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Properties of High Performance Lightweight Concrete Sandwich Panels Using Local Additives

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Abstract

The main aim of this investigation is to produce high performance lightweight concrete sandwich panels consisting of two layers of mortar having different mesh reinforcement and feeded polystyrene concrete core in between. Locally pozzolanic material (ultra – fine feldspar) is used to produce the high performance mortar as partial replacement of cement. The effect of various factors such as core thickness, volume fraction and type of reinforcement (polyimide grids, polypropylene meshes and chicken wire meshes) has been investigated. The work covers the physical properties of the mortar and polystyrene concrete core. Also the structural properties and behaviour of eight series of 1000mm length and 200mm width concrete sandwich panels with two reinforced mortar faces of 20 mm in thickness and core of 30 and 50mm in thickness from polystyrene concrete were investigated by nondestructive and destructive methods.

The nondestructive tests included the density and dynamic modulus for mortar and polystyrene concrete. Also the density and dynamic properties of the concrete sandwich panels as a whole (dynamic modulus of elasticity, Poisson's ratio and stiffness constant) were determined by ultrasonic pulse velocity. Flexural properties such as, first crack and ultimate loads, moment capacity, modulus of rupture, resilience, ductility and toughness of the concrete sandwich panels were investigated from the destructive tests .

The results show that the ultimate moment increases as the core thickness and the volume fraction of different types of reinforcement increase and the modulus of rupture increases as volume fraction of reinforcement increase. Also it was shown that concrete sandwich panels with high toughness and ductility can be obtained by using polyimide grids or polypropylene meshes to reinforce the compression and tension faces of the panels.

خواص البلاطات الخرسانية المركبة عالية الأداء وخفيفة الوزن بأستخدام مضافات محلية

الخلاصة:

الغرض الاساسي من هذا البحث انتاج بلاطات خرسانية مركبة عالية الأداء وخفيفة الوزن تتكون من طبقتين من المونة مسلحة بأنواع مختلفة من مشبكات التسليح ومغذاة بطبقة لباب من خرسانة البولي ستايرين بينهما. تم استعمال مادة بوزولانية محلية (غبار الفلدسبار فائق النعومة) كبديل جزئي للأسمنت لغرض الحصول على مونة عالية الأداء. تمت دراسة تأثير متغيرات متعددة مثل سمك اللباب الوسطي والنسبة الحجمية ونوع التسليح (مشبكات البولي مايد, مشبكات البولي بروبلين ومشبكات الأسلاك الفولاذية (اسلاك قفص الدجاج)).

الدراسة تشمل الخواص الفيزيائية للمونة وخرسانة البولي ستايرين للباب.كذلك تمت دراسة الخواص الأنشائية والتصرف ألأنشائي لثمان مجاميع من البلاطات الخرسانية المركبة بطول ١٠٠٠مم وعرض٢٠٠ مم ذات طبقتين من المونة المسلحة بسمك ٢٠ مم وطبقة لباب وسطية من خرسانة البولي ستايرين بسمك ٣٠ مم و٥٠ مم بأستخدام طرق فحص أتلافية ولااتلافية.

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شملت الفحوصات اللا تلافية فحص الكثافة ومعامل المرونة الديناميكي للمونة وخرسانة البولي ستايرين. كذلك تم أيجاد الكثافة والخواص الديناميكية للبلاطات الخرسانية المركبة (معامل المرونة ونسبة بواسون الديناميكيان وثابت الجساءة) بأستخدام طرق قياس سرعة الذبذبات فوق الصوتية. تم ايجاد الخواص الأنشائية للبلاطات المركبة التي شملت حمل الشق الأول, الحمل الأقصى, قابلية العزم القصوى, معاير الكسر, الأرتدادية, المطيلية والصلابة من الفحوصات الأتلافية.
أظهرت النتائج ان العزم الأقصى يزداد بزيادة سمك طبقة اللباب والنسبة الحجمية لأنواع التسليح المستعملة كذلك فأن معاير الكسريزداد بزيادة النسبة الحجمية لأنواع التسليح المستخدمة. وتشير النتائج ايضا الى انه يمكن الحصول على بلاطات خرسانية مركبة ذات مطيلية وصلابة عالية بأستخدام مشبكات البولي مايد والبولي بروبلين لتسليح طبقتي الشد والأنضغاط لهذه البلاطات.

1-Introduction

Sandwich panels are extensively used in roofing. They offer a number of desirable properties such as good thermal insulation, enhanced sound absorption, and reduced dead load. The simple structural idealization of sandwich system is that the core provides shear transfer between the faces which provide flexural and compression resistance [1].

Previous studies [2,3] indicate that the polypropylene fibres as a mesh provide a continuous reinforcing network in a mortar matrix, so it offers relatively high strength. A relatively high volume fraction of reinforcement (up to 7%) is used and the bond is substantially improved mechanically because continuous mesh is used instead of discrete fibres. In general polypropylene fibres are considered to be an effective material for improving the shrinkage cracking characteristics, toughness and impact resistance of cement pastes, mortars and concrete.

Very little work has been done to investigate the behaviour of ferrocement sandwich panels[1,4], and no detailed studies are found on the behaviour of concrete sandwich panels with faces of high strength cement – sand mortar reinforced with polypropylene meshes or polyimide grids and core of polystyrene concrete. This investigation is suggested to study the properties of this type of sandwich panels, and to try to improve their properties by using local and low cost materials.

2. Experimental Work

2-1 Materials

2-1-1 Cement

Ordinary Portland cement was used. It conforms to the provisions of Iraqi specification No.5-1985.

2-1-2 Fine Aggregate

Natural sand of maximum size 4.76mm was used. It was brought from Al-Ukhaider region and its gradation lies in zone 4. The grading test results conform to Iraqi specification No.45-1984.

2-1-3 Feldspar

Feldspar taken from Bahar Al-Najaf was used throughout this work, it was grounded by pulverizing by air plast, and then it was grounded using "Porcelain Ball Mill" for 20 hours. The specific surface area of feldspar powder (FP) was 12200cm^2/gm which was found by Blain method according to ASTM C-204. The specific gravity of feldspar powder was 2.733 determined according to ASTM C-188 and the pozzolanic activity index was 98.9% determined according to ASTM C-311.

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The chemical and mineralogical analysis by using X-ray diffraction showed that feldspar is mainly consists of high percentage of potassium feldspar ($KALSiO_3O_8$) and silica (SiO_2) as shown in Table (1) and Fig.(1).

2-1-4 Superplasticizer

A high range water reducing (HRW) admixture (superplasticizer) was used. Chemically it is Naphthalene formaldehyde sulphonate, and it is known commercially as Sikament N-N. It was used in its liquid state as a percentage of cement content (by weight).

2-1-5 Expanded Polystyrene Beads

The sieve analysis of the expanded polystyrene beads used in this work is given in Table (2).

2-1-6 Reinforcement

Three locally available types of reinforcement were used in this investigation: Polyimide grids (GP) with 3×3 mm size of opening, Polypropylene meshes (PL) with 5×5 mm size of opening and galvanized hexagonal chicken wire mesh (H) with an average wire diameter of 0.72mm.

2-2 Mixes and Mixing

Several trial mixes were carried out in previous work in order to obtain a high performance mortar. The mix proportion of the mortar used to produce the faces of sandwich panels was 1:1 cement: sand by weight with 17% of feldspar powder as a partial replacement of cement by weight, water – cement ratio 0.249 and superplasticizer dosage 4% by weight of cement with 28 days compressive strength of 79.5 N/mm^2.

Mixing of cement – feldspar mortars was carried out according to ASTM C-305. Before mixing, the required amount of feldspar powder (FP) was added to the quantity of cement, and then the materials were mixed dry by using porcelain ball mill for a period of 15 minutes to make FP particles thoroughly dispersed within the cement particles. The core of sandwich panel was prepared from polystyrene concrete with cement to polystyrene ratio of 1:4 by volume. The water – cement ratio was 0.38 by weight. Polystyrene and cement was mixed first by hand, and then the water was gradually added. Mixing lasted six minutes to ensure a uniform distribution of polystyrene beads in the mix.

2-3 Preparation of Specimens

Wooden moulds with internal dimensions of 200×1000mm and depth of 70 and 90mm were used in order to cast sandwich panels. The mould sides and the base were oiled slightly, then the bottom layer of the mortar mix was first cast and polystyrene concrete mix was placed over it, then the upper layer of the mortar mix was placed over polystyrene concrete. Each layer was compacted by knocking the sides of mould by a steel rod. Control specimens were prepared from the same mortar, polystyrene concrete and reinforcement meshes used in sandwich panel specimens. After casting, all specimens were covered with polyethylene sheet for about 24 hours and then the specimens were demoulded and cured by covering them with burlap and spraying water on them every day. The specimens were cured for 60 days after that they were kept in the laboratory for 7 days to be normally dried until the time of testing .Only the polystyrene concrete specimens were cured by covering them with sealed air – tight polyethylene sheets.

2-4 Details of the Tests

Indirect transmission method of ultrasonic pulse velocity test for concrete sandwich panels was carried out according to (ASTM C-597) and to (B.S.1881:part 203) to determine the

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dynamic properties of the concrete sandwich panels by using an equipment commercially called PUNDIT (Portable Ultrasonic Non-destructive Digital Indicating Tester) with transducers of variable frequencies of 37, 54, 150 and 200 kHz. A minimum of ten readings were taken for each distance of three specified distances located on the panel surface. The dynamic Poisson's ratio (u) was determined for the concrete sandwich panels according to the following expression [5]:

$$\frac{Vp}{Vs} = \frac{1+u}{0.87+1.13u} \cdot \sqrt{\frac{2}{1-u}} \quad \ldots\ldots\ldots\ldots(1)$$

The dynamic modulus of elasticity for concrete sandwich panels (E_d) was calculated by using the following equation [5]:

$$E_d = rVp^2(1-u^2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where:

Vp: plate wave velocity (km /sec)

Vs: surface wave velocity (km /sec)

u : dynamic Poisson's ratio

r : density (kg /m^3)

E_d : dynamic modulus of elasticity (GPa)

Also the cube and cylinder specimens were tested nondestructively by direct transmission ultrasonic pulse velocity to determine pulse velocity and dynamic modulus of mortar and concrete using equation (2), ignoring Poisson's ratio [5]:

$$E_d = rV_c^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The panels in static flexural test were simply supported on 900mm span and two concentrated line loads were applied at third points. A dial gauge of ± 0.01mm accuracy was used at the mid – span in order to calculate the deflection. Modified unconfined compression test apparatus with a proving ring dial gauge of maximum capacity 20kN was used; the specimen was covered with a thin layer of gypsum under the concentrated loads to ensure full contact and uniform distribution of load along the panel section width. The specimen was placed on the supports, then the first readings of all gauges were recorded and the specimen was loaded with a constant rate of loading. Readings of deflection were recorded at each interval of load as well as recording the first crack load and the failure load consequently.

The following destructive tests were carried out for the control specimens of mortar and polystyrene concrete:

1-Three cylinders of 150×300mm to evaluate the compressive strength of concrete.

2- Three cylinders of 150×300mm to evaluate the static modulus of concrete.

3-Six cubes of 50mm to determine the compressive strength of mortar.

4- Three prisms of 100×100×400mm to evaluate the modulus of rupture of concrete.

5- Three prisms of 40×40×160mm to evaluate the modulus of rupture of mortar.

6- Three cylinders of 150×300mm reinforced with the same volume fraction and type of reinforcement used in panel specimens, to evaluate the static modulus of reinforced mortar.

2-5 Test Variables

Test specimens were classified to eight series, for all specimens the thickness of both faces was 20 mm. The variables studied in the test series were the thickness of polystyrene concrete core, type and volume fraction of reinforcement meshes used to reinforce the faces of the panels. Details are shown in Table (3).

3- Results and Discussions

3-1 Properties of Mortar and Polystyrene Concrete

Table (4) shows some of the mechanical properties of the mortar and polystyrene

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concrete used in this investigation at age of 60 days. It can be seen that the mortar is dense and has high compressive strength and modulus of rupture, this is because of the reduction in water – cement ratio due to incorporation of superplasticizer and the activity of feldspar powder as a result of its high fineness, resulting in reducing porosity, in producing homogeneity and reducing microcracks in the system leading to an extremely dense matrix [6].

Also Table (4) indicates that the density, compressive strength and modulus of rupture of polystyrene concrete are low. Consequently this lightweight concrete is classified as very light nonstructural concrete (insulating concrete) which is employed primarily for high thermal resistance [7,8]. The results also show that the modulus of elasticity is also very low and this is attributed to the very low modulus of polystyrene beads, so the gross modulus depends primarily on the cement content. These results are in agreement with those of other investigators [7,9].

Table (5) shows the results of static and dynamic moduli of elasticity for plain mortar and mortar reinforced with various types of reinforcement. It can be noticed that there is a decrease in static and dynamic moduli for the mortar reinforced with polyimide grids and polypropylene meshes as volume content of reinforcement increases, while the static and dynamic moduli for the mortar reinforced with chicken wire meshes increases as volume content increase. This may be due to the fact that polypropylene meshes and polyimide grids possess a very low modulus of elasticity when compared with that of hardened matrix and chicken wire meshes (steel). This affects directly the modulus of elasticity of the mortar [10].

3-2 Nondestructive Tests of Concrete Sandwich Panels

3-2-1 Density

The results in Table (6) indicate that the density of all concrete sandwich panels significantly decreases as compared with the density of the high performance mortar which is used to produce the faces of the panels (2360 kg/m^3). This may be due to the low density (470 kg/m^3) of the core material (polystyrene concrete). Also it can be noted that for specimens with similar type and volume content of reinforcement there was an average reduction of about 8% in density as the core thickness increases, from 3 to 5cm.

3-2-2 Determination of Poisson's Ratio

The ultrasonic pulse velocity test was applied to the concrete sandwich panels using the indirect (or surface) transmission arrangement. It is appear that the velocity of plate waves is obtained as the frequency of transducer approaches 37 kHz, while the velocity of surface waves was obtained when the frequency approached 200 kHz, so these two frequencies were used throughout the testing. The relationship between the velocity of plate waves and surface waves for all types of panel specimens is shown in Fig. (2). The slope of the fitted line passing through the origin was found to be 1.76, which represents the ratio Vp/Vs. By substituted this value in Equation (1), the Poisson's ratio of the panels is found to be 0.244.

3-2-3 Dynamic Modulus of Elasticity

The dynamic modulus of elasticity for the panels was obtained by substituting the value of the dynamic Poisson's ratio (υ= 0.244) in Equation (2). So the experimental relationship between the dynamic modulus and the stiffness constant for plate wave velocity ($\rho\ V_p^2$) is:

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$$E_d=0.94\,\rho\,V_p^{2} \qquad \text{.........................} \quad (4)$$

Table (6) and Fig. (3) indicate that the increase of volume fraction of polyimide grids and polypropylene meshes decrease the dynamic modulus, also it can be seen that by using chicken wire meshes instead of polyimide or polypropylene meshes to reinforce the tension face of the panels in series 6, 7 and 8, the dynamic modulus was increased as compared with specimen in series 2, 3 and 4 respectively and the increase in volume fraction of chicken wire meshes increases the dynamic modulus. This may be attributed to the high dynamic modulus of the chicken wire meshes as compared with polyimide grids and polypropylene meshes according to the rule of mixture. It can be noted from Table (6) that the dynamic modulus of specimens with similar type and volume fraction of reinforcement decreases as the polystyrene concrete core thickness increases, the average percentage of reduction is about 7%. This is attributed to the fact that the elastic modulus of polystyrene beads is much lower than that of ordinary cement – sand mortar [9].

3-3 Behaviour of the Concrete Sandwich Panels in Flexure

3-3-1 Load – Deflection Relationship

The load – deflection curves of the concrete sandwich panel specimens are presented in Figures (4) to (7). It is clear from these curves that these panels generally exhibit three stages in load – deflection relationship, the elastic or uncracked stage at which the deflection increases almost linearly with load, the matrix and the reinforcement in this portion act as a continuum. Further increase in the load above the point of deviation from linearity, causes the first crack to occur and beyond the first crack load, there is a high increase in deflection. The second stage is a quasi – elastic stage, it is associated with cracking of matrix and the stress in the matrix is progressively transferred to the reinforcement. The third stage is the plastic stage which represents the failure of all specimens corresponding to the failure of tensile face of the panels caused by either debonding or yielding of the reinforcement.

3-3-2 Moment Capacity

Table (7) indicates that there is a significant increase in ultimate moment capacity for the panels reinforced with either polyimide grids or polypropylene meshes as the core thickness increases. This may be attributed to the increase in section modulus of the panel specimens with the increase in core thickness. Generally, it can be seen that the first crack and ultimate moments improved for most specimens when chicken wire meshes are used instead of polyimide grids or polypropylene meshes to reinforce the tension face of the panel. Also the first crack and ultimate moment increase as volume content of chicken wire meshes increases. This is probably because of the high bonding strength of chicken wire meshes as compared with polyimide grids and polypropylene meshes.

3-3-3 Modulus of Rupture

Table (7) and Fig.(8) show that the modulus of rupture for the specimens reinforced with either polyimide grids or polypropylene meshes increases as the volume fraction of reinforcement increases, also it can be observed that the core thickness has very little effect on the modulus of rupture for both panel specimens reinforced with polyimide grids or polypropylene meshes. The results also indicate that there is a considerable increase in the modulus of rupture for most of specimens in series 6, 7 and 8 relative to specimens in series 2, 3 and 4 respectively, this is because of the increase in ultimate moment as a result of using chicken wire meshes to

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reinforce the tension face of panel specimens in series 6, 7 and 8 instead of polyimide grids or polypropylene meshes used in series 2, 3 and 4.

3-3-4 Resilience

Table (8) shows the values of resilience of the concrete sandwich panels. Generally it is noted that the resilience value for specimens with the same volume content and type of reinforcement increases with the increase in core thickness from 3cm to 5cm. This increase in resilience may be attributed to the low modulus of elasticity and the high strain capacity of the core material (polystyrene concrete) due to high compressibility of expanded polystyrene aggregate. It can be observed also, that the increase in volume content of polyimide grids from 2.8% to 5.6% decreases the resilience, while for specimens reinforced with polypropylene meshes the resilience increases, this may be due to the low bonding strength of polyimide grids with mortar especially at high volume content and this low bonding strength causes a decrease in the value of first crack load. The results also show that there was a very considerable increase in resilience by about 167%, 121% and 137% for specimens in series 6, 7 and 8 respectively when the volume fraction of chicken wire reinforcement increases.

3-3-5 Ductility

Ductility gives an indication to the amount of deflection just before failure[11]. In general, it can be observed from Table (8) that the ductility of reinforced specimens is greatly enhanced relative to the unreinforced specimens and the increase becomes high as the volume fraction of all types of reinforcement increases. The concrete sandwich panels reinforced with polypropylene meshes show a very considerable increase in ductility by about 3043% for both specimens 1PL3 and 2PL3 in comparison with the reference specimen P3. The ductility of most specimens with tension faces reinforced with chicken wire meshes decreases in comparison with those of the same core thickness but with tension face reinforced with either polyimide grids or polypropylene meshes. This may be attributed to the fact that synthetic fibres such as nylon and polypropylene possess low interfacial bond strength relative to steel fibres and therefore substantially increase the impact resistance of the unreinforced matrix [12].

3-6- 3Toughness of Concrete Sandwich Panels

3-3-6-1 Measurement of Toughness Indices

The toughness index values were calculated by using ASTM C1018 method[13], which based on determining the amount of energy required first to deflect and crack a fibre reinforced concrete beam loaded at its third points and then to select multiples of the first crack deflection. In general, the end point deflection for an index I_N is (N+1) / 2 times the first crack deflection, so the toughness indices I_5, I_{10} and I_{20} are then calculated as ratios of the area under the load – deflection curve up to 3, 5.5, 10.5 times the first crack deflection divided by the area up to the first crack deflection respectively. It should be pointed out that the value I_N is unity for an elastic perfectly brittle material behaviour. The subscripts N in these indices are based on the elastic – plastic analogy such that for a perfectly elastic – plastic material the index I_N would have a value equal to N.

3-3-6-2 Toughness Indices Results

The areas under the load – deflection curve up to the first crack deflection and at selected multiples of first crack deflection of concrete sandwich panels were calculated by integration after fitting the curves to a polynomial

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equation of third up to fifth degree depending on the best value of the coefficients of correlation (from 0.98 to 0.99).

The values of toughness indices of all the tested specimens have been presented in Figures (9) and (10) and in Table (8). Generally, it can be seen that the toughness of all reinforced specimens is considerably enhanced over that of unreinforced specimens. This enhanced performance of reinforced specimen's results from their improved capacity to absorb energy during fracture, while the unreinforced specimens fail in a brittle manner at the occurrence of cracking stresses. The ductile reinforcement in reinforced specimens continues to carry stresses beyond matrix cracking, and this helps to maintain structural integrity and cohesiveness in the material. Further, the reinforcement undergoes pullout processes, and the fractional work needed for pullout leads to a significantly improved energy – absorption capability [14].

It can be also noticed that the values of I_5, I_{10} and I_{20} for specimens 2GP5 and 2PL3 were higher than the standard values (5, 10 and 20 respectively). These represent that up to 10.5 times the cracking deflection, the post – cracking performance of these specimens is better than the elastic –plastic behaviour. The value of I_5 and I_{10} for specimens 1GP3, 2GP3, 1GP5 and 2PL5 are higher than the standard values 5 and 10 respectively.

This indicates that up to 5.5 times the cracking deflection the post – cracking performance of these specimens is better than the elastic – plastic behaviour. Specimens in series 6, 7 and 8 (except specimen 2HGP5) have I_5 value more than 5, this indicates that post – cracking performance of these specimens up to 3 times the cracking deflection is better than the elastic – plastic behaviour

4-Conclusions

1- The dynamic Poisson's ratio for concrete sandwich panels was determined from the slope of the fitted line passing through the origin for the relationship between plate and surface wave velocities of all panel specimens. It was found to be 0.244.

2- The dynamic modulus of elasticity of concrete sandwich panels with both core thickness (3 and 5cm) and reinforced with either polyimide grids or polypropylene meshes decreases with increasing of the volumetric content of reinforcement.

3- An empirical relationship is derived between the dynamic modulus of elasticity(E_d) and the stiffness constant (ρV_p^2) of the concrete sandwich panels:

$$E_d=0.94\,\rho\,V_p^2$$

4-The ultimate moment of concrete sandwich panels increases as the core thickness and the volume fraction of different types of reinforcement are increased.

This is due to the increased bending forces and the arm in the section.

5- The results show that using chicken wire meshes instead of polyimide grids or polypropylene meshes to reinforce the tension face of the concrete sandwich panels increases the ultimate moment (due to increased bending force capacity).

6- The modulus of rupture for the concrete sandwich panels increases as the volume fraction of different types of reinforcement used in this work increases.

7- The resilience of the concrete sandwich panels increases with the increase in core thickness. The percentage of increase depends also on

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the type and volume fraction of reinforcement.

8- A high ductile concrete sandwich panels has been obtained by using polyimide grids or polypropylene meshes to reinforce the compression and tension faces of specimens. The ductility increased with the increase in volume fraction of reinforcement.

9- The results show that superior ductility is exhibited by the concrete sandwich panels reinforced with polypropylene meshes.

10- The toughness of all reinforced concrete sandwich panels is considerably enhanced relative to unreinforced specimens; the values of toughness index I_5 for all concrete sandwich panels are higher than the standard value 5. This indicates that up to 3 times the cracking deflection the post – cracking performance of the concrete sandwich panels is better than the elastic- plastic behavior.

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Substance	Percentage
SiO_2	86.34
Al_2O_3	8.49
Na_2O	1.4
K_2O	2.2
Fe_2O_3	0.7
CaO	0.4
MgO	0.11
SO_3	0.1
L.O.I	0.26

Table (1) Chemical analysis of feldspar powder

Sieve size mm	% Passing
6.7	100
4.75	60.64
2.36	2.38
2.0	1.91
1.7	1.09
1.18	0.54
1.0	0.09
0.85	0

Table (2) Polystyrene beads sieve analysis

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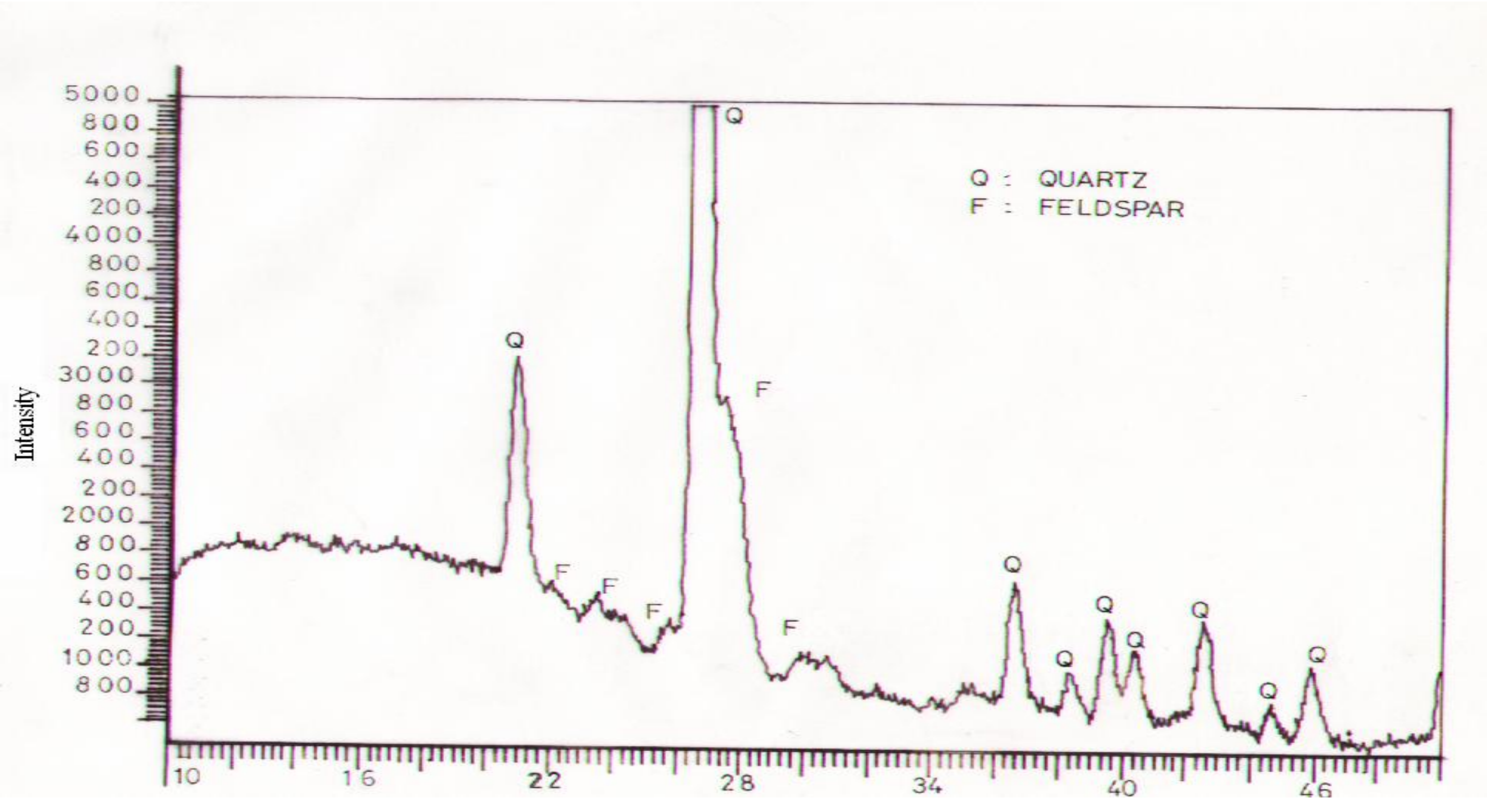

Diffraction angle - 2Φ

Fig. (1) X – ray diffraction analysis of feldspar

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Table (3) Details of test sandwich panel specimens

Series No.	Designation	Core thickness mm	Upper face			Lower face		
			Type of Reinforcement	**Volume fraction of Reinforcement Vf %**	**No. of layer of reinforcement**	**Type of reinforcement**	**Volume fraction of reinforcement Vf %**	**No. of layer of reinforcement**
1	P3	30	Non	—	—	Non	—	—
	P5	50	Non	—	—	Non	—	—
2	1GP3	30	Polyimide grids	2.8	1	Polyimide grids	2.8	1
	2GP3	30	Polyimide grids	5.6	2	Polyimide grids	5.6	2
3	1GP5	50	Polyimide grids	2.8	1	Polyimide grids	2.8	1
	2GP5	50	Polyimide grids	5.6	2	Polyimide grids	5.6	2
4	1PL3	30	Polypropylene meshes	2.8	1	Polypropylene meshes	2.8	1
	2PL3	30	Polypropylene meshes	5.6	2	Polypropylene meshes	5.6	2
5	1PL5	50	Polypropylene meshes	2.8	1	Polypropylene meshes	2.8	1
	2PL5	50	Polypropylene meshes	5.6	2	Polypropylene meshes	5.6	2
6	1HGP3	30	Polyimide grids	2.8	1	Chicken wire	0.32	1
	2HGP3	30	Polyimide grids	5.6	2	Chicken wire	0.64	2
7	1HGP5	50	Polyimide grids	2.8	1	Chicken wire	0.32	1
	2HGP5	50	Polyimide grids	5.6	2	Chicken wire	0.64	2
8	1HPL3	30	Polypropylene meshes	2.8	1	Chicken wire	0.32	1
	2HPL3	30	Polypropylene meshes	5.6	2	Chicken wire	0.64	2

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Table (4) Properties of mortar and polystyrene concrete used in this work

Property	Mortar	Polystyrene Concrete
Compressive strength (N/mm^2)	84.4	0.76
Modulus of rupture (N/mm^2)	9.8	0.37
Static modulus of elasticity Gpa	22.4	0.45
Pulse velocity km/sec	4.36	2.31
Dencity kg/m^3	2360	470.2
Dynamic modulus of elasticity Gpa	44.9	1.3

Table (5) Static and dynamic modulus of elasticity for reinforced mortar

Type of reinforcement	Volume fraction Vf%	Pulse velocity (V_c) km/sec	Density (ρ) kg/m^3	Dynamic modulus (E_d) GPa	Static modulus (E_s) GPa
Without reinforcement	0	4.36	2360	44.9	22.4
Polyimide grid	2.8	4.3	2190	40.5	21.8
	5.6	4.2	2159	38.1	20
Polypropylene mesh	2.8	4.25	2171	39.2	14
	5.6	4.1	2135	35.9	11.7
Chicken wire mesh	0.32	4.47	2365	47.3	25.3
	0.64	4.5	2380	48.2	27

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Table (6) The ultrasonic pulse velocity results of concrete sandwich panels

Series No.	Designation	Density (r) kg/m^3	Plate wave velocity (V_p) m/sec	Surface wave velocity (V_s) m/sec	Stiffness constant ($r\,V_p^2$) GPa	Dynamic modulus of elacticity (Ed) GPa
1	P3	1500	4890	2739	35.9	33.75
	P5	1370	5000	2725	34.25	32.2
2	1GP3	1570	4770	2732	35.7	33.56
	2GP3	1646	4580	2673	34.53	32.46
3	1GP5	1420	4750	2684	32	30.1
	2GP5	1490	4600	2656	31.5	29.6
4	1PL3	1598	4664	2627	34.76	32.67
	2PL3	1651	4348	2624	31.21	29.34
5	1PL5	1440	4700	2654	31.8	29.9
	2PL5	1540	4400	2652	29.81	28
6	1HGP3	1628	4817	2698	37.8	35.53
	2HGP3	1651	4820	2689	38.36	36.1
7	1HGP5	1500	4800	2694	34.56	32.5
	2HGP5	1590	4900	2680	38.2	35.9
8	1HPL3	1620	4860	2704	38.3	35.96
	2HPL3	1650	4910	2700	39.8	37.4

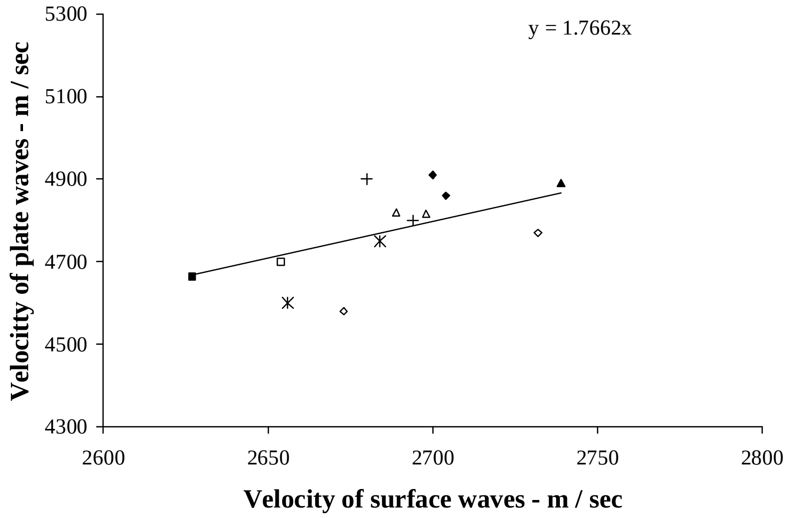

Fig. (2) Relationship between plate and surface wave velocities for concrete sandwich panels

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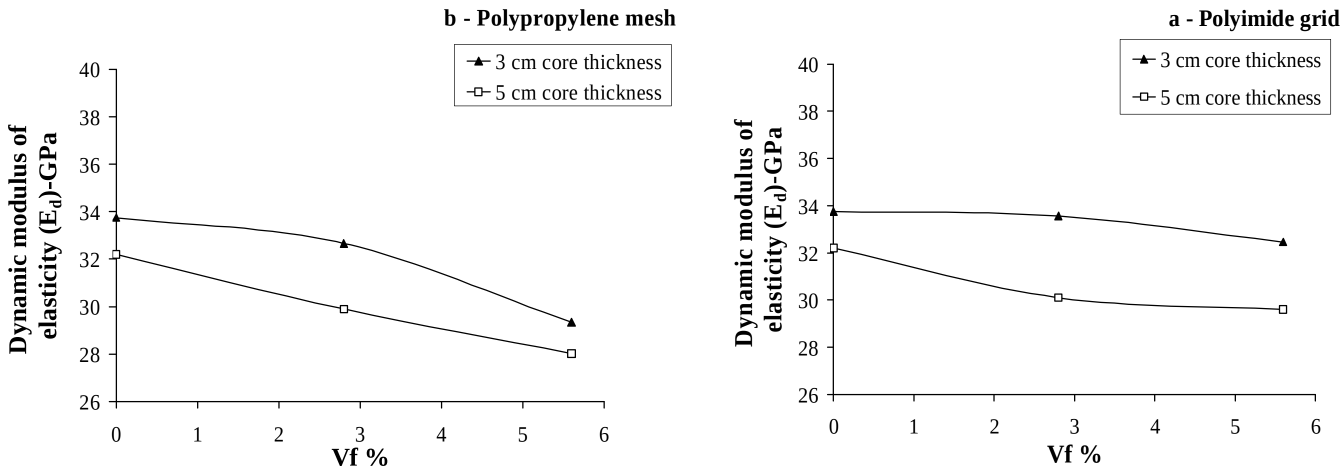

Fig. (3) Relationship between volume fraction of reinforcement and dynamic modulus of concrete sandwich panels

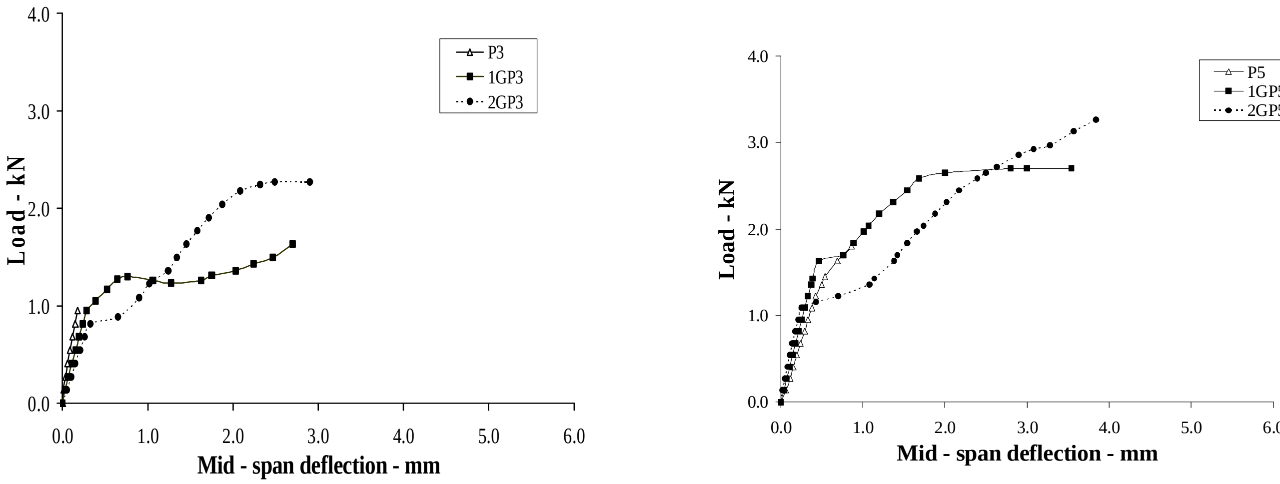

Fig. (4) Load – deflection curves at mid – span for concrete sandwich panels in series (2) and (3)

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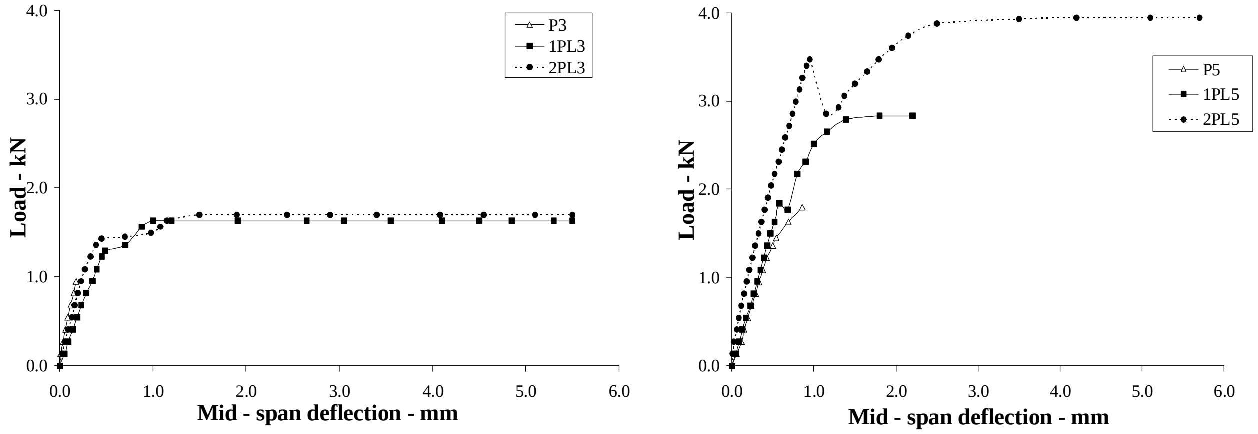

Fig. (5) Load – deflection curves at mid – span for concrete sandwich panels in series (4) and (5)

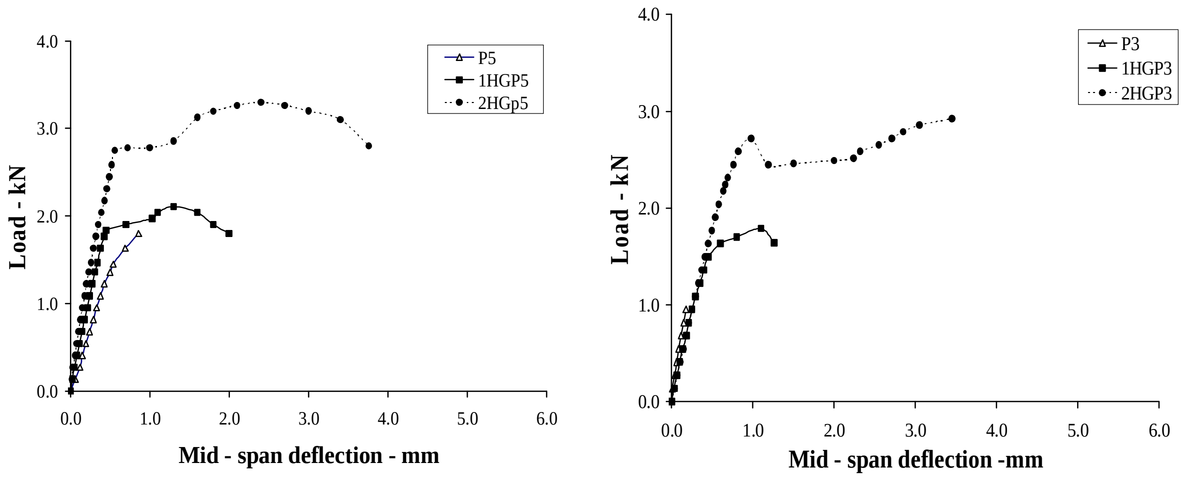

Fig. (6) Load – deflection curves at mid – span for concrete sandwich panels in series (6) and (7)

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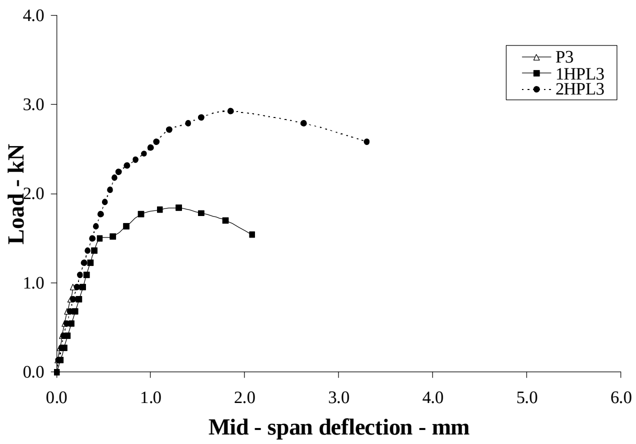

Fig. (7) Load – deflection curves at mid – span for concrete sandwich panels in series (8)

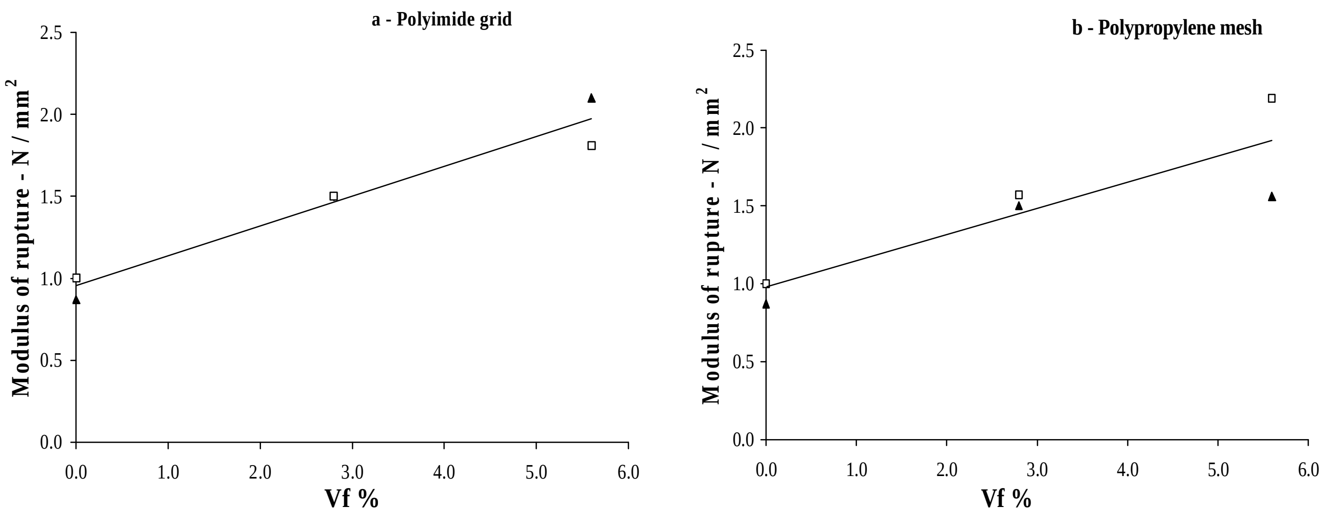

Fig. (8) Relationship between volume fraction of reinforcement and modulus of rupture for concrete sandwich panels

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Table (7) Flexural test results of concrete sandwich panels

Series No.	Designation	First crack load (P_{cr}) kN	First crack deflection (Δ_{cr}) mm	First crack moment (M_{cr}) kN.mm	Ultimate load (P_u) kN	Ultimate deflection (Δ_u) mm	Ultimate moment (M_u) kN.mm	Modulus of rupture N/mm^2
1	P3	0.95	0.175	142.5	0.95	0.175	142.5	0.87
	P5	1.23	0.42	184.5	1.8	0.86	270	1
2	1GP3	0.95	0.29	142.5	1.63	2.7	244.5	1.5
	2GP3	0.82	0.33	123	2.27	2.9	340.5	2.1
3	1GP5	1.63	0.47	244.5	2.7	3.54	405	1.5
	2GP5	1.09	0.25	163.5	3.26	3.84	489	1.81
4	1PL3	1.29	0.49	193.5	1.63	5.5	244.5	1.5
	2PL3	1.36	0.45	204	1.7	5.5	255	1.56
5	1PL5	1.84	0.58	276	2.83	2.2	424.5	1.57
	2PL5	3.33	0.88	499.5	3.94	5.7	591	2.19
6	1HGP3	1.36	0.4	204	1.79	1.1	268.5	1.65
	2HGP3	2.24	0.66	336	2.93	3.45	439.5	2.7
7	1HGP5	1.77	0.43	265.5	2.11	1.3	316.5	1.17
	2HGP5	2.75	0.56	412.5	3.3	2.4	495	1.83
8	1HPL3	1.36	0.43	204	1.84	1.3	276	1.69
	2HPL3	2.18	0.62	327	2.92	1.85	438	2.69

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Table (8) Resilience and ductility of concrete sandwich panels

Series No.	Designation	Resilience N.mm	Ductility mm	Toughness indices		
				I_5	I_{10}	I_{20}
1	P3	92.3	0.175	1	1	1
	P5	266.6	0.86	1	1	1
2	1GP3	155.6	2.7	6.5	13.5	
	2GP3	134	2.9	5	12.3	
3	1GP5	379.4	3.54	6.5	13.8	
	2GP5	135	3.84	5.3	12.3	32.6
4	1PL3	310	5.5	6.2	12.3	18.1
	2PL3	358	5.5	5	10.5	23.6
5	1PL5	520.5	2.2	6.7		
	2PL5	1566	5.7	5.2	10.5	
6	1HGP3	301	1.26	5.2		
	2HGP3	803	3.45	5.75		
7	1HGP5	417.5	2	5		
	2HGP5	922	3.76	5.2	10.3	
8	1HPL3	313	2.1	5.4		
	2HPL3	741	3.3	5.7		

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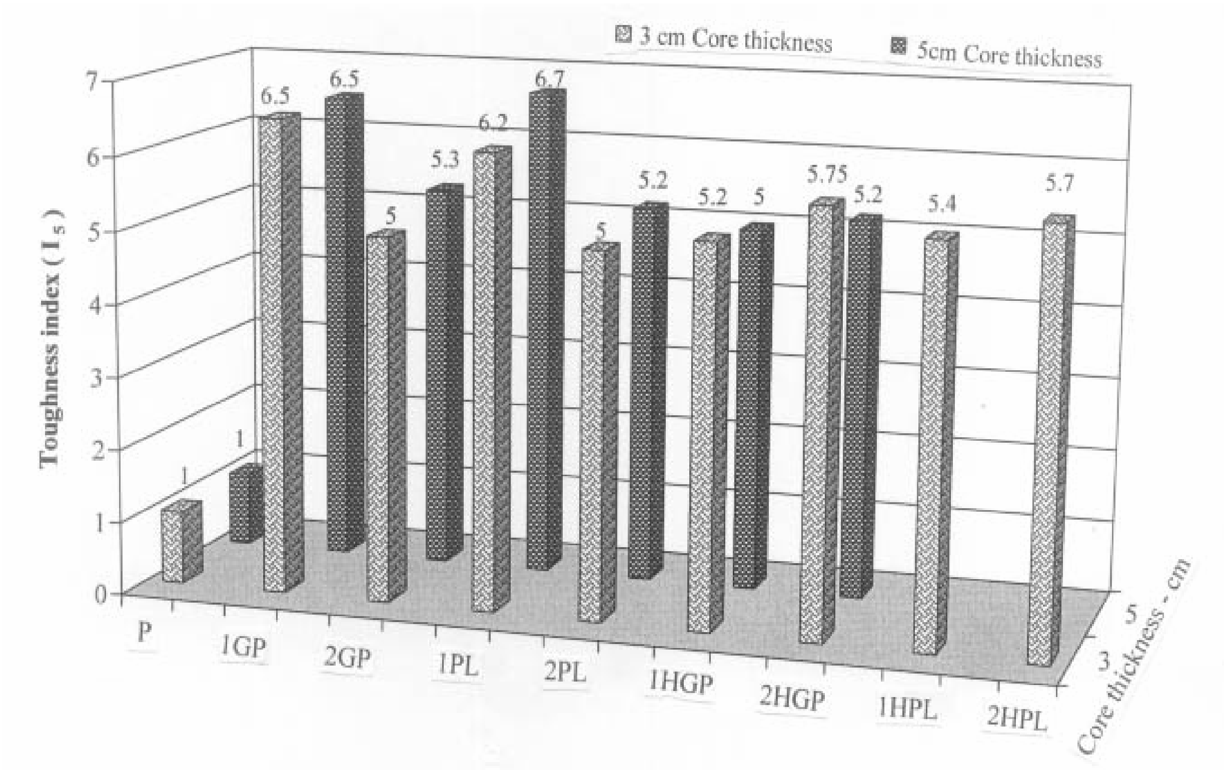

Fig. (9) Comparison of toughness index (I_5) of concrete sandwich panels

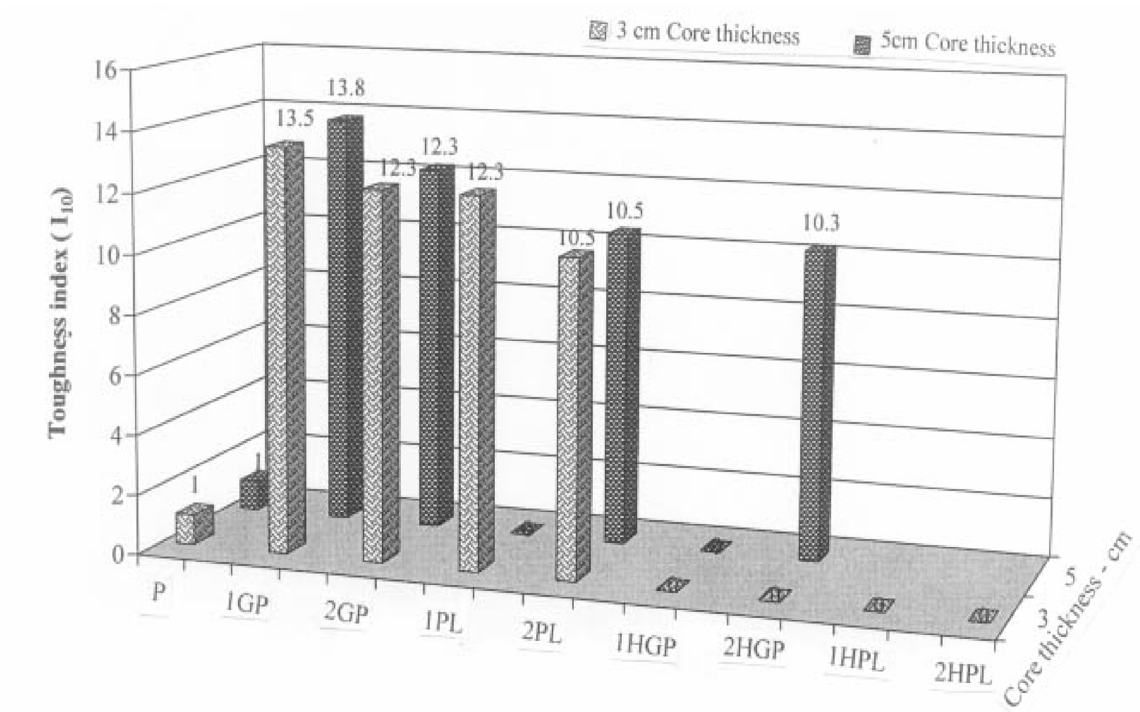

Fig. (10) Comparison of toughness index (I_{10}) of concrete sandwich panels

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