End of Project Report

SEPTEMBER 1999

Project No. 4424

EVALUATION OF MIX SPECIFICATION AND PFA AS A CEMENT REPLACER IN CONCRETES USED IN SILAGE STORAGE STRUCTURES

Beef Production Series No. 22

Authors

J.J. Lenehan and P. O'Kiely

Teagasc, Grange Research Centre, Dunsany, Co. Meath
in collaboration with M. Richardson, Dept. of Civil Engineering, UCD

Teagasc
Agriculture and Food Development Authority

GRANGE RESEARCH CENTRE,
Dunsany,
Co. Meath
ISBN 1 84170 088 6
September 1999

EUROPEAN UNION
European Agricultural
Guidance and Guarantee Fund

CONTENTS

INTRODUCTION

The most popular method of harvesting silage is by metered chop harvesters with a very short time interval allowed between mowing and picking up the crop. The mean dry matter concentration of the silage produced is 211 g/kg (O'Kiely, P. *et al* 1993). Concrete silos are typically used in Ireland for the storage of silage. They allow the efficient utilisation of storage space, facilitate the anaerobic storage of the crop, permit the safe collection of any effluent produced and aid the effective removal of the silage for feeding. The system of conservation produces large volumes of effluent which has a B.O.D. value of 12,000-90,000 mg O_2/l (McDonald, P. *et al* 1991). This effluent must be effectively contained and managed, usually by landspreading, to avoid pollution. The volume produced is typically 140 l/t (DAFF, 1985). The effluent contains a range of organic acids (e.g. lactic acid, acetic acid and other volatile fatty acids) and typically has a pH value of approximately 4.0 (O'Donnell, C. *et al* 1995). The concrete in the silos is susceptible to corrosion by the acids in the effluent. At present, concrete for silage storage structures is specified by the Irish Farm Development Service (DAFF, 1992) in terms of a characteristic 28 day crushing strength of 40 N/mm^2 and a minimum cement content of 350 kg/m^3. In addition, the maximum aggregate size used must not exceed 20 mm and the slump of the unplasticised concrete must not exceed 75 mm. There is no stipulation on the maximum water to cement ratio to be used. This specification represents a high strength concrete for agricultural use and has been upgraded to this level in an attempt to improve the material's resistance to corrosion by silage effluent. A cement content of 350 kg/m^3 is regarded as a relatively high cement content and may promote thermal cracking in the structures (Blackledge, 1990). This would result in a concrete which would be more susceptible to attack by corrosive effluent. A system of carrying out accelerated durability tests on concrete specimens under controlled conditions has been developed by Teagasc and University College Dublin (O'Donnell, C., 1993). Trials carried out by O'Donnell, indicated that cement content had little influence on the durability of concretes exposed to silage effluent for the ranges of mixes examined, but the use of excess water resulted in marked increases in deterioration. The present study aims to further examine the effect of (i) cement content and (ii) the use of PFA as a cement replacer.

MATERIALS AND METHODS

Experimental facility

An existing experimental facility, developed by O'Donnell *et al.* (1995) was upgraded for use in controlled accelerated tests. Panels of concrete, nominal plan dimensions 0.280 m x 0.280 m and 0.075 m thick, were subjected to a constant flow of effluent at a rate of 143 l/m^2 days over 10 cycles, with each cycle being of 28 day duration. The flow rate and cycle duration were based on observations of the typical flow rate experienced at the front of a 200 t silo draining from back to front. The volume of flow and length of each cycle replicated the volume and expected period of effluent flow at the front of a well-drained 200 t horizontal silo in service. The rig did not, however, simulate the additional effect of mechanical wear.

A total of 6000 l of effluent from grass silage was collected for use in this experiment. The effluent had a pH of 4.0 and a dry matter content of 65 g/kg, which is typical of grass silage in Ireland. The lactic acid content was 20 g/kg and the acetic acid content was 5.0 g/kg. The effluent was pumped (Monopump, CM311) from the bulk storage tank (capacity 6000 l) through a filter (40 x 10^{-6} m pore size) into a 100 l plastic feeder tank. The effluent flowed by gravity through 19 mm internal diameter flexible tubing to nine 20 l header tanks. Each header tank supplied 15 stainless steel needles (22 gauge Misawa) with effluent at constant head, through 8 mm internal diameter p.v.c. tubing, followed by a short length of 4 mm silicone tubing, maintaining a flow rate of 143 l/m^2/days. A significant design feature of the rig is that the specimens are subjected to flowing effluent, as occurs in practice, and the specimens are not immersed. The effluent was distributed over the top surface of the concrete test panels using a single layer of hessian cloth saturated in effluent. Each concrete panel was subjected to a controlled flow of effluent from a nozzle overhead, one nozzle per specimen. Flow rates were checked at least twice per week. Fifteen concrete panels (three treatments) were placed in each stainless steel tray (2.3 m x 1.1 m x 0.1 m) in three rows (one treatment per row) along the length of the tray. The panels were raised off the bottom of the trays by timber battens 0.025 m square. A galvanised steel grid was positioned across the trays to maintain the nozzles in the desired position. The effluent was drained from each of the nine trays into a 100 l tank from where it was pumped back into the main storage tank as shown in Figure 1. The effluent was sampled and analysed fortnightly to check for consistency of composition during the experiment.

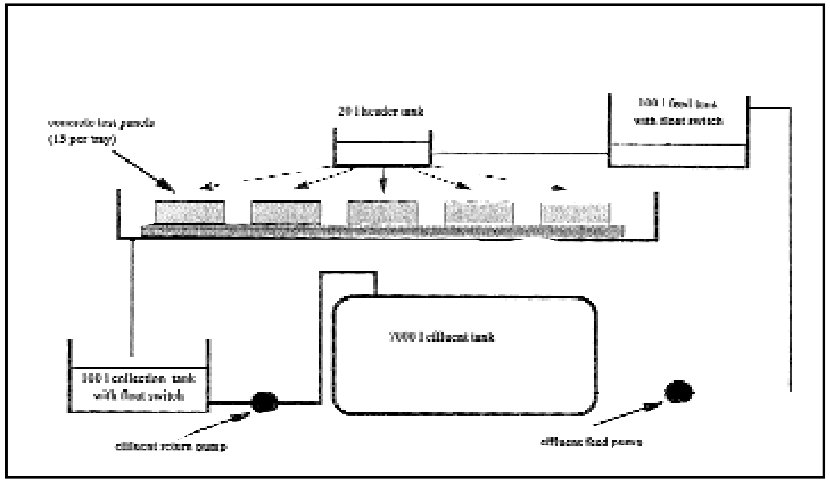


Fig 1: Schematic diagram of experimental facility

Specimen preparation

Six test panels of nominal dimensions 0.280 m x 0.280 m x 0.075 m were cast per treatment using three-panel gang moulds. Variability was minimised by preparing each treatment in a single batch using a 56 l pan mixer. Sufficient concrete was prepared per batch to cast the six panels, take a slump test and make three cubes for compressive testing.

The panels were compacted on a vibrating table. A textured surface finish, suitable for farm construction, was given to the panels by brushing the surface with a plastic brush. The panels were covered in moist hessian and plastic for the first 24 h. The panels were then demoulded and stored in water at 20°C until an age of 7 days. Subsequent curing was in a store room (approximate temperature 20°C, relative humidity 80%) until they were at least 28 days old. The panels were cast and cured at the Civil Engineering Department Laboratories, University College Dublin, and were subsequently moved to the Teagasc, Grange Research Centre for exposure testing.

Prior to exposure to the effluent, a two-part polyurethane sealant (RS Glazecoat) was applied to the underside and the four edges of each panel leaving only the brushed-finish top surface exposed. This had previously been found to be effective in ensuring that the effect of the effluent was one-dimensional. Two coats of primer and two of top coat were applied in accordance with the manufacturer's instructions.

Test cycles and measurement methods

Five of the panels for each treatment were exposed to flowing effluent in the experimental facility during 10 cycles of 28 days. The panels were soaked in water for 2 days prior to first exposure to effluent and after each cycle of effluent exposure. This ensured a consistent and repeatable conditioning prior to measurement being taken at a definite end to the period of exposure.

After 2 days, the panels were removed from the water and washed to remove loose material. The surfaces of the panels were dried with paper towelling immediately prior to weighing, giving a value for the "saturated surface dry" mass of the panel. The panels were then left to dry in air for 24 h. Direct depth was then recorded at 16 points on the top surface of each panel. Consistency was achieved at each observation interval by clamping each panel onto a cast iron surface plate (flatness to within 0.01 mm) and stainless steel frame. The depth at each point was measured to an accuracy of 0.01 mm using digital dial gauges (Mitutoyo) mounted on magentic bases. The system allows the same 16 points to be located each time with a good degree of accuracy (Plate 1).

Statistical analysis was performed using one-way analysis of variance with each cycle being analysed separately; *a priori* treatment contrasts were made using least significant difference procedure.

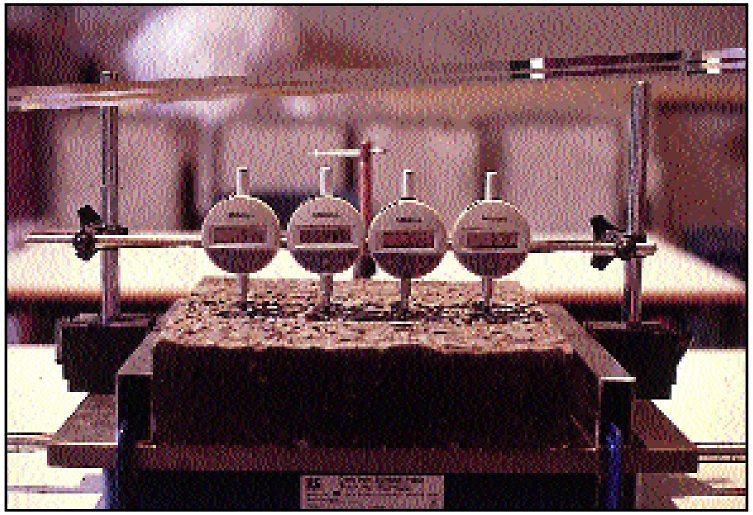


Plate 1. Depth change measurement device.

EXPERIMENT SERIES 1:

Influence of Cement Content and Water/Cement Ratio on the Durability of Portland Cement Concretes Exposed to Silage Effluent

The starting point in the determination of mix parameters was the design of a reference mix conforming to the DAFF specification for concrete in contact with silage effluent. The specification provides guidance on minimum 28 day characteristic strength (40 N/mm^2), minimum cement content (350 kg/m^3) and workability (maximum slump 75 mm). The reference concrete mix for the trials was designed to satisfy these limits as economically as possible. The resultant reference concretes (mix code D) had a mean 28 day strength of 53 N/mm^2, cement content of 375 kg/m^3, and slump of 75 mm. The water/cement ratio was 0.55.

An experiment was designed around a matrix of concrete mixes, initially with cement contents ranging from 250 to 450 kg/m^3 and water/cement ratios in the range 0.45-0.80. Consideration of workability constraints resulted in a range of ten mixes being selected for the experiment. Cement contents ranged from 275 to 425 kg/m^3, and water/cement ratios from 0.45 to 0.75. Details of the mix parameters are given in Table 1.

Cement used in the programme was “Normal Portland Cement”, complying to Irish Standard I.S.1 (CEM I category), supplied in one batch. The reported results of standard mortar tests with the cement yielded a 28 day compressive strength of 52.7 N/mm². The specific surface was reported at 343 m²/kg.

The coarse aggregate was a basalt known to be resistant to silage effluent. This aggregate was used to reduce the number of variables detected in weight loss measurements, thus allowing a clearer interpretation of the influence of cement content and water/cement ratio in the trials.

Table 1. Specification of mix parameters used in experiment series 1.

Mix code	Cement content, kg/m³	Water /cement ratio	Fine aggregate kg/m³	Coarse aggregate, kg/m³	Measured slump, mm	Mean 28 day cube strength, N/mm²
A	425	0.45	715	1070	45	63
B	425	0.50	715	1025	90	59
C	375	0.50	750	1085	45	59
D	375	0.55	755	1040	75	53
E	375	0.60	755	995	100	48
F	325	0.55	800	1105	25	58
G	325	0.60	805	1065	80	45
H	325	0.65	810	1030	105	41
I	275	0.70	860	1050	85	41
J	275	0.75	870	1025	95	36

RESULTS

The results of the weight loss measurements are presented in Table 2 and Figure 2 while the depth change measurements are presented in Table 3 and Figure 3. After 10 years of simulated exposure to effluent there was no significant difference in the performance of the two concretes (A & B) produced with the highest cement content of 425 kg/m³ and water to cement ratios of 0.45 and 0.50 in terms of mass loss or change in surface depth. Within the remaining groups of concretes made with cement contents of 375 (C, D & E), 325 (F, G & H) and 275 (I & J) kg/m³ and varying water to cement ratios, the concretes of lowest water to cement ratios performed significantly better in terms of lower mass loss recorded. The trend was similar but inconsistent for measured depth changes and the differences recorded were not statistically significant. Concretes with cement contents of 375 and 325 kg/m³ and water to cement ratios of 0.50 and 0.55, respectively, performed significantly better in terms of reduced mass loss than either of the concretes manufactured with cement content of 425 kg/m³.

Figure 2. Effect of water and cement content on change in concrete mass

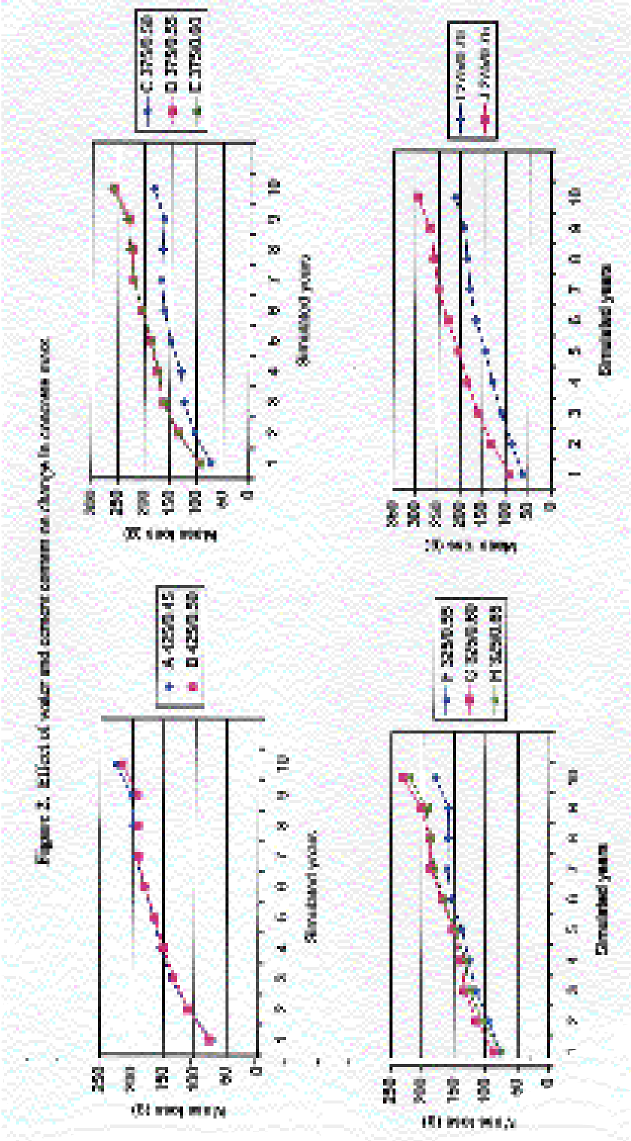


Figure 3. Effect of water and cement content on change in concrete depth

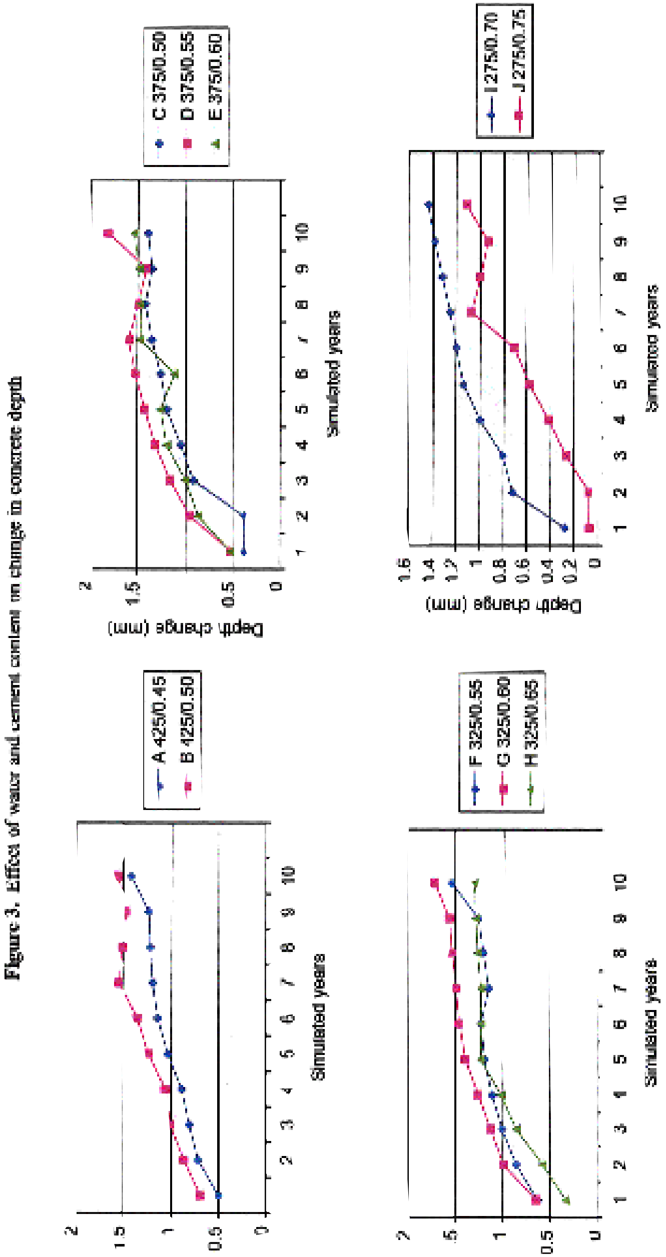


Table 2. Effects of water and cement content on mean changes in concrete mass (g).

Cycle	A	B	C	D	E	F	G	H	I	J	SED	Sig.
	Mix code											
1	73.6	77.6	73.6	95.4	94.2	77.2	88.2	75.4	63.0	89.0	9.9	*
2	109.4	110.2	103.8	133.8	137.2	95.2	113.6	105.0	86.0	130.0	11.4	***
3	138.2	132.6	124.0	163.8	164.4	115.2	132.2	125.2	110.0	161.0	11.5	***
4	154.6	150.8	129.6	175.2	172.8	125.8	138.6	132.2	129.4	182.8	12.1	***
5	166.2	163.0	150.2	188.8	186.4	137.0	151.5	148.4	145.4	203.8	12.2	***
6	180.8	181.0	162.6	205.4	204.4	154.6	169.8	167.4	166.8	229.2	12.3	***
7	195.2	190.8	168.6	220.2	221.0	161.2	187.2	182.4	179.4	250.0	13.3	***
8[1]	-	-	-	-	-	-	-	-	--	-	-	
9	202.2	192.0	163.4	228.4	235.0	159.2	202.8	193.8	192.0	269.0	14.1	***
10	226.0	216.6	182.2	258.0	262.6	180.6	232.8	221.4	213.0	296.2	15.4	***

[1] No values measured for cycle 8

Table 3. Effects of water and cement content on mean changes in concrete depth (mm).

Cycle	A	B	C	D	E	F	G	H	I	J	SED	Sig.
	Mix code											
1	0.49	0.68	0.38	0.51	0.52	0.63	0.65	0.33	0.28	0.08	0.09	NS
2	0.71	0.86	0.38	0.95	0.86	0.86	1.00	0.58	0.72	0.08	0.09	*
3	0.80	1.01	0.91	1.16	0.99	1.01	1.13	0.86	0.81	0.27	0.10	*
4	0.89	1.06	1.05	1.32	1.20	1.12	1.26	1.02	1.00	0.42	0.10	*
5	1.03	1.23	1.20	1.42	1.26	1.20	1.40	1.24	1.14	0.58	0.13	NS
6	1.14	1.35	1.26	1.53	1.11	1.23	1.46	1.24	1.20	0.71	0.15	NS
7	1.20	1.55	1.36	1.60	1.47	1.16	1.50	1.24	1.26	1.07	0.10	*
8[1]	-	-	-	-	-	-	-	-	-	-	-	-
9	1.24	1.48	1.35	1.41	1.49	1.26	1.57	1.29	1.38	0.93	0.19	NS
10	1.42	1.56	1.39	1.81	1.54	1.54	1.72	1.30	1.44	1.12	0.21	NS

[1] No values measured for cycle 8

EXPERIMENT SERIES 2:

Influence of Pulvarised Fuel Ash as a Cement Replacer on the Durability of Concrete Exposed to Silage Effluent

Pulvarised fuel ash (PFA) is a waste product produced when pulvarised coal is burned in power station furnaces. Most of the ash is fine enough to be carried away with the flue gases and to prevent atmospheric pollution this "fly ash" is removed from the gases by electrostatic precipitators.

The precipitated material is a fine powder which can have pozzolanic properties, i.e. when mixed into concrete it can react chemically with the calcium hydroxide that is produced during the hydration of Portland cement. The products of this reaction are cementitious, and in certain circumstances PFA can be used to replace part of the Portland cement in concrete mixes. At present there is little use of PFA as a cement replacer in Ireland.

Not all PFAs are suitable for use in concrete, mainly because the quality can vary as a result of fluctuations in the demand for electricity. The most consistent PFAs come from base-load stations which run continuously under constant operating conditions, and it is from these sources that PFA is usually processed and graded for use in concrete.

Substitution for PFA for Portland cement is not a straightforward replacement of like for like, and the following points have to be borne in mind when designing PFA mixes:

1. PFA reacts more slowly than Portland cement, and at early ages it contributes less strength; the potential strength after three months is likely to be greater than OPC provided that the concrete is maintained in a moist environment.
2. The water demand of PFA may be less than that of Portland cement.
3. The density of PFA is about three-quarters that of Portland cement.
4. The reactivity of a PFA and its effect on water demand and hence strength depends on the particular PFA and the particular OPC with which it is used. A change of PFA source or OPC source may require a change in the proportioning of the PFA and OPC.

To achieve the same 28 day cube strength with a mix containing PFA, the weight of added PFA needs to be greater than the reduction in Portland cement. Typically, and depending on the characteristics of the OPC and the PFA, a mix containing 300 kg/m^3 of OPC might be replaced by a mix containing 240 kg/m3 of OPC and 100 kg/m^3 of PFA.

An experiment to assess the effects of using PFA as a cement replacer on the durability of concrete used in silage storage structures was undertaken. The individual treatments are outlined in Table 4. Five replicates of each concrete were exposed to effluent and corrosion was measured as saturated weight loss and change in surface depth. Table 5 details the weight loss. Table 6 details the change in surface depth. The experimental procedure used was similar to Experiment Series 1.

Table 4. Specification of mix parameters used in Experiment Series 2.

Mix code	Cement (kg/m^3)	PFA (kg/m^3)	Slump (mm)	28 day cube strength (N/mm^2)	Density (kg/m^3)
PFA 0	359	0	40	63	2480
PFA 15	328	58	40	62	2455
PFA 30	285	121	50	58	2415
PFA 40	259	173	45	54	2413
PFA 50	230	230	50	48	2410

Table 5. Effects of PFA content on mean changes in concrete mass (g)

Cycle	Mix code						
	PFA 0	PFA 15	PFA 30	PFA 40	PFA 50	SED	Sig
1	42.7	19.6	47.6	46.6	17.8	14.1	NS
2	63.2	38.8	62.4	58.6	13.6	15.7	*
3	91.9	55.6	73.2	53.9	20.1	18.0	*
4	125.4	101.2	113.6	114.2	59.0	13.3	*
5	183.9	150.8	161.5	171.0	97.8	16.7	***
6	229.6	174.6	181.8	188.2	122.0	17.3	***
7	293.1	225.4	240.3	221.4	145.0	16.9	***
8	324.4	249.9	254.9	250.9	167.4	20.7	***
9	342.5	262.8	266.9	260.0	172.9	23.5	***
10	327.8	258.1	258.7	252.3	165.1	21.2	***

Table 6. Effects of PFA content on mean changes in concrete depth (mm)

Cycle	Mix code						
	PFA 0	PFA 15	PFA 30	PFA 40	PFA 50	SED	Sig
1	0.14	0.24	0.30	0.20	0.21	.107	NS
2	0.23	0.27	0.32	0.20	0.21	.097	NS
3	0.37	0.30	0.37	0.22	0.20	.077	NS
4	0.43	0.34	0.54	0.40	0.40	.154	NS
5	0.72	0.84	0.69	0.66	0.66	.148	NS
6	1.19	1.44	1.52	1.15	1.15	.239	*
7	1.48	1.42	1.21	0.91	0.91	.163	***
8	1.77	1.62	1.28	1.26	1.26	.433	NS
9	1.95	1.15	1.33	1.36	1.36	.339	NS
10	2.05	1.75	1.61	1.53	1.53	.180	NS

RESULTS

The results of the weight loss measurements are presented in Table 5 and Figure 4, while the depth change measurements are presented in Table 6 and Figure 5. All concretes containing PFA had significantly improved performance, measured as reduced weight loss at the end of 10 years simulated life with the PFA 50 mix performing best. The improved performance trend was also recorded in the depth change measurements. While the durability of the concretes is improved by adding PFA, the 28 day cube strengths are reduced as increasing contents of PFA are used. This may have implications for use of PFA where there is a short interval between construction and use of a structure.

Figure 4. Effect of PFA used as a cement replacer on changes in concrete mass

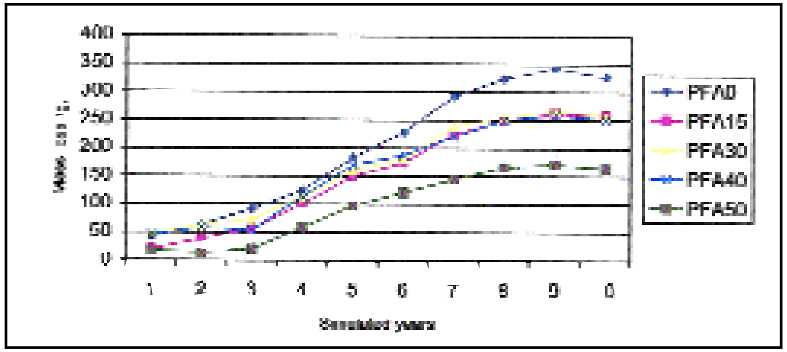
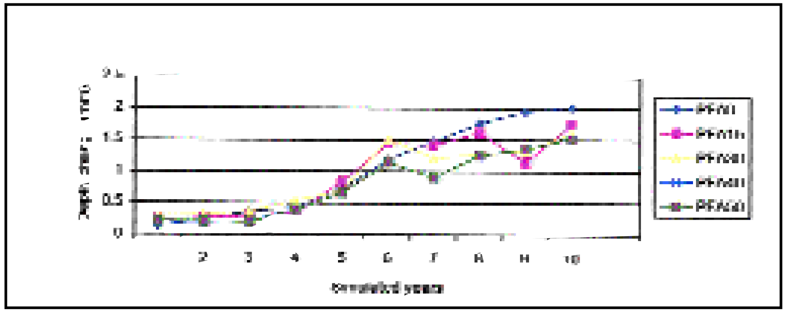


Figure 5. Effect of PFA used as a cement replacer on changes in concrete depth



DISCUSSION

It would appear that optimum performance of concrete exposed to silage effluent involves production of a mix with a low water/cement ratio and an acceptable cement content. These two properties are not independent in practice due to the additional need for adequate workability. Water/cement ratios of 0.50 to 0.55 would appear to be optimal for unplasticised concrete in this context and this implies that a maximum water/cement ratio should be considered in specification. Furthermore, the results of the experiment indicate that it may be beneficial to limit the cement content to a value consistent with the production of good quality workable concrete. This could be achieved in practice by specifying both a minimum and maximum cement content. The consequential practical implications of assessing criteria for conformity of concrete on site would need to be considered.

The addition of pulverised fuel ash (PFA) allows more durable concretes to be produced. This may be of further value in the context of an optimum mix for silo construction. It is worth consideration in the formulation of future standards.

Restrictions on maximum water/cement ratio and maximum cement content would be beneficial in reducing the risk of crack occurrence in silage silos and would limit the extent of crack width increase over time. The occurrence of defects likely to be a potential pollution hazard were identified in up to 40% of existing concrete silos by Culleton and Regan (1992) with unsealed joints and cracks being the most common problems. Design of a concrete structure to minimise the risk of crack occurrence involves, *inter alia*, careful consideration of joint detailing and mix specification. Although it is beyond the scope of the small-scale experiments in this study, it is worth noting that high cement content concretes are subject to a significant risk of early thermal contraction cracking. The current DAFF specification of a minimum cement content of 350 kg/m3 may in fact represent an optimum cement content. The water cement ratio must also be considered since it influences the occurrence of “drying shrinkage cracking” and the final crack width.

CONCLUSIONS

Least mass loss was recorded with concretes produced with 325 kg/m^3 cement content and 0.55 water/cement ratio and those with 375 kg/m^3 cement content and 0.50 water/ cement ratio.

The treatment which exhibited the greatest mass loss was that with the lowest cement content and highest water/cement ratio (275 kg/m^3, 0.75).

The mass loss generally increased with increasing water/cement ratio in each cement content group.

The use of PFA should be considered by readymix concrete manufacturers to produce more durable concrete for use in silage storage structures.

The significance of water/cement ratio, more so than minimum cement content, in the production of durable concrete for silos indicates that consideration should be given to altering the parameters commonly used in specifications. The current requirements based on concrete grade and minimum cement content could be superseded by limitations on the maximum water/cement ratio and both minimum and maximum cement content.

REFERENCES

Blackledge, G.F. Concrete Practice ISBN 07210 13589, British Cement Association, UK 1990.

Culleton, N. and Regan, S. (1992). Building Silage pits to protect the environment. Irish Farm Buildings Association Annual Journal 1992.

DAFF (Department of Agriculture, Food and Forestry - Dublin). Guidelines and Recommendations on Control of Pollution from Farmyard Wastes, 1985.

DAFF (Department of Agriculture, Food and Forestry - Dublin). Farm Development Service. Minimum Specification for Concrete Walled Silos. S120. February 1992 (Annex May 1993).

McDonald, P., Henderson, A.R. and Heron, S.J.E. The Biochemistry of Silage 2nd Edition. Chalcombe Publications, 1991.

O'Donnell, C., A Study of the Effect of Silage Effluent on Concrete. M.Eng.Sc. Thesis, National University of Ireland, 1993.

O'Donnell, C., Dodd, V.A., O'Kiely, P. and Richardson, M. A Study of the Effects of Silage Effluent on Concrete : Part 1, Significance of Concrete Characteristics. J. Agric. Engng. Res, 1995, 60, 83-92, (a).

O'Kiely, P., Power, R. and O'Donnell, C. Grass Conservation, Storage and Feeding in Ireland. Farm and Food, 1993, 3: 4-7.