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EXPERIMENTAL BEHAVIOR OF RPC HEMISPHERICAL DOMES UNDER CONCENTRATED LOAD AND SITTING ON FOUR SUPPORTS

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Abstract: The main objective of the current research is estimating of the structure performance of reactive powder concrete hemispherical domes and the effects of the changing of its thickness and steel fiber ratio on structural behavior. The current paper presents an experimental program included casting and testing up to failure for six domes. Four of them made fully of Reactive Powder Concrete, and two made of Ferrocement Concrete. All specimens have 800 mm diameter, 400 mm height, and they were reinforced with welded wire meshes. The variables in domes are the values of thickness which are (20 mm, 15 mm), steel fiber ratio (1%, 2%) and type of concrete (reactive powder, ferrocement). A single point load applied at the crown of dome until the failure is happened. The dome is sitting on four supports. In general, the ultimate strength capacity of the dome increases with the increase of thickness, steel fiber ratio and concrete strength.

Keywords: *Hemispherical Dome, Ferrocement Concrete, Reactive Powder Concrete, Welded Wire Mesh, Four Supports*

السلوك العملي للقباب النصف كروية المصنعة من خرسانة المساحيق الفعالة تحت تأثير حمل مركز و الجالسة على اربعة مساند

الخلاصة: الهدف الرئيسي من البحث الحالي هو تقدير الأداء للقباب النصف الكروية المصنعة من خرسانة المساحيق الفعالة و آثار السمك و نسبة الالياف الفولاذية على السلوك الانشائي لها. يقدم هذا البحث برنامجا تجريبيا لصب و تحميل الى حد الفشل لستة قباب. اربعة قباب تم صبها من خرسانة المساحيق الفعالة و اثنان منها مصنوعة من الفيروسمنت. جميع العينات ذات قطر 800 ملم و ارتفاع 400 ملم ، وكانت مسلحة بمشبك من الأسلاك الملحومة .المتغيرات التي تم ادخالها تضمنت كل من سمك الخرسانة (20 ملم، 15 ملم)، نسبة الالياف الفولاذية (1%، 2%) و كذلك نوع الخرسانة (المساحيق الفعالة، الفيروسمنت). الحمل المسلط كان مفردا و مركزا في اعلى القبة، التي اسندت في اربعة مناطق. وأشارت نتائج البرنامج التجريبي ان قيمة التحمل القصوى للقبة تزداد مع الزيادة في السمك، نسبة الالياف وكذلك مقاومة الخرسانة.

1. Introduction

Shells are curved surface structures that combine membrane and bending action to obtain an increase in stiffness.

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For this reason they are considered as a combination of the load-carrying behavior of plates in bending and membrane action. In civil engineering, shells are useful to create large open areas without the need of column support.

The first known encounter of shells used for this purpose is the Pantheon in Rome, build in 126 AD. Although the Romans lacked the engineering knowledge of the modern era, they intuitively understood the load carrying qualities of shells. To this day the structure is considered a construction marvel. Over the last centuries the theory of shells has been extensively studied, and a comprehensive amount of information are available to engineers in a wide range of engineering fields [1].

Generally speaking, shells are spatially curved surface structures which support external applied loads. The American Concrete Institute defines a thin shell as a three-dimensional spatial structure made

up of one or more curved slabs or folded plates whose thicknesses are small compared to their other dimensions. Thin shells are characterized by their three-dimensional load carrying behavior, which is determined by the geometry of their forms, by the manner in which they are supported, and by the nature of the applied load [2].

Reactive Powder Concrete (RPC) is a developing composite material that will allow the concrete industry to optimize material use, generate economic benefits, and build structures that are strong, durable, and sensitive to environment. It consists of a special concrete where the microstructure is optimized by precise gradation of all particles in the mix to yield maximum density. It uses extensively the pozzolanic properties of highly refined silica fume and optimization of the Portland cement chemistry to produce the highest strength hydrates [3].

This study aims at:

1. Evaluate the structural behavior of thin shell (dome) made with reactive powder concrete.
2. Evaluate the effects of the dome thickness, steel fiber ratio and concrete mix on the structural behavior.

3. Research Review

Elangouan and Santha in 1984[4] presented a study of the behavior of ferrocement funicular shell roof formed square ground plane The shell was supported continuously on edge beams which are supported on eight brick columns, at the four corners and at mid-spans of edge beams. Two layers of chicken mesh was placed on each face of shell. The shell was loaded with sand bags over its entire area to represent a uniformly distributed load. A maximum load, load deflection and crack pattern were included in that study. The study appears the effect and significance of ferrocement in concrete shells.

Wail and Azad in 2013[5] presented an experimental study for the effect of both skeletal reinforcement and thickness on the strength capacity and behavior of thin ferrocement dome structures under uniformly distributed load. The study has been concluded that the construction technique developed in the present investigation reflects the most economic approach, which reduces the nominal cost of such complex structures during construction. This investigation has shown the suitability of the ferrocement material to construct a dome structure. A decrease in skeletal steel reinforcement tends to decrease the initial cracking and ultimate loads. Reduction of skeletal reinforcement is more signification cracked stage than in the un-cracked stage. As skeletal steel content is reduced, the failure became more severe and sudden. An increase in the dome thickness plays the dominant role in increasing the initial cracking and ultimate loads. The tested models indicated that, whilst cracks appear in the sides and crown of the domes due to an increase of the load beyond the first cracking loads, the remaining parts of the dome were cracked continuously. The construction technique developed in that investigation reflects the most economic approach, which reduces the nominal cost of such complex structures during construction.

Shaheen, Y.B.I, Eltaly, B.A and Hanesh, A.A in 2014 [6] presented an experimental and FE simulations of ferrocement domes reinforced with composite materials, the main objective of the research is estimating the structure performance of ferrocement domes reinforced with composite material. The results of the experimental program indicated that the dome reinforced with fiberglass mesh has the highest service load and ultimate load and the dome reinforced with welded wire meshes achieved highest ductility ratio and energy absorption.

3. Experimental Program

3.1. Test Specimens

The experimental program of this work includes casting and testing six hemispherical dome specimens, all specimens have the same diameter of 800mm, and height of 400mm. The main variables included, the dome thickness (15 and 20mm), steel fiber ratio (1% and 2%), concrete type (reactive powder and ferrocement), and the number of welded meshes (1 and 2). Table (1) shows the domes designation.

Steel welded wire meshes were used as reinforcement, these mashes placed on the mold face before concrete casting and the fixing position taken in the shell middle thickness. Where only one copper mold was used for casting all domes.

All domes were sitting on four simply supported and steel ring was used to prevent the lateral displacements, a single point load was applied at the crown of dome until failure.

Table (1): Designations and Dimensions of tested specimens

Concrete Type	Dome Designation	Dimension (mm)		Thickness (mm)	Volume of Fiber	Wire Meshes
		H	D			
Ferrocement (FC)	DF1	400	800	20	-	1
	DF2	400	800	20	-	2
Reactive Powder Concrete (RPC)	DR1	400	800	15	1 %	2
	DR2	400	800	15	2 %	2
	DR3	400	800	20	1 %	2
	DR4	400	800	20	2 %	2

3.2 *Materials*

3.2.1 Cement

Iraqi ordinary Portland cement (Mass) (type I) is used in this study. The cement was stored in closed plastic containers throughout the experimental work to keep the cement in good conditions and to minimize the effect of humidity. The properties are conformed to the Iraqi Specification limits (IQS 5/1984) [7] for ordinary Portland cement.

3.2.2 Extra fine sand

Extra fine sand, anti-slip aggregate #4, with size (300-400) µm is used for RPC mix. This type is from Don Construction products and its grading in accordance with the fine grading of the IQS No.45/1984[8] (zone 3).

3.2.3. Water

Ordinary tap water was used in mixing and curing for all specimens.

3.2.4 Silica Fume

A grey densified grade 920 D silica fume (which is a byproduct from the manufacture of silicon or ferro-silicon metal) was used, which was imported from the Elkem Company in UAE. Silica fume is an extremely fine powder, its particles are hundreds of times smaller than cement particles, always used in 15 to 25% by of cement[9], as partial replacement of cement or as an additive (as used in the present work) to enhance concrete properties. The used silica fume conforms to the chemical and physical requirements of ASTM C1240-04[10]

3.2.5 High Range Water Reducing Admixture (HRWRA)

The HRWRA used in this work is a third generation super-plasticizer for concrete and mortar which is known commercially as (Glenium 51). Glenium 51 has been primarily developed for applications where the highest durability and performance are required. Glenium 51 is free from chlorides and complies with ASTM C494-16[11] type G and F.

3.2.6 Ultra-Fine Steel Fibers (UFSF)

Ultra-fine steel fibers are used throughout the experimental program. This type of ultra-fine steel fibers is manufactured by the Ganzhou Day Metallic Fibers Co, Ltd, China. The properties of the used steel fibers are presented in Table (2). Micro steel fiber is the material of Reactive Powder Concrete (RPC) and Slurry Infiltrated Concrete (SIFCON).

Table (2): Characteristics of Used Steel Fibers *

Type	Density (kg/m^3)	Length of fiber (mm)	Diameter of fiber (mm)	Tensile strength (MPa)	Modulus of Elasticity (GPa)
Straight	7800	15	0.2	2850	210

*Manufacturer properties

3.2.7 Welded Wire Mesh

Square welded galvanized wire meshes are used as tension reinforcement for domes. The main properties of these meshes are listed in Table (3).

3.3. Mix Proportions

Two types of concrete mixes were used in this investigation; ferrocement and RPC. The ferrocement mix was designed according to the ACI 549-97[12]. While, many mix proportions for RPC were tried according to pervious researches [13, 14] to get maximum compressive strength and flow of 95% according to ASTM C109-05[15] and ASTM C1437-01[16]. The details of these two concrete mixes are shown in Table (4).

Table (3): Properties of the Welded Wire Mesh*

Property	Specifications
Yield strength (fy)	320 MPa
Relative density	7860 kg /m^3
Modulus of elasticity (Es)	167 GPa
Average diameter	0.7 mm
Opening size of mesh	(13*13) mm

*According to manufacturer list.

Table (4): Mix Proportions

Concrete Type	Cement (kg/m^3)	Fine Sand (kg/m^3)	Silica Fume (kg/m^3)	V_f %	w/c %	G51 %
RPC1	933	1030	234	1	0.18	4%*
RPC2	933	1030	234	2	0.18	4%*
Ferrocement	650	1310	65**	-	0.35	1% *

*percent by weight (cement+ silica fume)
** 10% replacement of cement content

3.4. Experimental Procedure

The first step in the casting work procedure was cleaning the mold, and then oiled and covered by membrane layer. The welded wire mesh was placed at their position on the mold.

Four of the tested domes were casting by using RPC with varied in thickness, and in volume of steel fiber and the last two domes were made from ferrocement with different number of welded meshes. The ferrocement and RPC was cast by plastering. After 24h the hardened domes were removed from the molds and cured in water tank (of about 25-

30^{o}c temperature) until testing time, at age of 28 days. While, the first two days of RPC curing was by using hot water at a temperature of about 60^{o}c.

Before the test day, the hemispherical dome is lifted from the curing container, the specimens are cleaned, wiped and painted in white color to ensure the crack pattern could be observed easily on shell surface to attain clear visibility of cracks during test.

For the purpose of conducting examinations of the dome a steel frame has been used to support the dome models, the support form of a square which have the side (900 mm from center to center) and a height of approximately (150 mm) note that the template contains from the bottom on. Also, four equal prisms of iron with the dimensions (650 mm length 80 mm width 40 mm thickness) were used under the dome and sit on the steel frame. Ring steel of dimensions 100x4mm was used to restriction of the horizontal displacements at the dome base. All domes are tested using a universal testing machine which has a capacity of 3000 kN. The load is applied progressively in increments of 2.5 kN up to failure. Loading plate of dimensions 100x100x50mm was used to transform the load from machine to the dome specimen. Three dial gages were used to measure vertical and horizontal displacements (with 0.01mm accuracy). The vertical displacements were measured at two points, at top (VT) and at mid-height (VM), at distance 400 mm and 200 mm respectively from the dome base while the horizontal displacement was measured at the mid-height point (HM) at distance 200mm from the dome base.

Figure (1) shows the mold, the casting, and the testing procedure.

Figure. (1) Stages of Tested Domes.

4. Results And Discussion

For each mix, there are three cubes with (100 mm) dimensions are cast for determination the compressive strength and three cylinders of 100mm diameter and 200mm height are cast for determination the splitting tensile strength. The compression and tensile test results of the concrete are given in Table (5). The results explain the effectivity of using reactive powder concrete and their properties in comparison with ferrocement. The percent of increasing of compressive strength and tensile strength of mix RPC1 with respect to ferrocement is 225% and 53% respectively, while the increasing of mix RPC2 properties with respect to ferrocement is 388% and 131% respectively. The importance of using steel fiber in RPC is clear in improving the properties, by increasing steel fiber ratio from 1% to 2%, each of the compressive and tensile strength increasing by 50% and 51%, respectively.

Table (5): Concrete Strength

Concrete Type	V_f %	fcu (MPa)	fsp (MPa)
Ferrocement	-	40	4.68
RPC1	1	130	7.17
RPC2	2	195	10.83

Photos in Figure (2) show the crack patterns for the tested domes. It can be seen that all domes were failed due to punching shear and the cracks are observed on the corner of the loading plate area. The nature of failure and distance between the cracks on the face of the dome are not same and differ from dome to another. The failure area in ferrocement domes, DF1 and DF2, are narrower than reactive powder domes, DR1, DR2, DR3 and DR4. Whilst the cracks are much obvious in DR1 and DR2 than in DR3 and DR4.

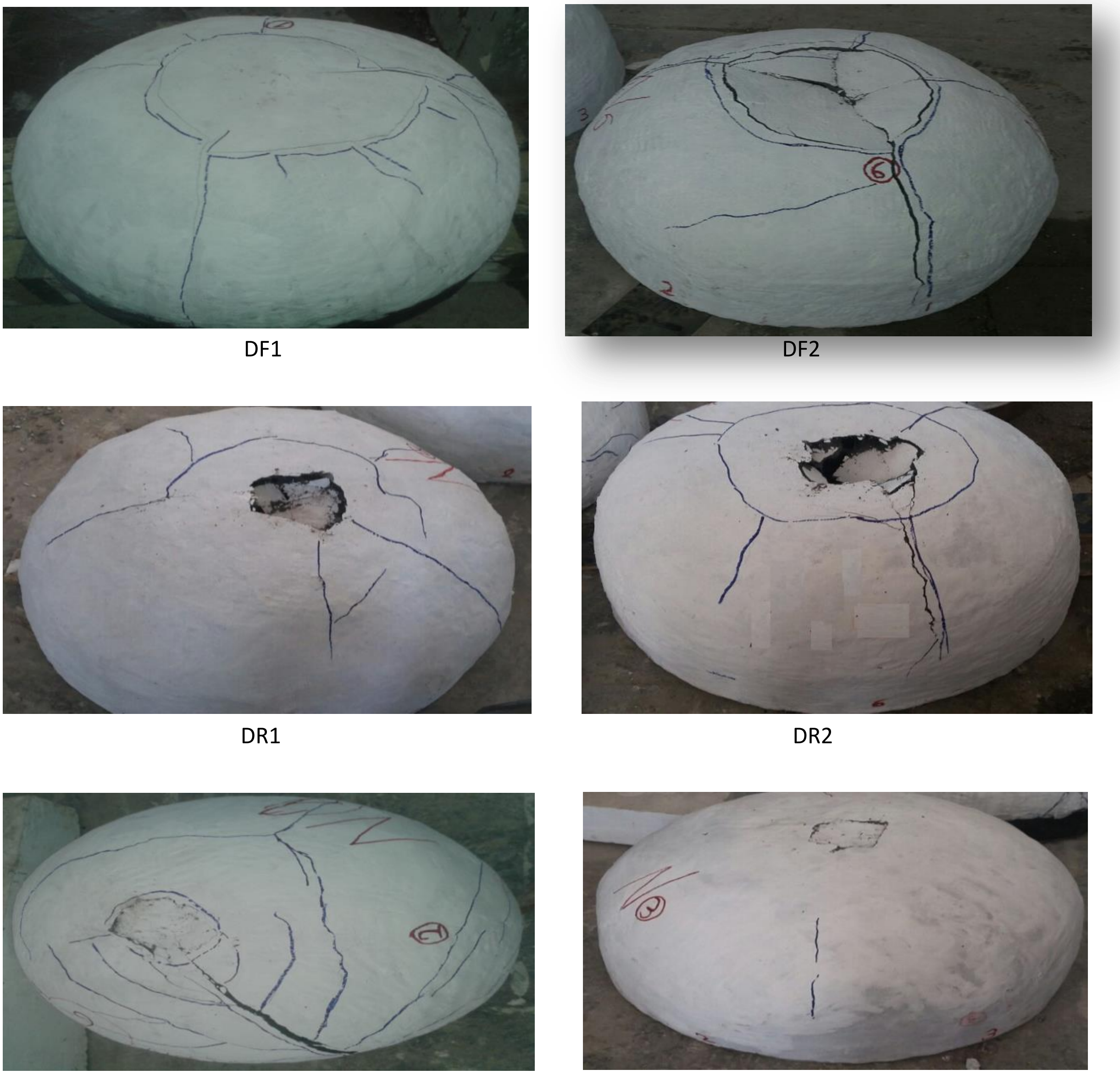
This can be attributed to the development of strength, the structural integrity and increase of thickness. Higher thickness and higher the value of V_f% in reactive powder domes leads to improve the properties of RPC matrix and make it more capable to carry significant stresses over a relatively large strain capacity in the post-cracking stage, while the ferrocement matrix will become the weakest substance and will fail before any crack can be noticed in RPC matrix.

It is noticed from Table (6) that, the cracking loads are about 27.9 % of the ultimate loads for ferrocement domes and about 22.1% for RPC domes with 15mm thickness, while the percent is decreased to 18.45% for RPC domes with 20mm thickness.

Table (6) shows the values of the ductility ratio, which defined as the ratio between the vertical displacements at ultimate load to that at the first crack load [6]. Increasing of welded mesh from one mesh to two meshes gives increasing of ductility ratio in about 26% for ferrocement. Also, the increasing of concrete thickness and steel fiber ratio for RPC have the importance factors for ductility enhancement.

Table (6): Results of Tested domes

Dome	Pcr (kN)	Pu (kN)	Pcr/Pu (%)	Displacement (mm)			Ductility ratio (%)
				Vertical Top (VT)	Vertical Mid-height (VM)	Horizontal Mid-height (HM)	
DF1	2.50	8.75	28.57	3.28	0.55	0.63	19.05
DF2	3.75	13.75	27.27	3.59	1.05	0.68	23.93
DR1	5.00	23.75	21.05	3.52	1.17	0.72	27.08
DR2	6.25	27.00	23.14	4.05	1.32	0.75	31.15
DR3	8.75	45.75	19.10	3.81	1.52	1.05	29.31
DR4	10.00	56.25	17.80	4.21	1.56	1.15	32.23



DF1 DF2

DR1 DR2

DR3 DR4

Figure. (2) Cracks Patterns and Failure Mode for the Tested domes

From all above, it can be concluded that:

1. In general, domes with RPC have higher percent of cracking loads and this may be the reason for the more ductile failure mode that occurs for ultra-high strength concrete domes. This may be illustrated that, the composition of RPC gives tensile strength higher than of ferrocement concrete. In addition, the used micro steel fibers improve the concrete tension, strength of splitting and rupture.
2. The cracking loads increase with the increase in compressive strength of concrete.

From Figures (3 to 6), which represent the load-displacement relation for hemispherical domes casting from ferrocement and RPC, it can be noticed that, domes show the lowest value of vertical and horizontal displacements for domes which have the highest thickness and fiber steel ratio (DR4).

This leads to conclude that, the higher thickness for RPC domes will result in low displacements. It is obvious to notice that, the difference in vertical and horizontal displacements between the domes are an indicator on the importance of RPC mix and domes thickness. This means that, the domes of RPC are more suitable and behave in more ductility before of failure. It is also obvious from these figures that the curves for domes become close to each at the beginning of the curves.

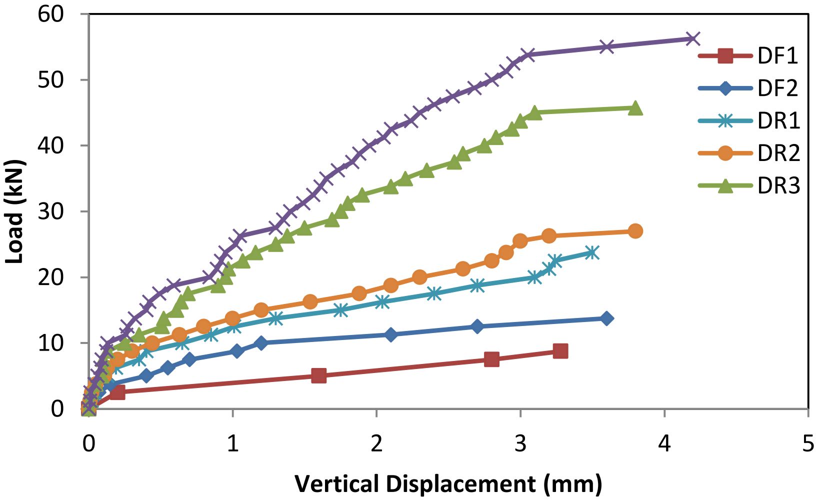


Figure. (3) Vertical displacement at top for all tested specimens.

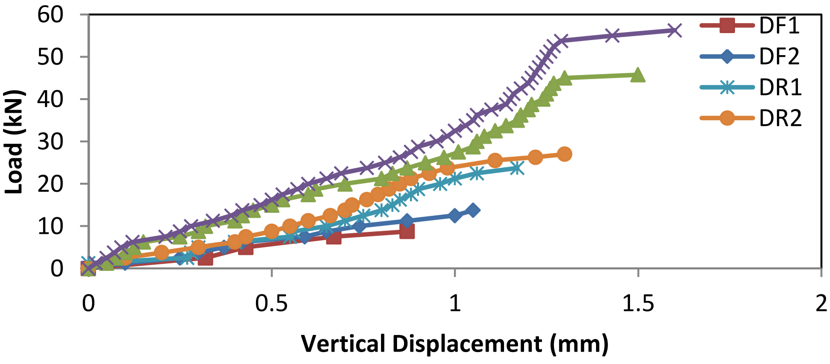


Figure. (4) Vertical displacement at mid-height for all tested specimens.

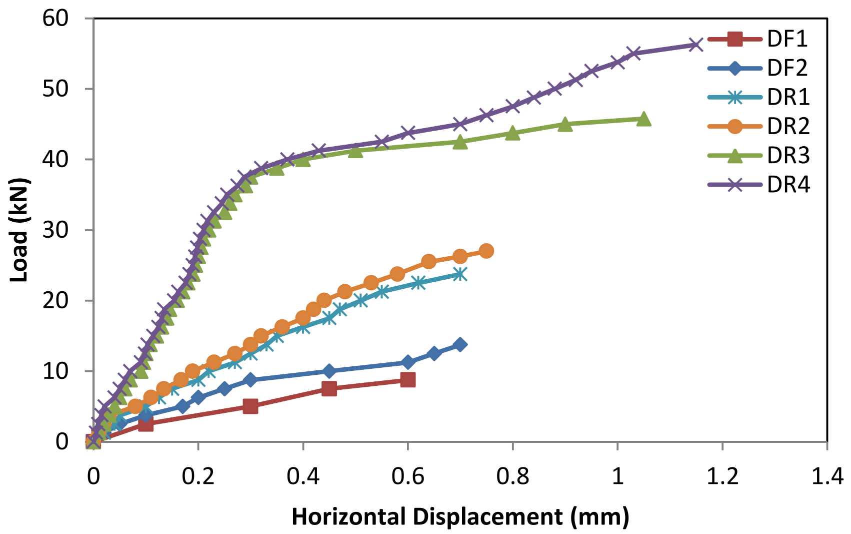
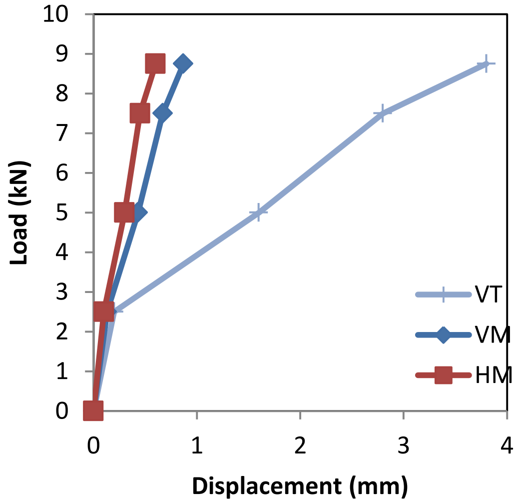
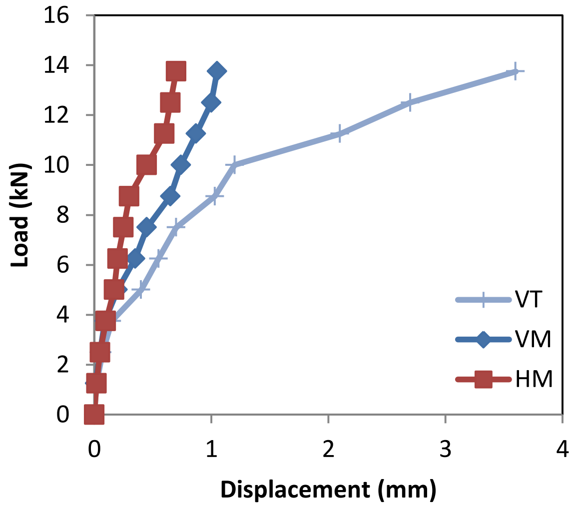


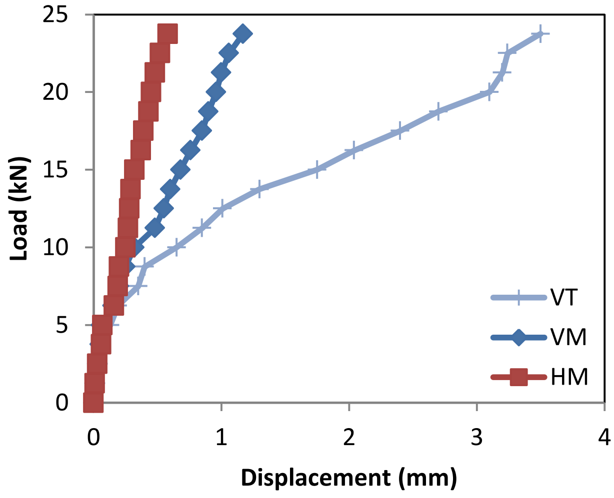
Figure. (5) Horizontal displacement at mid-height for all tested specimens.



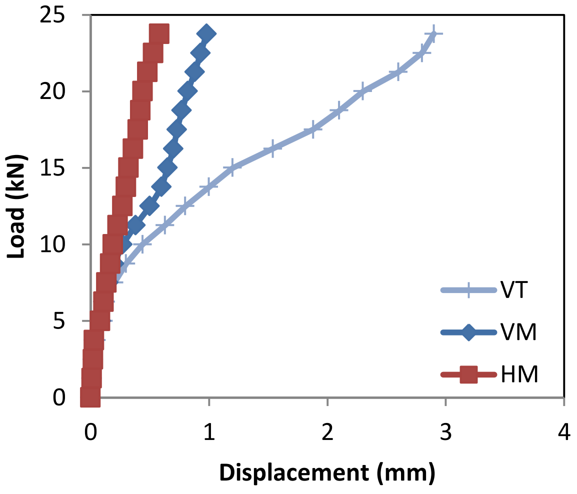
1-DF1



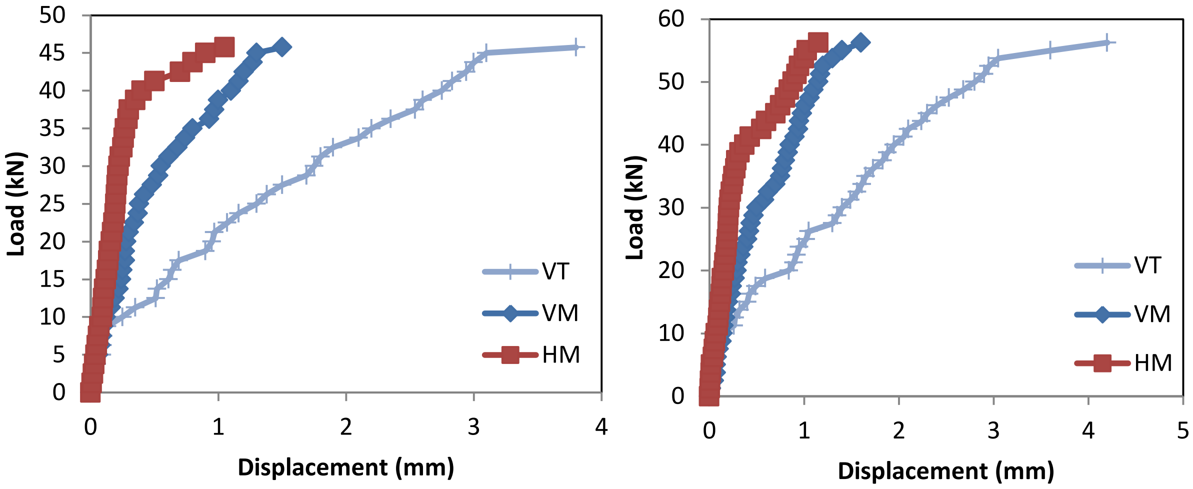
2-DF2



3- DR1



4- DR2



5- DR3

6- DR4

Figure. (6) Load- displacement relation for all tested specimens (VT:top vertical, VM: mid-span vertical, HM: mid-span horizontal displacement).

5. Conclusions

The following paper describes the structural behavior of hemispherical domes concentrically loaded at top and sitting on four supports. The results of the tested domes can be summarized in the following conclusions:

1. The ultimate strength capacity of concrete domes is affected by the concrete thickness. It is concluded that, the ultimate strength capacity of the dome increase with the increase in thickness. The increase in ultimate load for RPC is about 100%, for an increase in thickness from 15 mm to 20 mm.
2. The ultimate strength capacity of concrete domes is affected by concrete strength. The ultimate strength capacity of the dome increase with the increase in concrete strength. The increase in ultimate load for RPC is about 309%, for an increase in concrete strength from (40 to 195) MPa for dome when V_f= 2% and t= 20 mm (DR4 dome).
3. The ferrocement dome reinforced with two layers of welded weir meshes (DF2) gave higher cracking and ultimate load in comparison with dome reinforced by one mesh (DF1). The value of increasing is about 57% and 50% respectively for ultimate and first cracking load.
4. The ductility ratio increased with increasing of meshes reinforcement, concrete type and dome thickness. Ductility ratio is increased to 69% by using two welded wire meshes and change the concrete mix from ferrocement to RPC with 2% of V_f.
5. For RPC domes which have the same thickness, the effect of increasing of steel fiber ratio from 1% to 2% gives an increasing in ultimate load and cracking load by about 14% and 25%, respectively for domes which have 15mm thickness and 23% and 14%, respectively for domes which have 20mm thickness.

6. The most important conclusion of this work is the efficiency of using reactive powder concrete in construction of hemispherical domes by plastering.

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