Test

The bulk resistivity along the longitudinal axis of 40 × 60 mm^2 cylinders has been measured. This test was conducted using the testing procedure described by Spragg et al. [23]. A set of plate electrodes is placed at the ends of a cylindrical specimen and a potential difference is applied to the cylindrical specimen, thereby producing a current flow through the cylinder (Fig. 2). The potential difference and resulting current can be used to obtain the electrical resistance through the cylinder [23]. Then, this electrical resistance can be related to the resistivity using the approach shown in Eq. (3):

$$\rho = R \times \frac{S}{L} \quad (3)$$

where, ρ is the specimen resistivity, R is the measured electrical resistance, S and L are respectively the cross-sectional area and the length of the specimen.

2.3.3 Capillary Water Absorption Test

Water absorption test is carried out according to RILEM TC 116-PCD. This test method allows calculating the way that concrete samples can absorb water by capillarity. It measures the mass of water absorbed as a function of time. The method has been applied on 40 mm × 60 mm cylinders, immersed in a water container on a maximum height of 3 mm (Fig. 3). The side faces of every specimen were covered with a self-adhesive aluminium sheet to ensure that the water only flows along one direction and avoid evaporation through the side faces. The mass of water absorbed is determined by successive weighing of the samples.

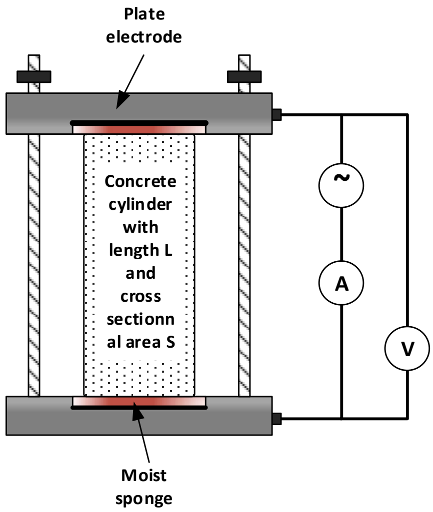


Fig. 2 Determination of electrical resistivity of concrete.

2.3.4 Thermal Conductivity, Specific Capacity and Thermal Diffusivity Test

In this study, Hot Disk TPS 2500 (Fig. 4) was used to measure the thermal conductivity, specific capacity and thermal diffusivity of concrete. The source of heat is an insulated nickel double spiral. This spiral is used for transient heating and precise temperature readings. The probe is placed between the plane surfaces of two dry sample pieces (40 mm × 20 mm cylinders) of the concrete under investigation.

2.3.5 Mechanical Tests of Concretes

Compressive strength was measured on 50 mm × 100 mm cylinders as per NF EN 12390: part 3. The properties were determined at the ages of 7, 14, 28 and 90 days. A hydraulic compression machine with a maximum capacity of 200 KN has been used at a constant speed load (0.25 mm/min).

To obtain the modulus of elasticity and the ductile behavior, 50 mm × 100 mm cylinders were instrumented with three LVDTs (linear voltage displacement transducers). During a compression test, the stresses and strains were recorded and the slope of the secant to the stress-strain curve was determined.

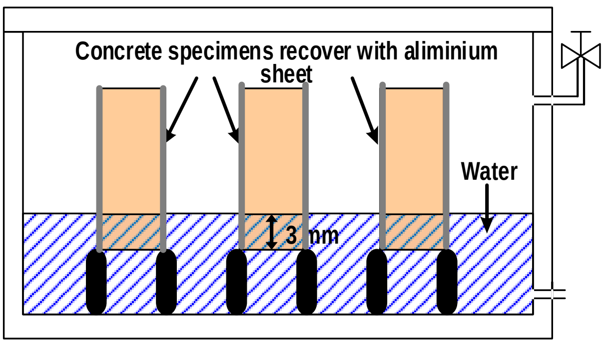


Fig. 3 Water absorption test on cylinder samples.

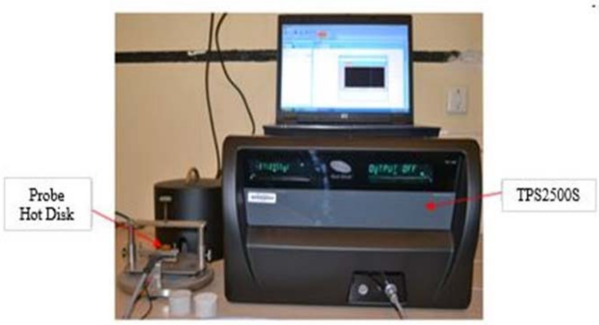


Fig. 4 Hot disk for measuring thermal properties.

The flexural strength was measured on prismatic specimens of 40 × 40 × 160 mm^3 cured 28 days, according to NF EN 12390: part 5.

For each test, the results were an average of three specimens.

3. Results and Discussion

3.1 Physical Properties

3.1.1 Dry Density and Apparent

According to ASTM and ACI, structural lightweight concretes normally have densities less than 2,000 kg/m^3 [14]. At 50% and 100% of granite aggregate substitution, the apparent density of OPS concrete decreased from 2,240 kg/m^3 to 1940 and 1,840 kg/m^3 respectively (Table). Therefore, OPS concretes containing 50% and more OPS aggregate can be used as structural lightweight concrete. The apparent density of OPS concrete decreased as the granite aggregate replacement increased. Indeed, OPS aggregate has a density of 1,340 kg/m^3 and this is approximately 50% lighter compared to the CGA. Consequently, concrete using OPS as aggregate will be more lightweight than CGA concrete.

On the contrary of apparent density, the porosity of OPS concrete increased proportionally compared to the substitution by OPS. Porosity increases from 11% for 0% OPS substitution to 14% for 50% OPS substitution and 17% for 100% OPS substitution (Table 4). This increasing porosity can also explain density decrease. The higher amount of pores in OPS concrete lightens the composite. This higher porosity of OPS concrete is due in part to air content. In fact, the irregular shapes of OPS hinder the full compaction of concrete, and contribute to higher air content. Moreover, as shown by water absorption (Table 2), OPSs are porous materials which may generate air entrapment inside concrete [24].

3.1.2 Electrical Resistivity

In general, the inherent electrical resistivity of

Table 4 Physical properties of hardened concrete.

	0%	50%	100%
Apparent density (kg/m^3)	2,240 (±8)	1,940 (±11)	1,840 (±6)
Apparent porosity (%)	11 (±0.4)	14 (±0.4)	17 (±0.2)
Water absorption capacity (%)	4.8 (±0.2)	7.2 (±0.1)	9.0 (±0.1)
Electrical resistivity (Ω.m)	97.18 (±5)	103.68 (±7)	106.33 (±6)

concrete is also affected by the porosity of concrete and the connectivity of its pores. The concrete pore water is an electrolytic solutions containing different ions (K^+, Na^+, Ca^{2+}…) [25]. Thus, in that test, made in saturated conditions, electrical resistivity should have decreased with the increase of concrete porosity. Table 4 shows that electrical resistivity does not vary significantly with OPS content even if concretes containing OPS have a higher porosity. An explanation is that, there is equilibrium between the high electrical resistance capacity of OPS and the low electrolytic resistance of the pore water. Concrete resistivity can be used to verify the quality of concrete. This parameter shows the facility with which aggressive agents can penetrate into the concrete, directly linked to the corrosion of reinforcement for example so to the durability of such structures [26]. The electrical resistivity ranges corresponding to corrosion as reported in literature indicate that concrete with resistivity values between 100-200 Ω·m is less susceptible to corrosion [27]. The resistivity values of this study are found to be in this range.

3.1.3 Capillary Water Absorption

A water absorption capacity was calculated as a percentage of dry mass (Table 4). The water absorptions of 50% and 100% OPS concrete were 7.2% and 9.0% respectively while that of 0% concrete was only 4.8%. The results were a quite less than that of Teo et al. [28]. The water absorption they have obtained, varies from 10.64% to 11.23% depending on the curing method. For Neville water absorption cannot be used to measure the quality of concrete, but the best concretes have an absorption lower than 10% [29]. Other authors have reported a water absorption value of 3-6% for expanded polystyrene aggregates concrete [30] and 14-22% for pumice aggregate concrete [31]. It seems that water absorption is not directly governed by the type of lightweight aggregates used. Actually, the absorption characteristics indirectly represent the capillary porosity [32]. Porosity of OPS concrete increases with OPS content, therefore water absorption also increases with OPS content.

But, water absorption depends not only on the total porosity but mainly on the pore structure: intercomunicability, distribution, diameter [33]. In this case, the higher water absorption could be due to the pores in the bulk paste a weak interface between aggregate and cement paste.

The kinetics of absorption is presented by the variations of quantity of water absorbed by unit area according to the square root of time. Fig. 5 shows the absorption kinetics of the concrete tested. The first part of the curves, between 0 and 1 h indicates the filling of the biggest pores of the samples. It is noted that this initial absorption is even stronger when concrete contained OPS aggregate. The second part of the absorption curve (located after one hour) reflected the filling of the finest capillaries. We can see in this portion that the slope increases, with the content of OPS aggregate. This confirms that concrete made with OPS generally has a structure of more porous.

3.1.4 Thermal Properties

Thermal conductivity of concrete is a parameter that gives the capability of concrete to transfer heat. It

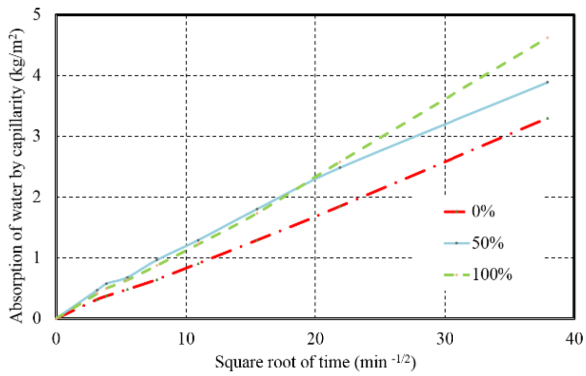


Fig. 5 Kinetics of absorption of concrete samples.

allows determining the temperature field in concrete. The results reported in Table 5 show that using OPS aggregate has reduced the thermal conductivity. Previous studies reveal that water/cement ratio, type and volume fraction aggregate, admixtures, moisture content and temperature have significant influences on thermal conductivity of concrete [34]. In fact, these factors all changed the porosity of concrete and thereby influenced its thermal conductivity. Replacing normal aggregate with OPS increases the overall porosity of concrete which affects the conductivity. Enclosed pores due to the low thermal conductivity of air (0.024 W/mK) reduce the conductivity of the composites. The reduction in thermal conductivity of composite is also due to the insulating effect of OPS aggregate, which had a low thermal conductivity. In reality, Okpala et al. [13] have reported the thermal conductivity of OPS to be 0.19 $Wm^{-1}\cdot C^{-1}$, which is much lower than the value 1.4 $Wm^{-1}\cdot C^{-1}$ of stone aggregate.

The specific heat is the property that measures the capacity with which concrete can bear temperature changes. Table 5 presents the effect of OPS content on volume-specific heat. The results indicate that volume-specific heat increases when OPS is added to concrete. However, 50% OPS concrete has specific heat of 2.95 MJ/m^3K which is higher than that of 100% OPS concrete. The volume-specific heat of a concrete is greatly influenced by the moisture content, in which density and the types of aggregate were used. OPS aggregates have a high thermal insulating performance, but the decreasing weight and increasing porosity of concrete due to OPS content reduce the heat capacity of the composite. Both, the thermal insulating performance of OPS and the higher porosity of 100% OPS concretes can explain the observed decreased volumetric heat capacity value of 100% OPS concrete.

Thermal diffusivity is a measure of the time rate of temperature change as heat passes through a material. The results show that concrete containing OPS (50% and 100%) have a low thermal concrete than a concrete without OPS. It means that OPS concrete will achieve thermal equilibrium slower than the CGA concrete.

3.2 Compressive Strength and Ductile Behaviour

The evolution of the compressive strength of concrete in time is presented in Fig. 6. The curves show that the compressive is strength of concrete containing OPS aggregate still developing with curing age. A biological decay of OPS in time would have probably made the concrete less resistant. Therefore, we can conclude that even after 90 days and despite their organic nature, OPSs do not deteriorate inside concrete. The high lignin content of OPS makes it rigid and protects it from degradation giving them a resistance to decay [35]. Other authors have found the same result even after 6 months or one year for coconut shell [36].

When substituting CGA with OPS aggregate, the compressive strength of concrete remained under that of 0% substitution. The compressive strength of OPS concrete was 26% and 48% lower than that of normal concrete, respectively for 50% and 100% replacement

Table 5 Thermal properties of hardened concrete.

	0%	50%	100%
Thermal conductivity (W/mK)	2.13 (±0.04)	1.92 (±0.01)	1.54 (±0.004)
Specific heat (MJ/m^3K)	1.89 (±0.16)	2.95 (±0.1)	2.35 (±0.007)
Thermal diffusivity (mm^2/s)	1.13 (±0.08)	0.65 (±0.03)	0.66 (±0.003)

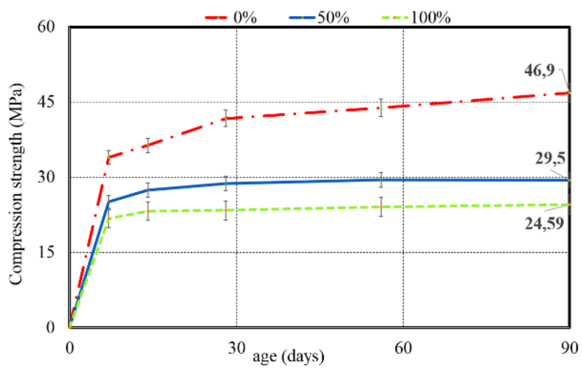


Fig. 6 Development of the strength of concrete tested.

of CGA. With different mixes design, Olanipekun et al. [9] and Osei et al. [37] have also found that the compressive strength of the concrete decreased as the percentage of OPS substitution increased.

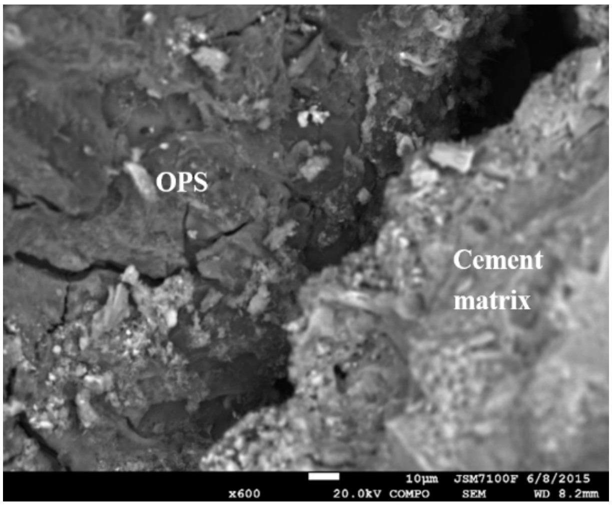
In general, the lower the density is, the lower is the strength [38, 39]. We have previously found that OPS concrete was lighter than the granite aggregates one. However, the loss of compressive strength is not only due to the loss of density. Porosity may also impact concrete compressive strength. The physical properties reported that OPS concrete has higher porosity than the CGA concrete. Moreover, it has been observed that the surface of OPS is smooth. Because of the smoothness of the different faces, a poor bond is created between the OPS and the cement matrix. At last, the mechanical properties are affected badly. In addition, OPS aggregate has the absorption of 23.3% (Table 2) at 24 h. Concrete using aggregate of higher absorption has been found to lead to greater pore area at the interfacial zone [40]. This more porous interfacial zone can also, affect the concrete strength.

An analysis of the bond between concrete and aggregate of the different samples has been performed using an SEM. SEM images (Fig. 7) illustrated a weak bond between the cement matrix and the OPS which do not exist between the matrix and granite aggregate. This implies that the bond between cement and OPS aggregate is determinant for the compression strength of concrete.

Otherwise, it was observed that most of the compressive strength development takes place in the early ages. Approximately 90% of the compressive strength at 28 days of OPS concretes was obtained at only 7 days.

The 28 days compressive strength of specimens, is presented in Table . The compressive strength varies from 23.4-28.8 MPa concrete containing 50% and 100% OPS. According to the specifications for lightweight aggregates concrete [41], the minimum 28 days compressive strength required in structural concrete is 17 MPa. It may be observed that concrete with OPS has the requirement to be used as structural lightweight concrete.

Fig. 8 presents the stress-strain curves for the samples. The strain at peak stress (ε) varies from 2.7 mm/m for CGA concrete to 3 mm/m for 50% OPS concretes and 4.3 mm/m for 100% OPS concretes. The value of the strain ε increases with the rate of substitution by OPS. In the same way, the ultimate strain value of 100% OPS concrete is higher than that of 50% OPS concrete and the granite concrete. The peak stress of CGA concrete is almost equal to the end of its stress-strain curve. It has been noticed that, the specimen broke abruptly when the load is applied up to the end-point. On the contrary, OPS concrete failed progressively. Therefore, using OPS as coarse aggregate



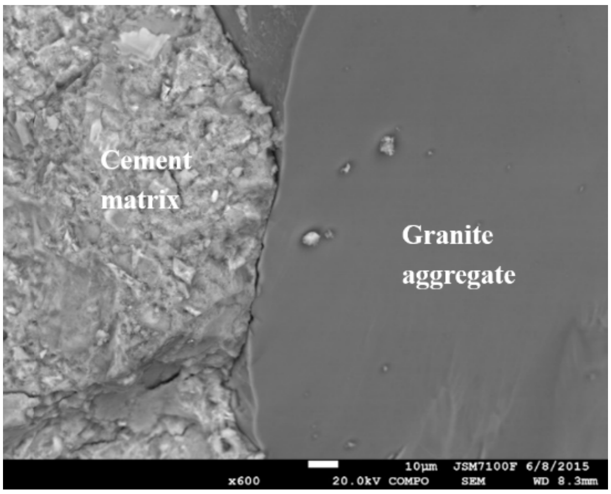


Fig. 7 SEM images showing the bond between OPS/CGA and cement matrix.

Table 6 Mechanical properties of concrete at 28 days.

	0%	50%	100%
Compression strength (MPa)	41.8 (±0.7)	28.8 (±3.1)	23.4 (±1.0)
Flexural strength (MPa)	4.6 (±0.5)	3.6 (±0.5)	2.8 (±0.3)
Elastic modulus (GPa)	26.3 (±2.5)	11.0 (±1.6)	9.7 (±1.0)

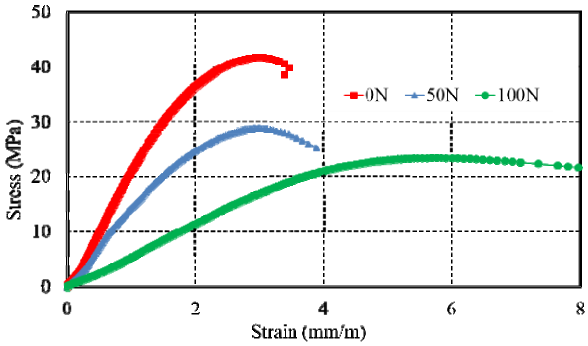


Fig. 8 Stain-stress curves of concretes.

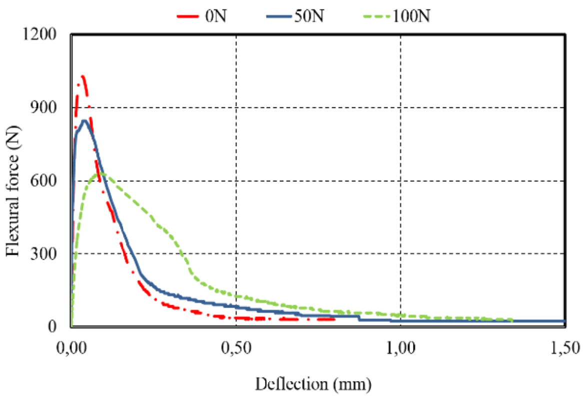


Fig. 9 Flexural force-deflection curves of concretes.

in concrete increases the ductility behavior of concrete.

3.3 Flexural Strength

Flexural strength also decreases with the substitution of OPS (Table). The flexural strength of the OPS concrete at 28-day varies from 2.8 to 3.6 MPa. That was ranging from 11.8% to 12.6% of the 28-day compression strength. The ratio of flexural/compressive strength of OPS concrete is quite above that of CGA concrete, which turns around 11%.

Fig. 9 shows the flexural force-deflection curves for the concrete tested. It has been observed as for the strain-stress curves, that, failure of OPS concrete was gradual. The sample was capable of retaining the load after failure without full disintegration. These results confirm the higher ductility performance of OPS concrete as well as exhibiting high energy absorption capacity under load. Teo et al. [11] obtained similar results. They have concluded that the gradual failure in OPS concrete is due to the good energy absorbing quality of the OPS aggregates. Actually, as indicated by Table 2, OPS aggregate had an aggregate abrasion value (13%) lower than the 42% of granite aggregate. Such gradual failure of concrete was also mentioned for expanded polystyrene lightweight concrete [42] and concrete containing shredded plastic aggregates [43].

Eq. (4) reported by Shafigh et al. [12], gives a relationship between the compressive strength and the flexural strength of moist cured lightweight concrete made using expanded shale and clay aggregates.

$$f_r = 0.46 * \sqrt[3]{{f_{cu}}^2} \quad (4)$$

where, f_r(MPa) is flexural strength and f_{cu}(MPa) is the cube compressive strength.

If the same equation is used without OPS concrete specimens, it overestimates the flexural strength. This shows that, the flexural strength of OPS concrete is lower than the lightweight concrete made with artificial lightweight aggregates.

3.4 Elastic Modulus

Table shows a decrease of the elastic modulus (E) when OPS content is raised. The E value for 100% OPS concrete was 9.7 GPa, 11.0 GPa for 50% OPS concrete and 26.3 GPa for granite aggregate concrete. It corresponds to a loss of 58% and 63% for concrete with 50% and 100% OPS aggregates respectively, when compared to CGA concrete. The results we have obtained are higher than that of other researchers. Mannan and Ganapathy [10] reported a 28-day E of 7.0 GPa for OPS concrete with a cement content of 420 kg/m^3. Later, Teo et al. [22] reported an E-value of 5.3 GPa with a cement content of 510 kg/m^3. This reduction can be caused by the poor bond between the

OPS aggregate and the cement matrix. The poor mechanical properties of the OPS used, did not improve the elastic modulus of the composite. However, this low value of elastic modulus makes the OPS concrete a more deformable material.

Eq. (5) proposed by Alengaram et al. [15], based on CEB/FIP model code formula, predicts a modulus of elasticity close to our experimental results.

$$f_r = 0.46 * \sqrt[3]{f_{cu}{}^2} \qquad (5)$$

where, E is the modulus of elasticity (MPa), f_{cu} is the cube compressive strength and w is the air dry density (kg/m^3). f_{cu} has been converted to a cylindrical compressive strength (f_{bu}) using $f_{bu} = f_{cu}*0.8$.

4. Conclusions

In this work, different properties of OPS concrete with OPS replacement of 0%, 50% and 100% by volume of granite aggregate were studied. The experimental investigations have shown that the porosity of concrete containing OPS increases with the content of OPS. As OPSs are lighter than CGA and because of the porosity induced, the concrete density is less than 2,000 kg/m^3 with the replacement of 50% or more of the aggregate. Even when 100% OPS aggregate is used, OPS concrete density is acceptable for a structural lightweight concrete. On the opposite of what was expected, the electrical resistivity of OPS concrete is enhanced. This predicts a good resistance to chloride diffusion.

The addition of OPS shows positive influence on lowering the thermal conductivity and enhancing the volumetric heat capacity of concrete. Replacing 100% of normal aggregate by OPS lowers thermal conductivity of about 28%. Thus, OPS concrete can be considered as a potential insulator material.

Losses in compressive and flexural strength of OPS concrete have been found. These reductions are partially due to the density of the concrete which becomes lighter when OPSs are used. Otherwise, this research has highlighted a weak bond between the OPS and the concrete, which is responsible for an early failure of the sample. Although, the 28-day compressive strength of all the specimens is greater than 20 MPa, according to ASTM C 330, OPS concrete can be used as structural lightweight concrete.

The results have also showed that the ductility behavior of concrete is improved with the use of OPS. Under compression load, OPS concretes do not fail abruptly after the curve pic, in the contrary of CGA concrete.

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