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THE FLEXURAL BEHAVIOR OF SUSTAINABLE LIGHTWEIGHT CONCRETE HOLLOW CORE SLABS

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Hollow slabs are reinforced concrete slabs with voids that enable less concrete to be used. To promote sustainability goals, this type of slab reduces material use and enhances insulating characteristics. This paper presents an experimental program for studying the flexural behavior of the sustainable hollow Slab elements of lightweight concrete with three different ratios of mixes using additives to choose the best ratio, which is then compared to a solid model with the same concrete mix with the best characteristics to clarify the variations in the structural behavior of voided slabs. In this investigation, hollow slabs with circular plastic tubes of 50mm diameter and 1020 mm length were used, organized as continuous voids with 30 mm spacing between the tubes. Three slabs were created, each measuring 1020 mm long, 420 mm wide, and 100 mm thick. All three slabs were tested via four-point loading. The best mix ratio was chosen and used to build a robust model. To analyse the key advantages of this technology over typical solid slabs, this solid model was compared to the best-performing model among the three hollow core slabs. Several properties such as load-carrying capability, deflection, crack patterns, and failure modes were observed in all loading steps. The results showed that using uniformly distributed uniaxial voids in the slab reduced concrete use by 23% as compared to solid slabs, Notably, the specimen with 200 kg/m^3 lightweight aggregate demonstrated greater crack distribution and crack breadth.

Keywords: lightweight concrete, voided slab, porcelanite, sustainability, hollow core slab

1 INTRODUCTION

Reinforced concrete slab is a very important structural component in buildings which is the largest element consuming concrete. In a general way, the slab is designed only to resist the vertical load. Moreover, when the building span increases, the slab increases and that leads to increasing column and foundation size which decreases the value of deflection. Thus, it makes buildings consume more materials such as concrete and steel rebars and this will lead to increasing costs [1]. Building energy consumption is increasing due to global warming and the activities of humans. The consumption is commonly because of thermal comfort due to the electrical requirements of heating and cooling [2]. Research in Mediterranean regions has shown that the energy invested in the thermal comfort of buildings amounts to about 47.8% of the entire annual energy expended in Spanish homes [3]. In Europe, approximately 30% of all energy is used to provide thermal comfort. As well, the electrical requirements of heating and cooling for residences account for about 50-70% of the energy used in America [4]. On average, around 25-40% of the total energy consumption is used for buildings which is commonly due to the requirements of heating or cooling [5]. According to Gervásio [6], the best way to achieve energy sustainability in buildings is through reducing material consumption and energy efficiency.

Therefore, optimizing the use of energy such as heating and cooling during the service life of the building is performed through the introduction of insulating material in the building. This has led to renewed attention to the conservation of energy and building components efficiency such as the precast concrete Hollow Core Slab (HCS) system which uses insulation as a thermal barrier. Not all interior concrete can be substituted, the concrete of the slab in the upper area is required to form a compressive block for flexural strength, and the concrete of the slab in the tension area needs to be bonded with the reinforcement to make it effective for the flexural strength as presented in fig.1. Besides, the upper and lower faces of the slab must be connected to work as a combined unit and confirm the stress transfer, while maintaining the slab's flexural strength because reducing the weight of the slab would reduce deflection and make larger spans attainable [7].

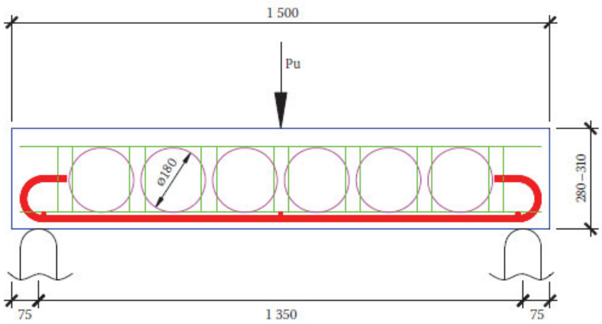

Fig. 1. Experimental setup [7]

The previous studies on the voided slabs were performed with different kinds of concrete. The hollow core slabs are usually made as precast prestressed segments with high tensile reinforcing steel. Mutashar [8] presented ten reactive powder concrete (RPC) samples of one way slab with dimensions of 416 mm wide, 1700 mm long, and 125 or 100 mm thick, under the flexural behaviour using two types of voided slabs: (Hollow Core slab) made of plastic pipes in the longitudinal direction with diameter of 75mm and length of 1500mm with spacing 25mm and (Bubble Deck) made of plastic balls in both directions, having the same diameter and the same spacing of plastic pipes. The factors evaluated were the position and number of steel mesh layers, slab types (hollow core, bubble, and solid slabs), percentage of steel fiber, and slab thickness. It was discovered that when the proportion of steel fibers rose from 1% to 2% in bubble, hollow core, and solid slabs, the deflection decreased by 30%, 20%, and 18.75%, respectively. The deflection was increased by 47% and 41% for hollow core and bubble hollow core slabs compared to solid slab. The slabs reinforced with lower and upper steel meshes exhibit lower deflection than the slabs that were reinforced with only lower steel mesh. The voids that exist in hollow core slabs and bubble slabs reduced the weight of the slabs by 43% and 18% compared to solid slab, as shown in Fig.2.

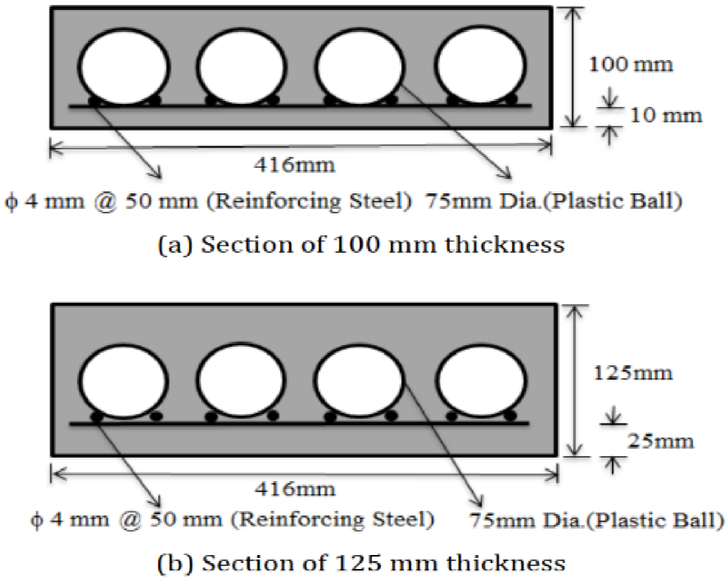

Fig. 2. Front view of reinforced bubbled slab [8]

Mahdi and Ismael [9] Investigated the behaviour of six slab specimens with dimensions of 435 mm × 1700 mm × 125 mm experimentally, one of which was a solid slab, and the others were Hollow-core slab (HCS) made from recycled plastic pipes. These slab specimens were distributed into two groups, the first group contained three HCS specimens having different numbers of voids in the longitudinal direction, and the second one contained three HCS specimens having the same number of voids in the longitudinal direction with different diameters. The test results presented that increasing the longitudinal voids number could provide the ultimate load with 93.47%, 87.63%, and 82.92% respectively, with an increase in the ultimate deflection by 8.72%, 21.57%, and 28.31%. Similarly, increasing the diameter of longitudinal voids can provide the ultimate load with 93.37%, 90.01%, and 87.63% respectively, of the load of the solid one. and increase the ultimate deflection by 6.58%, 13.26%, and 21.57%, respectively, when compared to the solid slab, as shown in Fig.3.

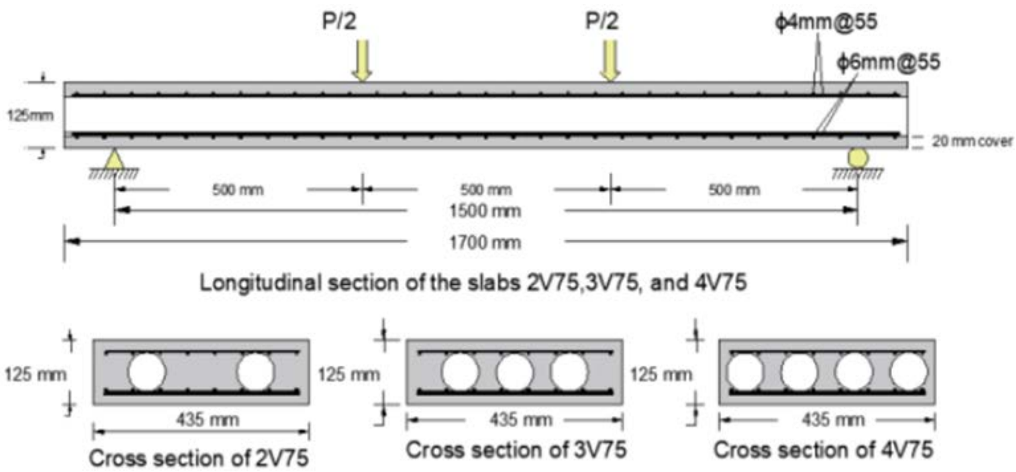

Fig. 3. Details of the HCS slabs in group two [9]

Lightweight concrete (LWC) was used in the second century, was introduced by the Romans, and then gradually developed into widespread use in many countries such as Sweden, the United States of America, and the United Kingdom. It is used to reduce the dead load of concrete and thus helps designers to reduce the size of footing, column, and other load-bearing elements. [10]. LWC produces with density from 300 kg/m^3 to 2000 kg/m^3, compressive strength 1 MPa to 60 MPa, and thermal conductivity from 0.2 W/m K to 1.0 W/m K. Moreover, normal concrete has a density of 2100 kg/m^3 - 2500 kg/m^3, compressive strength of 15 to more than 100 MPa, and 1.6 W/m K to 1.9 W/m K [11].

Currently, LWC is classified according to the type of lightweight aggregate used in its production and its manufacturing method, such that its specific gravity is less than 2.6. The other type is foamed concrete fabricated using bubble voids on the concrete. The last one known as no fine concrete characterized by no fine aggregate in the mixture and coarse aggregate of ordinary weight is used, as shown in Fig.4 [12].

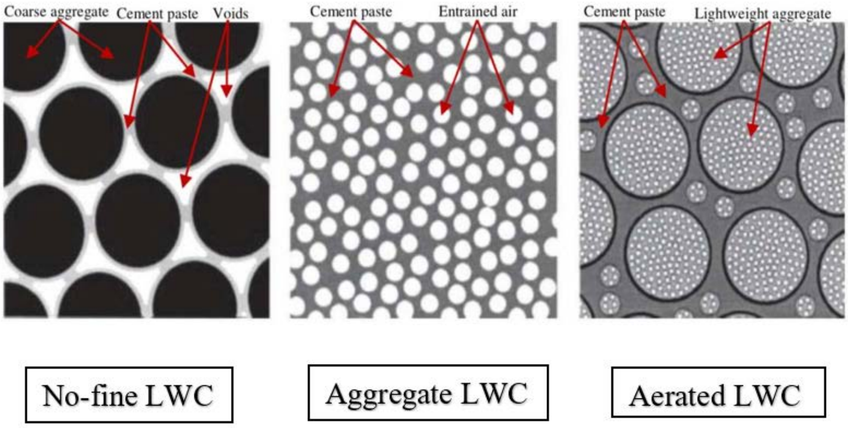

Fig. 4. The basic shapes of LWC [12]

Also, LWC can be categorized according to the utilizing purpose as:

1. Structural LWC has density ranges from 1400 kg / m^3 to 1920 kg / m^3 and compressive strength at the age of 28 days is equal to or larger than 17 MPa [10,14].
2. Masonry concrete has a density between 500 Kg/m^3 - 800 Kg/m^3 and a compressive strength range of 7 MPa -17 MPa [14].
3. Insulating concrete with a density less than 800 kg/m^3 and compressive strength varies between 0.7 MPa to 7 MPa [13,14].

The use of LWC with lightweight aggregate was specified to take advantage of the material by reducing the dead load of a structure, improving fire resistance, better thermal insulation, and easier handling, installation, and transportation so that it is economical [15,16].

The disadvantages of LWC are considerable brittleness, Low compressive, Low flexural strength, Poor fracture toughness, poor resistance to crack propagation, Low impact strength, and the mixing time is longer than traditional concrete [17].

Lightweight aggregate is a synthetic aggregate that can be made from a variety of raw materials. The characteristic of lightweight aggregates differs within wide range [18]. Usually, aggregates make up about 70 to 80% of the Portland cement concrete volume. Because of the great volume fraction, it occupies in concrete, aggregates apply a significant effect on the modulus of elasticity of concrete and can be predicted to have a major effect on another characteristic as well [19].

This research shows the results obtained from the experimental study of LWC hollow core slabs, porcelanite has been used as a lightweight aggregate in concrete mixes. The Effects of porcelanite aggregate (Maximum size 9.5 mm) on LWC properties were examined. For this purpose, three series were prepared for concrete samples. porcelanite aggregate was utilized as a full substitute for natural aggregate at levels of 200, 300, and 400 by volume. The porcelanite aggregate density is lower than that of the natural aggregate; the concrete with porcelanite aggregate becomes an LWC with a density of less than 2000 kg/m^3.

2 RESEARCH SIGNIFICANCE

The main aims of the present work are: to conduct an experimental investigation on the flexural behavior of a sustainable LWC hollow core slab by Using circular plastic pipes and comparing it with the solid slab. The area of the cross-section and the ratio of the steel reinforcement are the same in solid slabs and hollow core slabs. The investigation attempts to find the best HCS by searching the optimized lightweight mix modified where the hollow model was compared with the solid model.

3 EXPERIMENTAL WORK

The experimental program consists of the fabrication of four panels: one solid slab and three Hollow core slabs (with different concrete mixtures but with the same dimensions). The coding of these panels is shown in Fig. 5. The HCS specimens were designed according to (ACI 318-M14 2014) [20]. The clear dimensions of molds are 1020 mm × 420 mm ×100 mm.

The shape and type of specimens are shown in Fig.5. All the specimens (Hollow core slabs) have the same cross-sectional area of the slab and the same reinforcement ratio. The main parameters in this study are the best lightweight mix modified. The dimensions of the slab are 1020 mm long, 420 mm wide, and 100 mm thick. The slab section details are shown in Fig.6. Portland cement, very fine sand, silica fume, Coarse aggregate (porcelanite), and superplasticizer have been used with certain percentages to manufacture the lightweight concrete panels after many trial mixes as shown in Table 1. Porcelanite is a white lightweight natural rock with a density of 1400 Kg/m^3 and a size range of (5-18) mm. The tension test results of steel reinforcement are listed in Table 2. The mechanical properties of hardened LWC (compressive strength of the cube (fcu), compressive strength of the cylinder (fc'), the splitting tensile strength (fct), modulus of rupture (fr), modulus of elasticity (Ec), and the density) for average three specimens according to [21 to 24] are shown in Table 3.

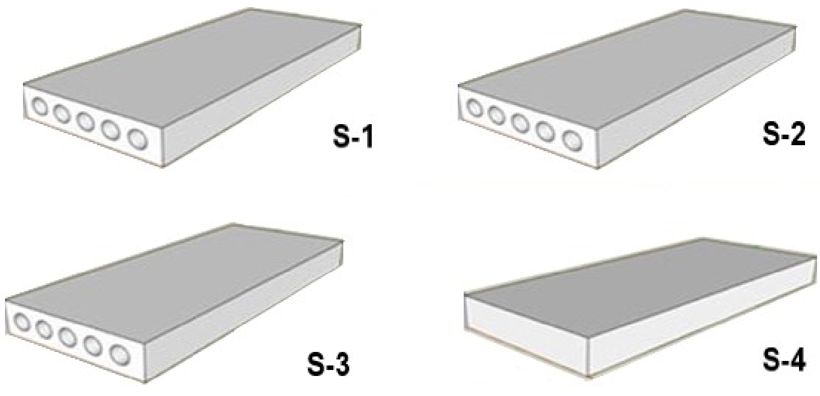

Fig. 5. Shape and type of specimens

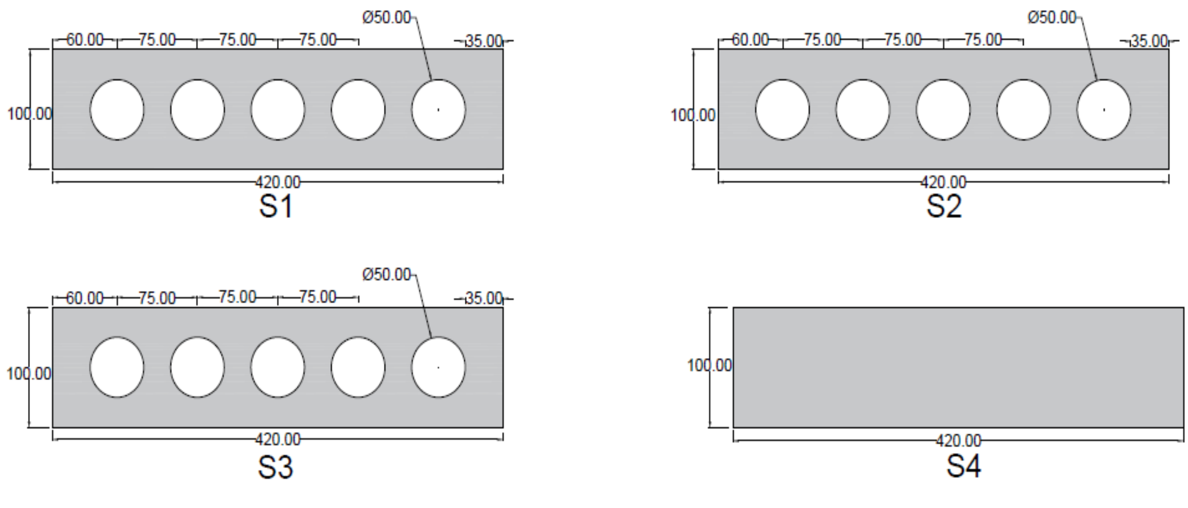

Fig. 6. Details of panel sections (All dimensions in mm)

Table 1. Mixes proportions for one m³

Mix Type	Cement kg/m3	Sand kg/m^3	Coarse Aggregate (Porcelanite) kg/m^3	Silica fume %	w/c	Superplasticizer % of Cementitious Materials
S1	750	750	200	6	0.4	6
S2	750	750	300	6	0.4	6
S3	750	750	400	6	0.4	6

Table 2. Test results of steel reinforcement

Shape	Modulus of Elasticity Es (MPa)	Elongation ΔL %	Yield Stress Fy (MPa)	Ultimate Stress Fu (MPa)	Actual Diameter (mm)	Nominal Diameter (mm)
Smooth	223300	10.9	580	640	5	5

Table 3. Mechanical properties of hardened LWC

Code Mix	f'cu (MPa)	f'c (MPa)	Splitting Tensile strength fsp (MPa)	Modulus of Rupture fr (MPa)	Modulus of Elasticity Ec (GPa)	Density Kg/m^3
S1	54.5	43.7	5.2	7.6	30.7	1885
S2	51.9	41.5	4.8	7.4	30.5	1870
S3	41.6	34.1	3.2	5.9	30	1790

Mesh reinforcement with bars diameter Ø5 mm at spacing 50 mm c/c in each direction is used in the top and bottom layers as shown in Fig.7.

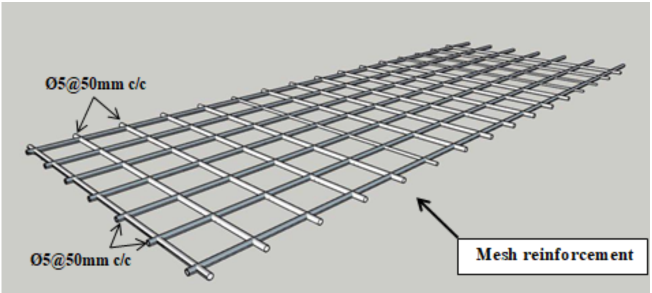

Fig. 7. Steel mesh reinforcement

4 RESULTS AND DISCUSSIONS

The main variables considered are the lightweight mixes (Solid Slab and HCS) and the three series of concrete samples in HCS:

A universal hydraulic machine of 100 kN capacity was used in the test of the slab specimens. The specimens were tested after 28 days under a two-point load as simply supported, which had a 340 mm clear span between the two loads that were held constant for all the slab specimens. The slabs were supported on a steel bar with cross-sectional dimensions of 30 mm × 30 mm and a length of 450 mm. The load was distributed to the two load points using two steel bars with the same dimensions of support bars located on the upper surface of the slab at the two loads. All the tests were performed under step loading 5 kN for all slab specimens. Fig.8 displays the Preparation of the testing slab, diel gage, and universal hydraulic machine.

Fig. 8. Preparation of testing slab, diel gage, and universal hydraulic machine

The experimental work observed the cracking and ultimate load for each slab. The test results are documented, and given in Table 4. Load versus deflection is recorded at the mid-span. The first crack of all slab specimens happened at mid-span and gradually increased when the load increased. At the initial loading stage, the first cracks appear in the lower part of the middle span in the tension zone. These cracks widen and go up and other cracks develop in a similar area when the load increases. The extra loading made the cracks expand and spread faster. At ultimate load capacity, the cracks extend to the compression zone until a failure happens. While the other cracks were spread to the left and right of the first crack. The ultimate crack happens in the bottom face along the specimen's width. When the load is increased, the displacement of the slab also starts to increase until it reaches the highest value at the ultimate load. The flexural failure modes in the slabs are shown in Fig.9.

Fig. 9. Failure of solid and hollow slabs (S1, S2, S3, and S4)

Table 4. Cracking and ultimate load and deflection results.

Slab Coding	Concrete Mix Code	First Cracking Load (P_{cr}) kN	Deflection at Cracking Load(Δ_{cr}) mm	Ultimate Load (Pu) kN	% of Difference in Ultimate Load	Deflection at Ultimate Load(Δ_u) mm
S-1	S1	16.5	13	54	0	30
S-2	S2	16	14	52.5	- 11 %	31
S-3	S3	12.5	16	46	- 25 %	36
S-4	S2	18	12	62.5	+ 16 %	27

4.1 Load-deflection relationship

The deflection was measured at the bottom surface in the mid-span of the slab using a 0.01mm dial gauge for each load increment.

4.1.1 Effect of lightweight mix proportion on the slabs' loading and deflection

The results show that ultimate load capacity decreased by 11% and 25% for slabs S-2 and S-3 respectively, when compared to slab S-1, while the deflection increased for slabs S-2 and S-3 by 10.5% and 31.5% respectively as shown in Figs.10 and 11. S-1 has the lowest value of deflection compared to the other two HCSs, which has a reduced weight of 23% lower than the solid slab because there are no voids in the solid slab that would increase the stiffness and impact of the first cracking and ultimate load with increasing in the stage of load. This increase in ultimate capacity is because of the increase in the stiffness of the section. Fig.10 shows the load-deflection Relationship for the Hollow core and normal slabs.

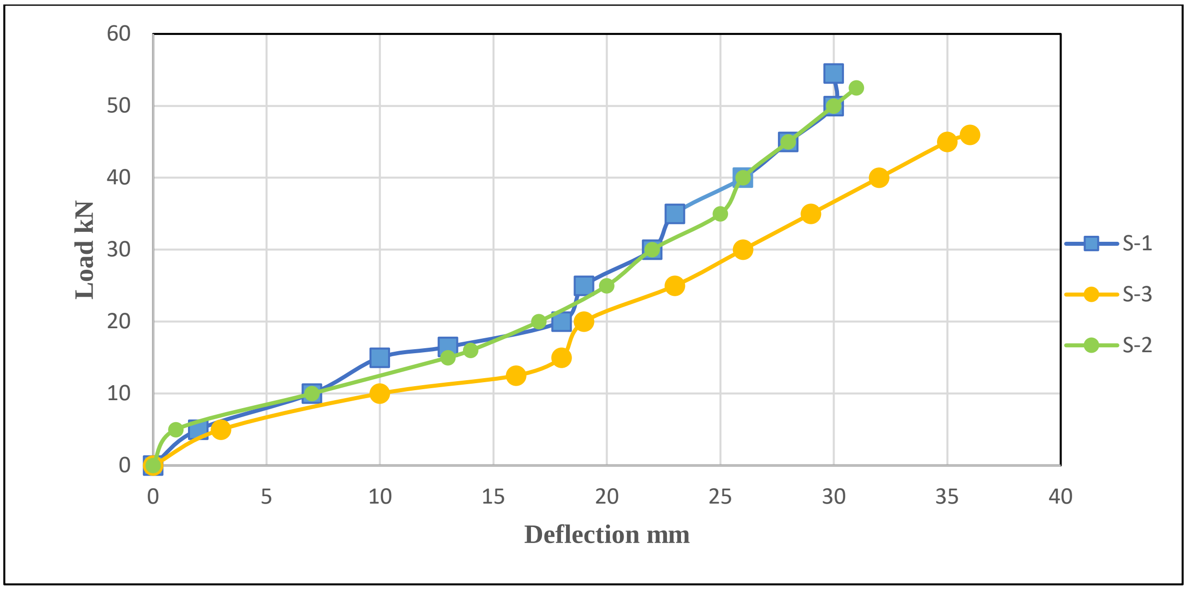

Fig. 10. Effect of mix type on load-deflection relationship of HCSs

4.1.2 Effect of mix type on HCSs

Although the circular type of holes has the advantage of distributing stresses around the holes and increasing the stress resistance compared to other holes, it is less than samples that do not contain holes due to the stresses being concentrated in the Circumference of these holes. The influence of the voids type (circular) for slab S-1 led to a decrease in the ultimate load capacity of the slab S-1 by 16% and an increase in the deflection by 11.1%compared to the slab S-4 at the same loading stage as shown in Fig.11.

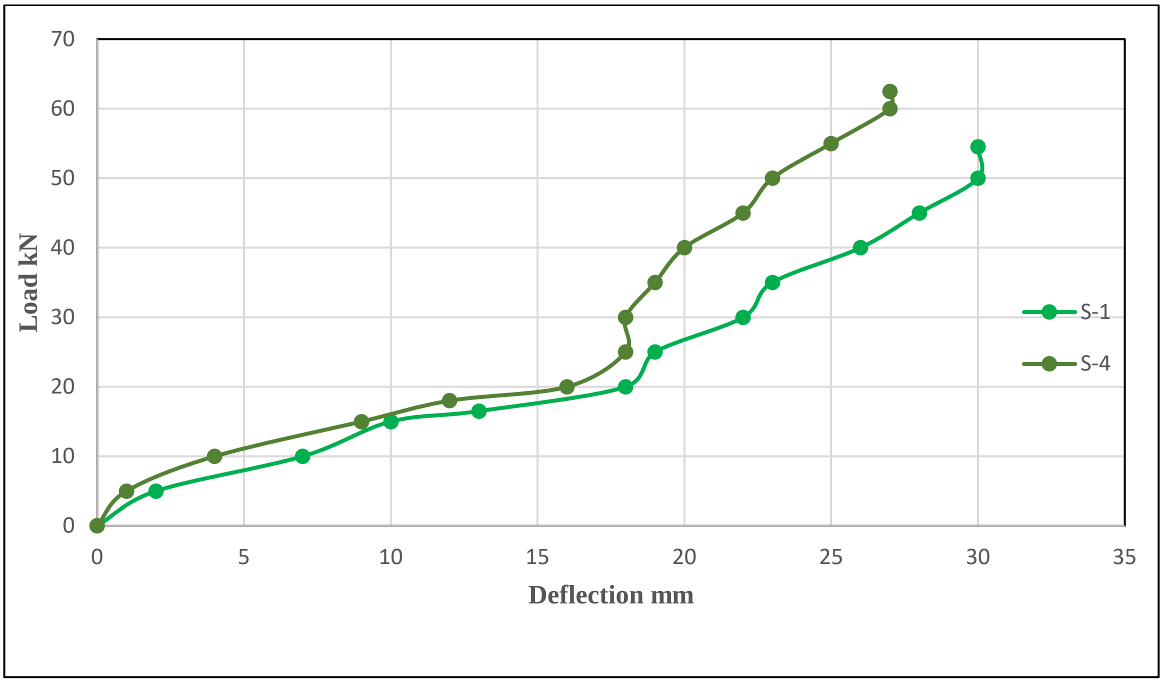

Fig. 11. Effect of the slab type on the load mid-span deflection

5 CONCLUSIONS

Based on the results obtained from the experimental work, the following main conclusions are presented:

- The experimental study showed that hollow core slabs lead to a decrease in the flexural bearing and used concrete volume compared to the traditional concrete slabs of the same section.
- The study indicated that these kinds of slabs meet the sustainability requirements.
- By preparing the concrete mix using different amounts of lightweight aggregate, it was found that the mix with a total content of 200 kg/m^3 of porcelainte is the best in terms of workability.
- The use of the lightweight mix with porcelainte aggregate 400 kg/m^3 was superior in terms of lower dead load, but the bearing capacity was significantly less than its predecessor, in addition to the shape and

distribution of the cracks that appeared, indicating that the mixture with the content of aggregate 300 kg/m^3 is better in terms of the homogeneous distribution of cracks and the width of cracking.

– By comparing the results of the S-1 model with the traditional model S-4 which was prepared with the same components of the S-1 mixture, it was found that the load bearing capacity of S-1 is slightly less than the traditional model, but despite that, the model S-1 has a significant decrease in the dead load, which is a very important factor and a main goal we seek it through the use of this kind of slab.

6 REFERENCES

[1] Chung, J.H., Choi, H.K., Lee, S.C. and Choi, C.S. Flexural capacities of two-way hollow slab with donut type void. Proceeding of annual conference of the architectural institute of Korea, 2018; 9-20.

[2] Ryan, E.M.; Sanquist T.F. Validation of building energy modelling tools under idealized and realistic conditions, Energy Buildings, 2011;47, 375-382.

[3] Domínguez, S.; Sendra J.; León A.; Esquivias P. Towards energy demand reduction in social housing buildings: Envelope system optimization strategies. Energies, 2012; 5 (7): 2263-2287.

[4] Al-Homoud, M.S. Performance characteristics and practical applications of common building thermal insulation materials. Building and environment, 2005; 40(3), 353-366.

[5] Robinson, A.; Lesage F.; Reilly A.; Mc Granaghan G.; Byrne G.; O'Hegarty R.; Kinnane O. A new transient method for determining thermal properties of wall sections, Energy Buildings, 2017; 142, 139- 146.

[6] Gervásio, H.; Santos P.; da Silva L.S.; Lopes A. Influence of thermal insulation on the energy balance for cold-formed buildings. Advanced steel construction, 2010; 6(2), 742-766

[7] Marais, C., Design adjustment factors and the economical applications of concrete flat-slabs with internal spherical voids in south africa, M.Sc. Thesis, University of Pretoria, August 2009.

[8] Mutashar, S. H., Flexural behaviour of sustainable reactive powder concrete voided slabs, M.Sc. Thesis, Mustansiriayah University, May 2017.

[9] Mahdi A. A. and Ismael, M.A., Structural behaviour of hollow core reinforced self-compacting concrete one way slabs, Conference Series: Materials Science and Engineering (iopscience.iop.org), 2020.

[10] ACI 213R-87, Guide for structural lightweight aggregate concrete, Detroit, Michigan, 1999.

[11] Newman, J., Choo, B. S. and Owens, P., Advanced concrete technology processes, Elsevier Ltd., 2003.

[12] Junaid, M. F., Rehman, Z. ur, Kuruc, M., Medveď, I., Bačinskas, D., Čurpek, J., Čekon, M., Ijaz, N., & Ansari, W. S. (2022). Lightweight concrete from a perspective of sustainable reuse of waste byproducts. Construction and Building Materials, 319(September 2021). https://doi.org/10.1016/j.conbuildmat.2021.126061

[13] Neville, A.M. and Brooks, J.J., Concrete technology, second edition, Prentice Hall, Pearson Education, 2010.

[14] Junaid, M. F., Rehman, Z. ur, Kuruc, M., Medveď, I., Bačinskas, D., Čurpek, J., Čekon, M., Ijaz, N., & Ansari, W. S. (2022). Lightweight concrete from a perspective of sustainable reuse of waste byproducts. Construction and Building Materials, 319(November 2021). https://doi.org/10.1016/j.conbuildmat.2021.126061.

[15] Adhikary, S. K., & Rudzionis, Z. (2020). Influence of expanded glass aggregate size, aerogel and binding materials volume on the properties of lightweight concrete. Materials Today: Proceedings, 32, 712–718. https://doi.org/10.1016/j.matpr.2020.03.323

[16] Abdulhussein, S., & Alfeehan, A. (2021). MECHANICAL PROPERTIES OF STRUCTURAL AERATED LIGHTWEIGHT CONCRETE REINFORCED WITH IRON LATHING WASTE. Journal of Engineering and Sustainable Development, 25. https://doi.org/10.1061/jsdeag.0003070.

[17] Zamzani, N. M., Mydin, A. O., & Abdul Ghani, A. N. (2018). Experimental investigation on engineering properties of lightweight foamed concrete (LFC) with coconut fiber addition. MATEC Web of Conferences, 250, 1–8. https://doi.org/10.1051/matecconf/201825005005

[18] Thakur, A., & Kumar, S. (2022). Mechanical properties and development of light weight concrete by using autoclaved aerated concrete (AAC) with aluminum powder. Materials Today: Proceedings, 56, 3734–3739. https://doi.org/10.1016/j.matpr.2021.12.508.

[19] A. Khan, M. Baluch, and A. Al-Gadhib, Repair and strengthening of reinforced concrete structures using CFRP plates, in Proceedings of international Bhurban conference on applied sciences and technology, 2004; 26 (2), Pakistan.

[20] ACI 318-14, Building code requirements for structural concrete, in American concrete institute, 2014.

[21] BS 1881-Part 116-2000, Method for determination of compressive strength of concrete cubes, British standards institute BSI, London, 2000.

[22] ASTM C496-04 "Standard test method for splitting tensile strength of cylindrical concrete specimens, Annual book of american society for testing and material standards, Concrete and aggregate, West Conshohocken, PA, United States, 4 (2), 2004.

[23] ASTM C78, Standard test method for flexural strength of concrete using simple beam with two points loading, Annual Book of ASTM standard, 4 (2), 2002.

[24] ASTM C469, Standard test method for static modulus of elasticity and poisson's ratio of concrete in compression, 2002 of wall sections, Energy Buildings, 2017; 142, 139- 146.

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