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The use of ferrocement in the construction of squat grain silos

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Abstract. In this study, an investigation is made from the statics and economic aspects of the possibility of using the composite material ferrocement on the surfaces of squat cylindrical grain silos. For this purpose, the geometry of two model silos, each of height 5 m and diameter 5 m and 12.5 m, was designed. Five different reinforced plates of 10 and 20 mm thickness were produced to research the most suitable ferrocement plates to be used on the surface of these silos. Most durable reinforcement type for covering the silo surface was determined by pressure and bending tests. Grade 30 and Grade 55 steel plates were also considered for use in covering steel-coated silos. In the statics analysis performed with SAP2000, the least plate thicknesses needed for silos surfaced with Grade 30 and Grade 55 steel were found to be 6.20 mm and 4.70 mm respectively for silos of diameter 5 m, and 6.70 mm and 5.00 mm for silos of diameter 12.5 m. In the economic analysis, it was found that 20 mm thick Type 4 (with a wire diameter of 0.30 mm and a mesh aperture of 2 mm x 2 mm square type) reinforced ferrocement surfacing material was 5.6-6.1 times more economical than Grade 30 steel surfacing material and 4.4-4.7 times more economical than using Grade 55 steel. These results show that ferrocement can be used in place of steel from the point of view both of statics and economy.

Keywords: ferrocement; silo; structural analysis

1. Introduction

Post-harvest loss, insect pests, inadequate grain storage practices and the absence of storage management are problems which often force small farmers into selling their product immediately after harvesting when prices are low, only to buy it back at a high price just a few months after harvest, thus causing them to fall into a poverty trap. Therefore, storage is a part of the farming system and is necessary for keeping and maintaining grains to ensure household food supply. (Tefera *et al.* 2011). In addition to this, agricultural storage structures are a necessity due to year-to-year variation in the production and consumption of cereal grain (wheat, barley, maize, oats, rye, rice, etc.). The best known agricultural storage structures are silos, which are built to store such non-cohesive particulate materials as grains. These can be stand-alone or form part of an engineering structure (TSE 1989).

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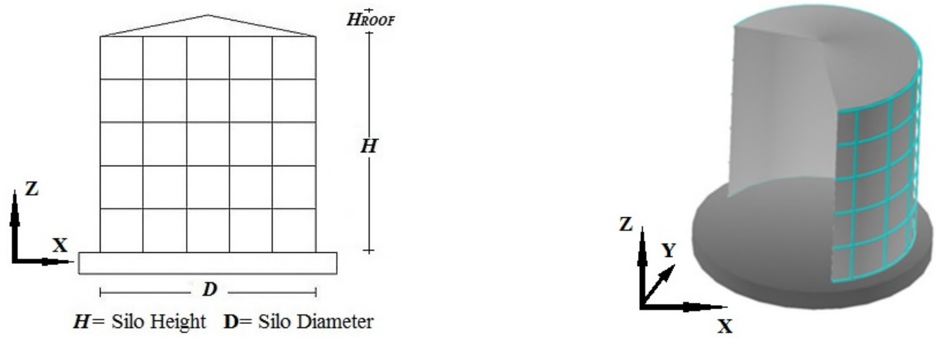
For example, since the 1980s when metal silo technology was established for safe storage, more than 230,000 small metallic silos have been introduced to prevent food losses in Central America. Since then, this technology has been used in many countries as a valid option for small and medium scale farmers to protect stored grains against pests (Tefera *et al.* 2011). Steel as a mass produced material and with a fewer risk factors is widely used as a silo construction material.

Maynard (2013) stated the many advantages of concrete silos compared with metal silos. For example they are less prone to corrosion, have no need of painting and cost less for large diameters. Steel silos carry the risk of wall thinning due to corrosion and of spoilage of the stored product. At the same time, the use of steel in place of concrete in silos increases the cost of construction. For this reason, it has been felt necessary to find a more economical material than steel, particularly to meet the needs of agricultural operations with low capacity storage needs. Thus, there is a need for research into the possibility of using alternative materials such as ferrocement to replace steel in the construction of silos to store agricultural products such as cereals.

Many researchers have studied the behavior and ultimate strength of ferrocement under different environmental and loading conditions. Tests have included strength, ductility, and resistance to fire and chemicals, and cost comparisons have been carried out between ferrocement and conventional concrete (Alnuaimi *et al.* 2009). Ferrocement is a composite material used in the production of thin shell components, made by strengthening cement with wire. Several layers of wire may be used to achieve the resistance needed for a shell component (McKinnon and Simpson 1975). Ferrocement as a high performance composite material has also found application in light weight structures of small thickness, but little research has been performed concerning the buckling behavior of ferrocement stiffened plates (Koukouselis and Mistakidis 2015). Ferrocement is used in many areas such as the construction of roofs, housing, wind turbines, water storage tanks and pools, as well as in boat-building and the repair of damaged structures. The principal reasons why ferrocement has such a wide range of uses are that it has higher resistance than thin shell concrete elements, it can be used to produce components of any desired shape, and it is simple to work with (Logan and Shaw 1973, Balaguru 1994). Ferrocement structures provide lower maintenance costs and longer lifetime in comparison with steel constructions (Ramli 2012). In a study, Kondraivendhan and Pradhan (2009) found that the ferrocement confinement increased the ultimate concrete compressive strengths by values of up to 78%. In the design of ferrocement structures, the finite elements method is preferred because of the sensitivity of the results it gives, and the program SAP2000 is widely used in structure analysis (CSI 2011).

Ferrocement plates are usually used as construction components in circular or curved form. Because of their geometric construction, the stresses on these components are along the axis of the material. This characteristic enables the use of ferrocement even as thin plates. This suggests that grain silos could be made of ferrocement, because the geometry and the stresses on the structure are similar to water storage tanks.

The most important factor in meeting the silo needs of agricultural operations and in spreading the use of silos is reducing cost. For this reason, it is worthwhile to research the use of ferrocement in silo construction, as it is easy and cheap to produce. In this study, the possibility of the use of ferrocement in the construction of silos to store cereal products has been investigated, and a comparison has been made of silos designed with ferrocement and steel liningsfrom the point of view of both statics and cost.



(a) Silo dimensions (b) Silo perspective

Fig. 1 Thin walled squat silo model

2. Material and method

2.1 The model silos

Two different types of model silos for use in grain storage were planned in the study, using lining materials of i) ferrocement and ii) steel plate.

These model silos were designed as thin-walled squat silos with a height/diameter ratio of 0.4-1 and a silo diameter/wall thickness ratio of over 200 (CEN 2006). Fig. 1 shows the characteristic dimensions (*H*=height; *D*=diameter) and the perspective images of the silos envisaged in the statics analysis. The aim of selecting this type of silo was to be able to construct it with simple building techniques and equipment. The design characteristics of the model silos are set out one by one below.

2.1.1 The ferrocement lined model silos

In designing these model silos, first of all beams for horizontal beams and vertical bearers were researched by statics analysis using SAP2000, so that extra load and displacement would not be

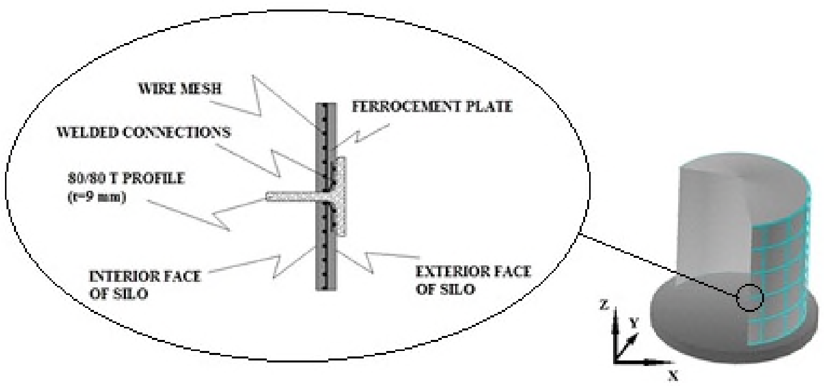


Fig. 2 Detail of ferrocement plate attachment to T beams

Table 1 Characteristic values of steel according to ASTM A 1011 standards (ASTM 2013)

Grade	Tensile Strength (MPa)	Yield Point (MPa)	Elongation (%)
Grade 30	min 340	min 205	21-25
Grade 55	min 480	min 380	9-15

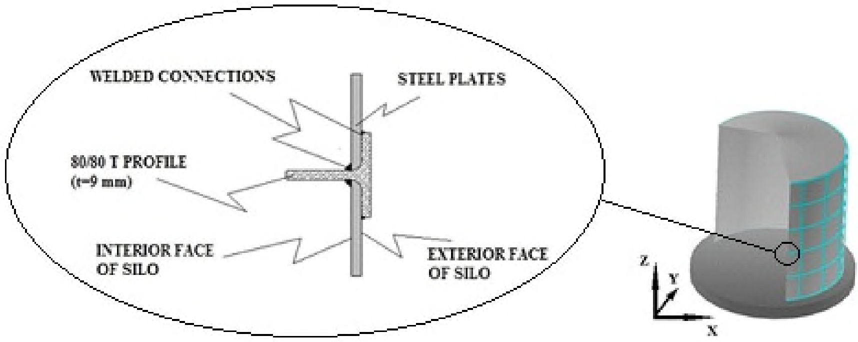


Fig. 3 Detail of steel plate attachment to T beams

caused to the plates. In the statics analysis of the beams, tensile and yield strengths were calculated taking the lowest safety coefficient value specified for steel components in TS500 (1.15) (TSE 2000). According to this, it was seen that 80/80 *T* beam of wall thickness 9 mm would be sufficient, and the structure was made out of these beams.

Covering the silo surfaces was achieved with ferrocement plates of 10 mm and 20 mm thickness made in the laboratory. In these silos, the horizontal beams and the vertical bearers were welded together so as to form 1m×1m openings, the ferrocement plate reinforcement was welded on to these beams, and later the ferrocement (ferrocement plate) surface of the silo was formed by spreading mortar on to this reinforcement. Details of the connection of the ferrocement plates to the T beams are shown in Fig. 2.

2.1.2 Steel lined model silos

Steel lined silos are widely used throughout the world, so in the design of the steel lined model silos, the covering was carried out with Grade 30 and Grade 55 steel plates produced according to the A 1011 standards of the ASTM (American Society for Testing and Materials). These steel grades include steels with the lowest and highest physical characteristics of the group of general construction steels of ASTM standards (ASTM 2013). The characteristics of Grade 30 and Grade 55 steels as specified in ASTM A 1011 standards are given in Table 1.

In the construction of these model silos the steel plates were welded on to the T beams. The connection details are shown in Fig. 3.

2.2 Laboratory studies

2.2.1 Production of ferrocement plates

(a) Plates during the production process (b) Plates during the setting process

Fig. 4 Production of ferrocement plates

Table 2 Physical and chemical properties of CEM I 42.5 R type cement used in ferrocement plate production

Physical Properties		Chemical Properties	
Specific Weight	2.98 gr/cm^3	Ignition Loss	% 1.20
Specific Surface (Blaine)	3135 cm^2/gr	SiO_2	% 19.80
Volume Expansion	3 mm	Al_2O_3	% 5.71
Initial Set	160 min.	Fe_2O_3	% 3.14
Final Set	235 min.	CaO	% 63.23
2-day Compressive Strength	25.0 MPa	MgO	% 2.43
7-day Compressive Strength	34.4 MPa	SO_3	% 2.85
28-day Compressive Strength	49.1 MPa	Cl	% 0.006

Different values have been reported in studies of the production of ferrocement plates of different thicknesses, amounts of reinforcement and mortar mix proportions regarding the ratio of the surface area of the reinforcement of ferrocement to its volume. This ratio is given by the ACI (American Concrete Institute) as 0.08 mm^2/mm^3, but some other researchers have reported a value of 0.2 mm^2/mm^3 or 1 mm^2/mm^3 (ACI 1988, Gambhir 2013).

In order to determine the modulus of elasticity of ferrocement plates in the ferrocement lined model silos, ferrocement plates were produced with dimensions of 300×600 mm and two different thicknesses and five different reinforcements (Fig. 4). Special ferrocement mortar was used in the production of these plates. In the preparation of this mortar, the cement/aggregate ratio was based on the recommended rate of 1/2 by weight. The water/cement ratio used in the construction of simple water storage tanks is 2/5 by weight, and should not be more than 3/5. In order to secure the highest level of waterproofing, the water/cement ratio should not be less than 3/10 (Nervi 1981). For this reason, the ferrocement plates in the study were produced with a water/cement ratio of 2/5 by weight.

In producing the ferrocement mortar, the use of type1 or type 2 normal Portland cement, sand cleansed of organic matter, and water cleansed of organic material and acidic chemicals is recommended (Pieck 1977). Accordingly, CEM I 42.5 R type Portland cement and sand with a unit volume weight of 1.547 gr/cm^3 and a particle size of less than 2.36 mm was used. The

Table 3 Granulometric structure of sand as recommended by ACI and used in the study in the production of ferrocement

Sieve Aperture Size (mm)		2.36	1.18	0.600	0.300	0.150	0.075
Passing Through by Weight (%)	Recommended (CEN 2006)	100-80	85-50	60-25	30-10	10-2	-
	Used	100	82.36	57.03	24.68	3.02	0.11

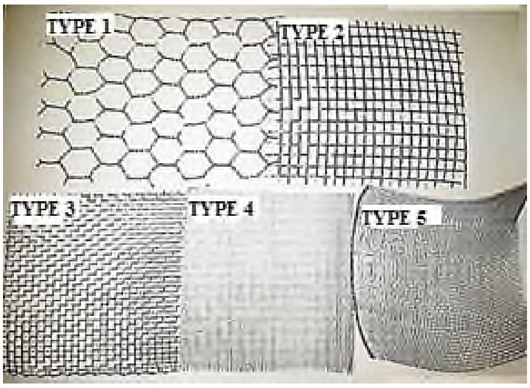


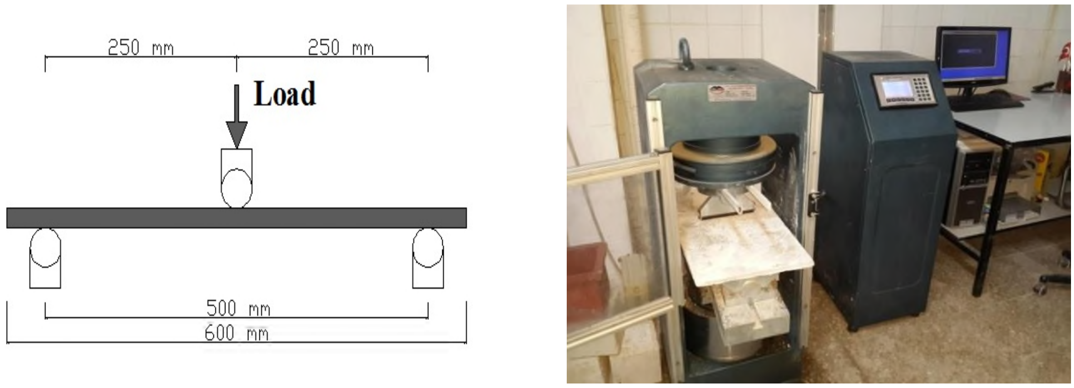
Fig. 5 Types of reinforcement used in the production of ferrocement plates

Table 4 Characteristics of types of reinforcement used in the production of ferrocement plates

Reinforcement Type	Reinforcement Wire Diameter	Reinforcement Mesh Aperture and Type	Surface Area of Reinforcement Wire per Unit Volume of Ferrocement Plates of Various Thicknesses (mm^2/mm^3)	
			10 mm thickness	20 mm thickness
Type 1	0.40 mm	12 mm (hexagonal)	0.033	0.016
Type 2	0.65 mm	4 mm×5 mm (rectangle)	0.074	0.037
Type 3	0.50 mm	3 mm×3 mm (square)	0.104	0.052
Type 4	0.30 mm	2 mm×2 mm (square)	0.111	0.055
Type 5	0.20 mm	1 mm×1 mm (square)	0.113	0.057

physical and chemical properties of the cement used are given in Table 2, while Table 3 shows the granulometric structure of the sand as recommended by the ACI and as used in the study.

Ferrocement plates must be supported by main reinforcements which will resist tensile stress and at the same time form a skeleton, and secondary reinforcements which will transmit stress in the plates to these main reinforcements. Shaheen *et al*. (2014) found out that beams reinforced with metal wire mesh emphasized better cracking patterns than those reinforced with non-metallic mesh. This could be attributed to the higher mechanical properties of metallic mesh compared with non-metallic mesh. It is recommended that as main reinforcement, 6 mm diameter steel rods should be laid horizontally and vertically at 15 cm intervals, and that chicken wire with 12 mm gaps and a diameter of 0.40 mm should be used (Thomas 1998). In the construction of 10 mm and 20 mm thick ferrocement plates in this study, five different reinforcements were used: along with the commonly used hexagonal chicken wire, sieve wire with rectangular or square gaps of four



(a) Experiment setup (b) Hydraulic press

Fig. 6 3-point bending test conducted on ferrocement plates

different thicknesses and gap sizes was used with the aim of reducing the amount of reinforcement in accordance with ACI committee 549 report. These reinforcement types are shown in Fig. 5, and their dimensions are given in Table 4.

2.2.2 Laboratory tests

In order to determine the characteristic compressive strength of the ferrocement mortar, a pressure experiment was performed using a concrete test press. For this experiment, cubic samples measuring 150 mm×150 mm×150 mm were prepared. The compressive strength of the concrete was calculated according to TS500 according to the average breaking values in the press of three samples each of 7 and 28-day concrete. In these calculations, the value of 1.50 given in TS500 for concrete was taken as the basis for the safety coefficient (TSE 2000).

For statics analysis, it is necessary to know the elasticity modulus of the ferrocement plates produced (Mehta 1986). For determining elasticity modulus, there are many empirical approaches in different standards, developed by a large number of researchers. However, according to these empirical approaches, the elasticity modulus for the same ferrocement mortar can vary in the range of 16600-31100 MPa. Therefore, the elasticity modulus must be determined experimentally (Arif and Kaushik 1999).

In order to determine the behaviour of each ferrocement plate produced under stress, 3-point bending tests were performed twice with three iterations after 7 and 28-day curing. For this reason, a total of 60 ferrocement plates of dimensions 30×60 cm were produced, six each for every reinforcement type and plate thickness. The 3-point bending test was performed manually on the 10 mm-thick plates and using the press machine on the 20 mm plates. The 3-point bending test setup applied to the plates and the hydraulic press used are shown in Fig. 6. The tests showed the amount of load which caused cracks in the plates. The amount of deflection of the plates under this load was measured with a gauge with a sensitivity of $\pm 10^{-3}$ mm.

The following equation was used to calculate the elasticity modulus of the ferrocement plates according to the loads applied in the 3-point bending test and the measured amount of deflection under these loads.

$$E = \left(PL^3\right) / \left(48\Delta_X I\right) \tag{1}$$

Where E: elasticity modulus (MPa); P: plate load (Newtons); L: space between supports (mm); Δ_x: amount of deflection at centre of plate (mm); I: plate moment of inertia (mm^4).

2.3 Statics and cost analyses

In the statics analysis of the model silos, Eqs. (2)-(4) were used to calculate the values of horizontal pressure (P_{hf}) at depth z from the highest point of the stored material, the tensile force (P_{wf}) arising from friction at the surface and the vertical pressure (P_{vf}) of the stored solid (the cereal grains) under symmetrical filling conditions of the squat silo structure (Özel 2007).

$$P_{hf} = P_{ho}.Y.R = \left(\frac{\gamma.A}{\mu.U}\right).\left(1 - \left[\left(\frac{z - \frac{r.\tan\phi_r}{3}}{\frac{A}{K.\mu.U} - \frac{r.\tan\phi_r}{3}}\right) + 1\right]^{-(1+\tan\phi_r).\left(1 - \frac{r.K.\mu.U.\tan\phi_r}{3}\right)}\right) \tag{2}$$

$$P_{wf} = \mu.P_{hf} \tag{3}$$

$$P_{vf} = \gamma\left(\frac{r.\tan\phi r}{3} - \left(\frac{1}{1-(1+\tan\phi_r).\left(1-\frac{r.K.\mu.U.\tan\phi_r}{3}\right)}\right)\right).\left(\frac{A}{K.\mu.U} - \frac{r.\tan\phi_r}{3} - \frac{\left(z + \frac{A}{K.\mu.U} - \frac{2.r.\tan\phi r}{3}\right)^{1-(1+\tan\phi_r).\left(1-\frac{r.K.\mu.U.\tan\phi_r}{3}\right)}}{\left(\frac{A}{K.\mu.U} - \frac{r.\tan\phi r}{3}\right)^{-(1+\tan\phi_r).\left(1-\frac{r.K.\mu.U.\tan\phi_r}{3}\right)}}\right) \tag{4}$$

Where P_{ho}: asymptotic horizontal pressure at great depth due to stored particulate solid; Y_J: Janssen pressure depth variation function; γ: weight of stored material (grain) per unit volume; A: cross-sectional area of vertical silo wall; μ: coefficient of friction of vertical wall; U: circumference inside vertical wall section; z: depth below equivalent surface when full; r: silo

Table 5 Cereal properties (CEN 2006)

Type of Particule Solid	Unit weight, γ		Angle of repose, ϕ_r (degrees)	Lateral pressure ratio, K		Wall friction coefficient, μ		
	Lower, γ_i (kN/m^3)	Upper, γ_u (kN/m^3)		K_m	a_K	Stainless steel wall	Ferrocement wall	a_μ
				Mean	Factor	Mean	Mean	Factor
Barley	7.0	8.0	31	0.59	1.11	0.33	0.48	1.16
Maize	7.0	8.0	35	0.53	1.14	0.36	0.53	1.24
Soya Beans	7.0	8.0	29	0.63	1.11	0.38	0.48	1.16
Wheat	7.5	9.0	34	0.54	1.11	0.38	0.57	1.16

equivalent radius; ϕ_r: slope angle of stored material; K: coefficient of lateral pressure.

The lowest value of K was calculated as K_m/a_K, and the highest value as K_m*a_K. In this way, the lowest value of the coefficient of surface friction was found to be μ/a_μ, and the highest value was $\mu * a_\mu$.

In the statics analysis of the model silos, barley, maize, soya and wheat, which are recognized as grain products among silo-stored materials in Eurocode 1, were taken as a basis, and the characteristic values of these grains are given in Table 5 (CEN 2006).

Even though the stored material is non-liquid, analysis was performed to ensure that the structural cracks will not occure in order to prevent the entry of rain water into silo structure. Therefore SAP2000 analysis was performed on linear mod. Model silos was supported to foundation as fixed type. Also the surface plates are fixed supported to T beams because of the welded connections of reinforcement.

In the statics analysis, plates were meshed at dimensions of 20 cm by 20 cm in order to determine plate deformation in a more sensitive way. Thus each steel and ferrocement plate used in model silos was divided into 25 equal parts. The properties of the materials used in the construction of model silo were obtained from the test results for the ferrocement and from ASTM A 1011 standards for steel.

In the analysis of costs of lining the ferrocement-surfaced and steel-surfaced model silos, the thickness of the covering materials of the model silos which were found to be sufficient from the point of view of statics was determined, and the costs of covering materials for each silo was calculated according to the selling prices of these materials in current market conditions (Aksteel 2015, Lme 2015).

3. Findings and discussion

3.1 Experimental results of ferrocement plates

The averages of the results obtained from breaking the prepared cubic samples in the concrete test press in order to determine the compressive strength of the ferrocement were measured as 20.56 N/mm^2 for the seven-day samples and 28.34 N/mm^2 for the 28-day samples.

Table 6 shows the load which brought about the first crack in the plates and the amount of deflection at the moment when the plates cracked in the 3-point bending tests performed on the ferrocement plates. An examination of Table 6 shows that the percentage of reinforcement in the ferrocement had an effect on the resistance of the plate. However, the percentage of reinforcement alone did not determine plate resistance: another important factor was the amount of tensile force which the reinforcement was able to meet. In comparing the first cracking loads of the plates, it was seen that even though the amount of reinforcement was greater in plates with type5 reinforcement, plates with type 4 reinforcement had greater resistance to cracking (see Table 6).

Table 7 shows elasticity moduli for ferrocement plates produced at thicknesses of 10 and 20 mm for each reinforcement type calculated with the help of Equation 1 according to the results of the 3-point bending tests. The highest resistance was shown by the elasticity modulus of type 4 reinforced plates at 28 days, with 12649.26 MPa for 10 mm thickness and 22843.57 MPa for 20 mm thickness (see Table 7). Because of its higher elasticity modulus results, type 4 reinforced plates were selected to compare with steel linings.

Table 6 Ferrocement plate breaking loads and amounts of deflection type of particle

Plate Type	Thickness 10 mm				Thickness 20 mm			
	7 Day		28 Day		7 Day		28 Day	
	First Crack Load (kN)	Deflection (mm)	First Crack Load (kN)	Deflection (mm)	First Crack Load (kN)	Deflection (mm)	First Crack Load (kN)	Deflection (mm)
Type 1	0.105	2.364	0.134	2.348	0.392	0.548	0.540	0.701
	0.085	1.904	0.108	1.944	0.459	0.622	0.618	0.765
	0.093	2.142	0.119	2.104	0.513	0.802	0.652	0.912
Type 2	0.157	1.716	0.162	1.756	0.413	0.335	0.642	0.532
	0.106	1.475	0.147	1.604	0.471	0.412	0.612	0.386
	0.113	1.618	0.141	1.505	0.484	0.446	0.714	0.586
Type 3	0.140	1.153	0.195	1.902	0.705	0.589	0.922	0.673
	0.193	2.262	0.202	2.121	0.622	0.455	0.895	0.602
	0.182	2.024	0.198	1.989	0.642	0.503	0.953	0.745
Type 4	0.158	1.436	0.204	1.715	0.792	0.491	0.958	0.513
	0.185	2.045	0.195	1.586	0.703	0.452	1.125	0.662
	0.174	1.852	0.219	1.788	0.685	0.401	1.026	0.597
Type 5	0.182	1.639	0.193	1.623	0.706	0.428	1.102	0.736
	0.161	1.438	0.201	1.673	0.739	0.520	0.917	0.434
	0.146	1.257	0.212	1.876	0.711	0.441	0.997	0.639

Table 7 Calculated moduli of elasticity of ferrocement plates

Plate Type	Elastic Modulus (MPa)			
	10 mm-Thick Plate		20 mm-Thick Plate	
	7. Day	28. Day	7. Day	28. Day
Type 1	4598.93	5878.97	9003.84	9907.16
Type 2	8144.64	9634.57	14930.57	17036.60
Type 3	9861.97	10308.43	16572.41	17857.24
Type 4	10097.95	12649.26	21113.58	22843.57
Type 5	11752.02	12204.65	20215.70	21701.39

3.2 Model silo statics analysis results

Changes according to depth (the distance from the free surface of the grain to the bottom of the silo) of horizontal pressure (P_{hf}), friction attraction (P_{wf}), and vertical pressure (P_{vf}) in model silos designed with dimensions D=5 m and D=12.5 m for H=5 m were calculated with the help of equations 2, 3 and 4. The results are given in Table 8. It was found that the greatest force acting on the silos was on 12.5 m silos at a depth of 5 m, and that this force occurred for steel lined silos

Table 8 Variation with depth of loads for *D*=5 m and *D*=12.5 m model silos according to cereal variety

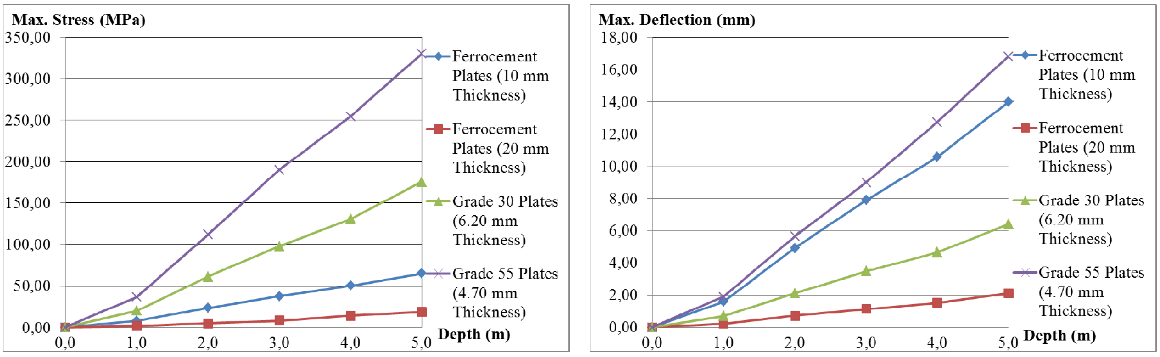
Cereal Varieties	Depth (m)	Steel Wall Silo						Ferrocement Wall Silo					
		P_{hf} (kPa)		P_{wf} (kPa)		P_{vf} (kPa)		P_{hf} (kPa)		P_{wf} (kPa)		P_{vf} (kPa)	
		D=5 m	*D*=12.5 m	*D*=5 m	*D*=12.5 m	*D*=5 m	*D*=12.5 m	*D*=5 m	*D*=12.5 m	*D*=5 m	*D*=12.5 m	*D*=5 m	*D*=12.5 m
Barley	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	3.68	2.16	1.41	1.52	7.71	7.88	3.48	3.88	1.94	2.16	7.59	3.88
	2	8.88	5.67	3.40	4.15	13.72	14.95	7.75	10.17	4.32	5.67	12.99	10.17
	3	12.32	8.36	4.72	6.32	18.45	21.27	10.23	15.00	5.70	8.36	16.94	15.00
	4	14.74	10.48	5.64	8.15	22.28	26.95	11.83	18.81	6.59	10.48	20.00	18.81
	5	16.52	12.18	6.32	9.70	25.48	32.08	12.93	21.87	7.20	12.18	22.47	21.87
Maize	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	3.03	3.26	1.35	1.46	7.77	7.90	2.86	3.19	1.88	2.09	7.67	7.86
	2	8.06	9.95	3.60	4.44	13.71	14.94	6.94	9.28	4.56	6.10	12.97	14.51
	3	11.22	15.36	5.01	6.86	18.23	21.12	9.15	13.81	6.01	9.07	16.69	20.06
	4	13.37	19.81	5.97	8.84	21.81	26.60	10.51	17.27	6.90	11.35	19.49	24.78
	5	14.91	23.53	6.66	10.50	24.75	31.49	11.42	20.00	7.50	13.14	21.72	28.85
Soya Beans	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**
	1	3.97	4.38	1.75	1.93	7.60	7.83	3.80	**4.30**	2.12	**2.39**	7.51	**7.79**
	2	8.80	11.15	3.88	4.92	13.28	14.72	8.02	**10.66**	4.47	**5.94**	12.78	**14.43**
	3	11.82	16.57	5.21	7.31	17.60	20.75	10.44	**15.51**	5.81	**8.64**	16.63	**20.08**
	4	13.86	20.99	6.11	9.26	21.05	26.09	11.98	**19.31**	6.68	**10.75**	19.61	**24.96**
	5	15.31	24.65	6.75	10.87	23.90	30.86	13.05	**22.34**	7.27	**12.44**	22.02	**29.24**
Wheat	0	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	0.00	0.00	0.00	0.00	0.00
	1	3.50	**3.77**	1.54	**1.66**	8.72	**8.88**	3.29	3.67	2.17	2.43	8.60	8.83
	2	9.04	**11.12**	3.99	**4.90**	15.43	**16.81**	7.75	10.35	5.12	6.84	14.55	16.31
	3	12.58	**17.12**	5.55	**7.55**	20.57	**23.81**	10.18	15.33	6.73	10.14	18.75	22.56
	4	15.01	**22.08**	6.62	**9.73**	24.68	**30.03**	11.69	19.16	7.73	12.67	21.94	27.90
	5	16.76	**26.24**	7.39	**11.57**	28.06	**35.62**	12.71	22.18	8.40	14.66	24.47	32.51

with wheat, and for ferrocement lined silos with soya (see Table 8).

In the statics analysis of the model silos, the loads on the plates forming the silo surfaces according to their depth were taken as irregularly distributed loads. According to this analysis, the least plate thicknesses to safely withstand this load for model silos of dimensions H = 5 m and D = 5 m were determined to be 6.20 mm for grade 30 steel and 4.70 mm for grade 55 steel. The highest compressive stress and deflection values occurring in 1 m×1 m plates on the surface of the silos in

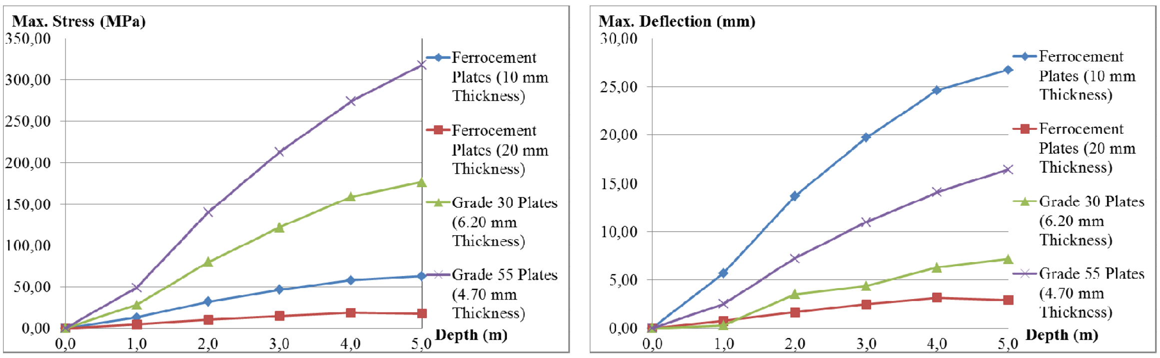
Table 9 Economic comparison of silo surface coating materials

Coating Material	Thickness (mm)	Cost	
		($/mm)	($/m^2)
Ferrocement (Type 4)	20.00	0.288	5.76
Grade 30	6.20-6.70	5.240	32.49-35.11
Grade 55	4.70-5.00	5.432	25.53-27.16



(a) Max. Stress Graph (b) Max. Deflection Graph

Fig. 7 Variations in compressive stress and deflection values of 1 m x 1 m ferrocement and steel plates used on the surfaces of silo models of dimensions *H*=5 m and *D*=5 m



(a) Max. Stress Graph (b) Max. Deflection Graph

Fig. 8 Variations in compressive stress and deflection values of 1 m x 1 m ferrocement and steel plates used on the surfaces of silo models of dimensions *H*=5 m and *D*=12.5 m

connection with silo depth are given in Table 9 for model silos of dimensions H = 5 m and D = 5 m, and in Table 10 for model silos of dimensions H = 5 m and D = 12.5 m.

The safe stress value (28.34 MPa / 1.5 = 18.89 MPa) for ferrocement plates with an elastic modulus of 22843.57 MPa and cube compressive strength of 28.34 MPa, type 4 reinforcement and a thickness of 20 mm was greater than the maximum stress value of 18.61 MPa acting on the plates of the 5 m diameter model silo (see Table 9) and the maximum stress value of 18.40 MPa

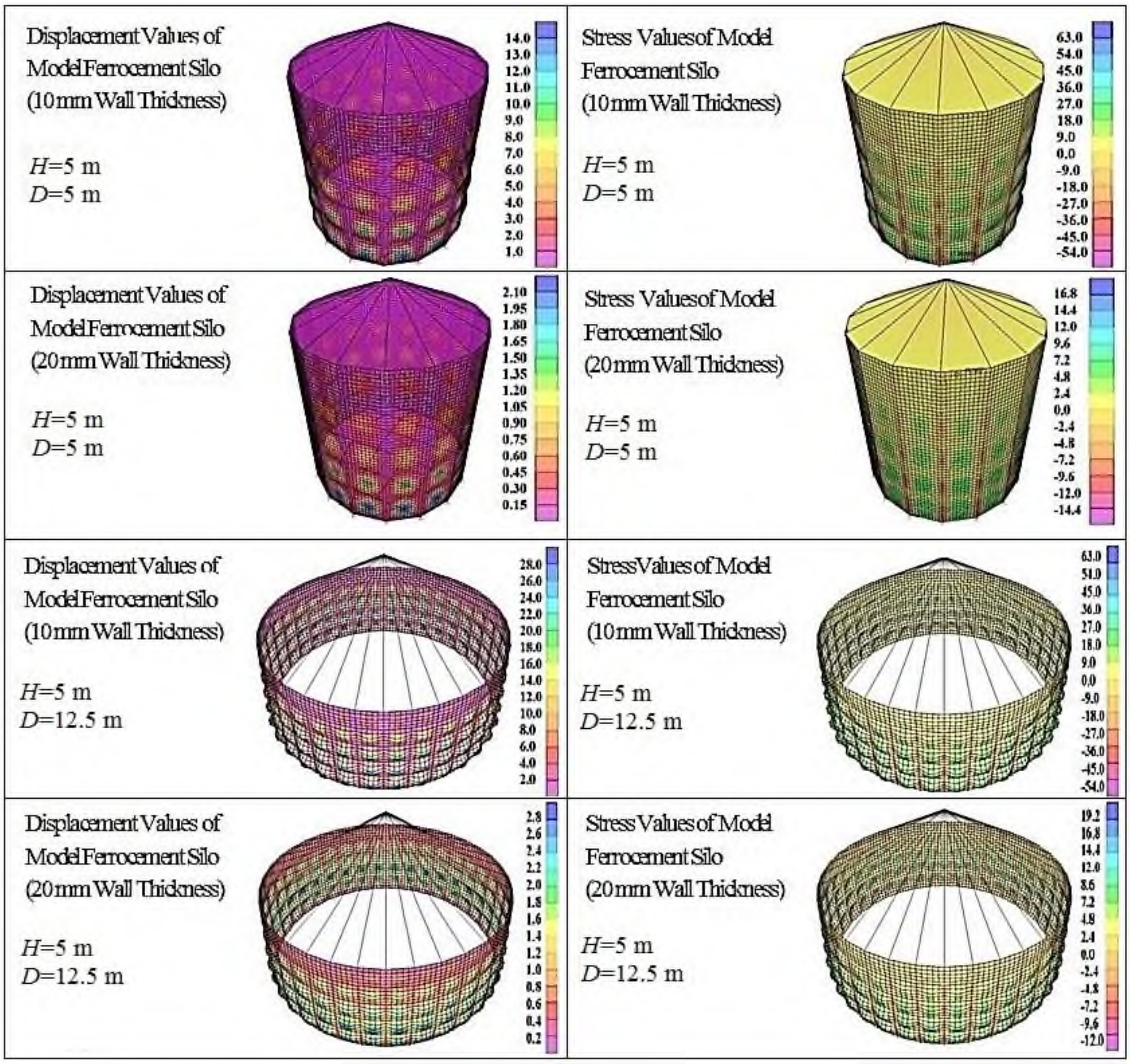


Fig. 9 SAP2000 screen images of stress (MPa) and deformation (mm) in ferrocement lined model silos

acting on the plates of the 12.5 m diameter silo (see Table 10). This shows that 20 mm thick plates with type 4 reinforcement can be safely used in model silos of either diameter.

However, the safe stress value (20.56 MPa / 1.5 = 13.71 MPa) of 10 mm thick type 4 reinforced plates, which had an elastic modulus of 12649.26 MPa and a cube compressive strength of 20.56 MPa, was found to be less than the values of 23.42 MPa and 31.98 MPa occurring at a depth of 2 m in the two model silos. For this reason, it was concluded that it would be impossible to store grain at a depth of greater than 1 m in silos of either diameter built with plates of 10 mm thickness and type 4 reinforcement (see Table 9, Table 10).

SAP2000 screen images concerning the analysis of the maximum stress values and amounts of deflection occurring in plates used in model grain silos with ferrocement and steel linings are shown in Fig. 7 and Fig. 8 respectively. For the finite element simulation to provide an acceptably

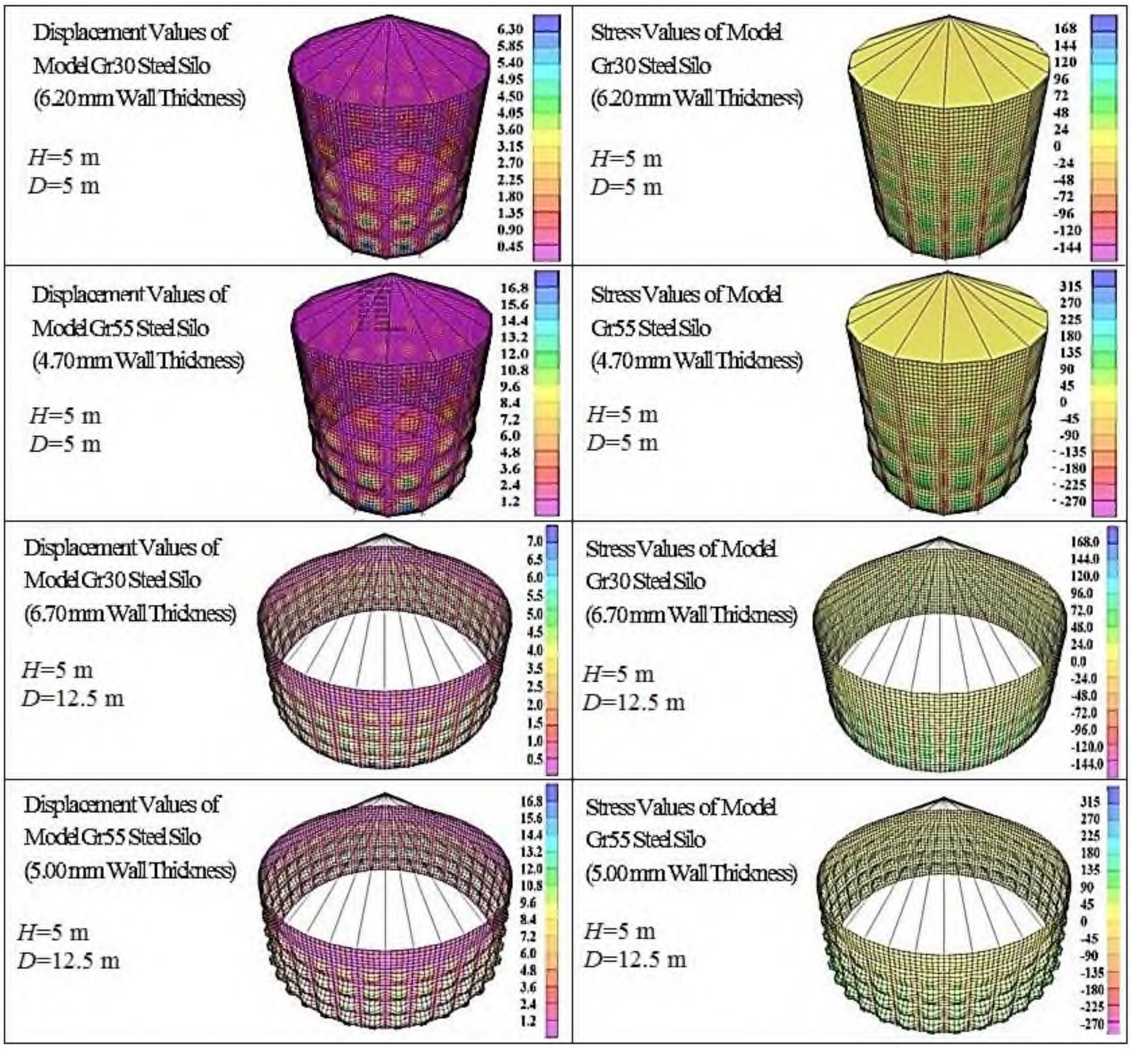


Fig. 10 SAP2000 screen images of stress (MPa) and deformation (mm) in steel lined model silos

accurate result, a sufficiently refined finite element mesh is necessary (Mokhatar *et al*. 2012). As can be seen in both figures, lateral load increased as the silo diameter increased, and in relation to this the values of stress and deflection occurring in the plates also increased. In addition, it was observed that stresses increased at the side lines of where the plates were supported, and deflection increased in the middle of the plates. Also, it was seen that silos lined with ferrocement plates showed considerably less deflection than those lined with steel plates.

3.3 Model silo economic analysis results

In order to produce a 1 m^2 ferrocement plate for use in a ferrocement lined model silo, 20 dm^3 (30.94 kg) of aggregate, 5.19 dm^3 (15.47 kg) of cement, 2.1 L of water and 1.05 m^2 including 5% loss of sieve or chicken wire must be used. Taking current market prices of the materials, the proportions of the total costs of silo production excluding labour were calculated as follows: reinforcement 43.5% ($3.47), cement 44% ($1.77), and aggregate 13% ($0.52).

At current market prices, the cost of the grade 30 and grade 55 hot-rolled steel needed for a steel-lined model silo was determined as $685-710/ton depending on thickness (15). Thus the cost of 1 m^2 of steel plate of 1 mm thickness was calculated as $5.24-$5.432.

Table 11 shows a comparison from an economic viewpoint of lining materials showing sufficient robustness in the design of model grain silos. It was seen that a ferrocement lining of 20 mm thickness and type 4 reinforcement was 5.6-6.1 times as economical as the use of grade 30 steel and 4.4-4.7 as economical as the use of grade 55 steel (see Table 11).

4. Conclusions

In this study, an evaluation was made of the practicality from the viewpoint of statics and economy of the ferrocement concrete technique in the construction of silos for use in storing grain, on squat model silos 5 m in height and 5 m and 12.5 m in diameter. The ferrocement silos were lined with ferrocement plates of two different thicknesses (10 mm and 20 mm) using ferrocement concrete mortar and five different types of reinforcement. The steel silos were lined with two types of steel plate of grade 30 and grade 55 steel. Later, calculations were made of the stress caused by four different stored grains (barley, maize, soya and wheat) according to the height of the silo. According to these values, it was found that the stress values for 20 mm thick ferrocement plates with type 4 reinforcement (wire thickness 0.30 mm and square gaps of 2 mm×2 mm) (elastic modulus 22843.57 MPa and cube pressure resistance 28.34 MPa) was above the stress values created by all the grains to be stored. Thus, it was concluded that 20 mm thick plates could safely be used for squat ferrocement lined silos of either diameter. In the case of 5 m steel lined silos, it was found that the least plate thicknesses needed to resist these stresses were 6.20 mm for grade 30 steel and 4.70 mm for grade 55 steel. With silos of 12.5 m diameter, the least plate thicknesses needed were determined to be 6.70 mm for grade 30 steel and 5.00 mm for grade 55 steel.

In the economic analysis of the materials which showed sufficient resistance for the construction of the model silos taking into account market prices and excluding labour, ferrocement lining of 20 mm thickness and type 4 reinforcement was shown to be 5.6-6.1 times more economical than lining with grade 30 steel, and 4.4-4.7 times more economical than the use of grade 55 steel.

These results show the practicality of using ferrocement in lining grain silos from the viewpoint of statics and economy compared with widely-used steel construction. In other words, ferrocement plates produced with the reinforcement type and dimensions determined in statics analysis are to be preferred to steel plates in the construction of grain silos of different dimensions, and in this way grain storage can be provided in silos which are more economical.

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