EXPERIMENTS ON INDUSTRIAL BY-PRODUCT UTILIZATION AS A CONCRETE ADMIXTURE TO REDUCE RADON GAS TRANSPORT PROPERTIES

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ABSTRACT

This paper assesses the utilization of industrial by-products as a concrete admixture to reduce the radiological transport properties of radon gas through concrete. Laboratory experiments were conducted to measure the diffusion coefficient (D). the air permeability (K) and the porosity (ε) of concrete samples that contained various amounts of industrial by-products. These industrial by-products included: Type-C fly ash. bottom ash. slag. silica fume as well as crumb rubber. A fractional factorial experimental design was used to statistically identify an optimal concrete mixture with regards to controlling radon gas transport. Within this design method a comparison with a conventional concrete mix is presented. Details of the innovative experimental setups and procedures are discussed.

The results of this study can be applied to improve the current radon-resistant residential construction technology. It also provides an environmentally safe and economically feasible recycling avenue for the discarding of rapidly accumulating industrial by-products.

INTRODUCTION

Variations or additions to the conventional concrete formulation are known as admixtures. Admixtures often exhibit enhanced performance properties and have been used fairly commonplace for many years (Popovics 1979: Dodson 1990: Ramachandran 1995). Fly ash. a very fine particulate matter collected by electrostatic precipitation from the smoke stacks of coal burning electric plants. has been shown to be a successful admixture constituent (Joshi and Lohtia 1997). Bottom ash and slag are two other by-products of coal combustion that have been used as a concrete admixture. Silica fume. a waste product now prepared to commercial standards, has been shown to be an effective corrosion inhibitor in concrete construction by lessening the penetration of water and salt.

Most research into concrete admixtures as related to the transport of radon gas has focused on reducing the porosity of the final product. It has become commonplace to add fly ash or silica fume in practical applications to lower the porosity and increase the strength or resistance of

hardened concrete. The use of a denser concrete aggregate has also been employed (Popovics 1979). Decreasing the water to cement ratio is another easily adjusted variable (Sanjuan and Munoz-Martialay 1996). The addition of superplasticizer, a commercial concrete additive that aids the flow of the wet mix, can greatly reduce the water demands of the concrete mix and could therefore reduce the porosity and related transport properties (Biagini 1995).

While there are many advantages to using industrial waste materials in concrete there have also been some shortcomings. The negative effects of using uranium mill tailings in construction materials and as backfill lead to an intense study to combat the influx of radon (Culot et al. 1976). In another study where concrete samples contained gypsum (a by-product of the phosphate industry), it was found that the radon gas exhalation rate was twice that of concrete without the admixture (Ulbak et al. 1984).

Other studies have been more encouraging. A recent study concluded that building materials and concrete with fly ash were not the primary source of radon in typical houses (Ingersoll 1983). A Norwegian study concluded that while adding Danish fly ash increased the radium content of concrete, the exhalation rate was actually lowered (Stranden 1983). A Dutch study showed that the increased exhalation rates of fly ash containing concrete decreased in time, particularly after the first two years (Roelofs and Scholten 1994). These investigations suggest that the addition of fly ash and other industrial by-products can possibly be used as concrete admixtures to modify the radon transport dynamics in a beneficial manner.

This paper presents the experimental results of an original method of controlling radon gas entry for use in residential new construction. The objective of this research is to utilize industrial by-products as a substitute ingredient in concrete mixtures to retard radon gas diffusive and advective fluxes. Three original test systems were designed, fabricated and implemented to quantify the radiological transport properties of a conventional concrete mix and admixtures enhanced with by-products or waste materials. The fractional factorial experimental design was used to statistically identify optimal concrete mixtures with minimal values of radon gas diffusion coefficient, air permeability and percent porosity as well as maximum compressive strength.

EXPERIMENTAL DESIGN AND PROCEDURES

Fractional Factorial Experimental Design
Fractional factorial experimental design (FFED) is a statistical augmentation to the traditional experimental method. In the traditional experimental method, only one parameter known as the independent variable is varied at a time in each sample. Sample test results are then compared with results from a control or standard specimen. Result variation between sample and control can then be attributed to the single parameter varied in the sample. FFED permits multiple parameters to be varied simultaneously such that an optimal combination of parameters taken together can be statistically determined by testing only a small portion of the total possible simultaneous combinations.

Seven parameters, more commonly referred to as factors in FFED, were studied as potential radon transport inhibitors in concrete. These factors were: water to cement ratio and the addition of fly ash, bottom ash, slag, silica fume, ground tires (crumb rubber) and superplasticizer. The addition of fly ash, silica fume and superplasticizer and the water to cement ratio have noted effects on the performance characteristics of concrete. Superplasticizer, a commercial product, is often used in concrete construction to make the concrete flow more freely, especially within forms. Decreasing the water to cement ratio, often through the use of a superplasticizer and adding fly ash, can substantially increase the strength and density of the concrete.

The statistical basis of FFED stems from the total number of possible combinations of factors and levels that can occur. In this investigation seven factors were tested at two levels (i.e., two different water to cement ratios and samples with and without the six other factors). This gives rise to 2^7 possible combinations or 128 formulations. Using FFED, only 16 samples are necessary to calculate the optimal combination of the factor levels tested. Choosing which 16 formulations to sample is of particular importance.

The design matrix in Table 1 is an aid in determining the sample compositions for a sixteen-run or sixteen-sample experiment (Lochner and Matar 1990). As shown, rows represent samples and columns represent performance factors that can be varied. The particular level or condition each factor should take on in the sample is noted by a 1 or a 2 at the column and row intersection. Note that for every factor half of the samples are level 1 and half are level 2. Normally level 2 represents a higher level of a constituent.

Similarly, the statistical analysis of the sixteen results is simplified by using Table 2. Sample results are entered in each blank space across each row. Columns are then added and the averages computed. The difference between the levels, the average of level 2 minus the average of level 1, is the observed effect of going from level 1 to level 2.

Tables 1 and 2 contain fifteen columns representing up to fifteen different factors. To evaluate only seven factors certain columns must be used so that each factor and level will be weighted equally in the statistical calculations. Additionally, factors may have a tendency to interact with one another at certain levels producing a pronounced result inherent to that particular combination. The possibility of interactions should be carefully examined and minimized so the final calculated effects are indicative of changing the factor levels independently of other factors. Specific columns are statistically more susceptible to contain interactive influences. Idle columns not assigned a working factor constituent can measure the effect of certain interactions of the working factor columns.

When using the design matrix in Table 1 for seven factors, the following columns are used for the factors: 1, 2, 3, 4, 11, 12 and 13 (Lochner and Matar 1990). Designating these columns as A through G, respectively, the interactions shown in Table 3 are inherently manifested in the other columns. The effect calculated for the unused columns is indicative of the combination of the listed interactions. The method suggests that only one of the potential three interactions occurs or dominates over the others. To minimize the possible combination of two-way interactions, the

factors were assigned to specific columns based upon a computer analysis of potential interactions.

There are 7 factorial or 5040 possible assignments of the seven factors (concrete constituents) to designations A through G. Each factor was given a value from 1 to 10 ranking the potential that constituent has to interact with another (10 = greatly interactive) as noted in Table 4. Suggestive judgment based on a review of the literature was used to define these values. A computer program was then written to add the rankings of the two-way interactions according to the interaction table for all possible factor assignments. Thus, three sums representing the additive interaction potential of the interacting factors (e.g., A+B, C+E, and D+F for column 5) were produced for columns 5, 6, 7, 8, 9, 10 and 15 five thousand and forty times. The standard deviation of the three sums was also computed. A large standard deviation for each column is desired as it indicates a potential dominant interaction among the three interactions expressed in that column. A composite value was computed for all possible factor assignments by adding the standard deviations of all the columns. A maximum composite value would help assure that the factors are assigned in a manner that would produce a dominant interaction in all the columns simultaneously. Table 5 shows the factor to column assignments selected out of a few possible combinations that produced the same maximal composite value.

Incorporating the information from Tables 3 and 5 into the design matrix (Table 1) results in Table 6. For readability, the unused columns are darkened out.

FFED also necessitates that the levels used be carefully contrived so that the effects of changing factor levels can be appreciably measured while interactions are minimized. Note that the factors of Sample 1 are all level 1 and those of Sample 16 are all level 2. Thus, sample 1 does not contain any waste material and can be proportioned as a conventional concrete and used as a traditional reference sample. Sample 16 contains all waste materials, superplasticizer and the higher water to cement ratio. Thus, the combined presence of all five waste products must also be taken to mind.

It is common to base the level of admixture ingredients on a percentage of one of the constituents within the conventional mix, normally the cement that is replaced by prozzolanic or cementitious materials. In this investigation, we based the added amount of waste products as a percentage of the total weight of sand and aggregate of the conventional mix. This produced workable numbers and seemed appropriate since the cement was not being replaced and because of the unpredictability of the effects of combining materials of differing prozzolanic and cementitious properties. Understanding that replacing some of the sand with waste material would affect the amount of water available for hydration, especially in the case of fly ash and silica fume, it was concluded that these levels should be rather low. It was also desired not to replace more than half of the sand in the most limiting batch, sample 16. Table 7 displays the level of waste material selected as a percentage of the conventional mix sand and aggregate weights combined. Formulations were based on a cubic yard of conventional concrete with 55% water to cement ratio proportioned as in Table 8.

A 60% water to cement ratio chosen for the higher water level tested. Pea gravel was used as aggregate to help homogenize the small sample size. Table 9 lists the 30 pound batch formulations used to prepare the sixteen FFED samples.

Concrete Admixtures

Table 10 provides a description of the waste products used in this research. In addition, a commercial superplasticizer was used in this investigation. The amount employed was calculated by the manufacturer guidelines to obtain an additional 3 inches of slump, which presumably would create a measurable effect on the radon transport properties of the concrete.

Sample Preparation

Aluminum sample holders were used to mold and contain the concrete samples. The wet mixes were prepared by weighing the batch proportions per Table 9. A digital platform scale was used to measure the aggregate, sand and cement, while a triple beam pan balance was used to measure the admixture ingredients. Water was measured by an accurate graduated cylinder. Each cast sample was approximately 8.89 cm in diameter and 5.08 cm in thickness. A 10.2 cm diameter x 20.3 cm tall strength test cylinder of each batch was similarly prepared. Details of the preparation and leak checking procedures can be found in Lambert (1999).

Radon Gas Diffusion Apparatus

Figure 1 is a schematic of the experimental system used to measure the radon gas diffusion coefficients through the concrete samples. Two continuous radon monitors were used to measure the radon concentrations in both the source and collection chambers. Theses monitors utilized a Lucas scintillation cell and a photomultiplier tube to count the number of alpha emissions given-off by the radon gas present. A diaphragm pump was used in each loop to assure that the air and radon gas was thoroughly mixed. A filter is placed at the entrance of each scintillation cell to remove dust and radon daughter products within the air stream. Two flow meters were used to monitor the flow rates since the calibrated sensitivity of the continuous radon monitors were dependent on the flow rate. The radon source (a commercially available passive radon gas source) was used to build-up the radon gas concentration in the Radon Gas Source Chamber. The High and Low Concentration Chambers were attached to each face of the concrete sample to allow the full facial area of each concrete sample to be exposed to the radon-air mixture. Toggle valves and other hardware were employed to create the desired radon gas flow configuration.

A sensitive pressure transducer monitored the pressure differential across the concrete samples so that pure diffusion transport mechanism could be verified. Environmental conditions (e.g., relative humidity, temperature and barometric pressure) were measured with high-accuracy sensors. A modern PC-data acquisition system was employed to read the electrical signals of the sensors and radon monitors and to display and record the data. The main apparatus was contained in an environmental chamber that maintained the temperature and humidity levels constant.

In this investigation, the radon gas diffusion coefficients through the concrete samples were calculated by using Fick's Law (Renken and Rosenberg 1993). Fick's Law as applied to a slab of

concrete experiencing one-dimensional fixed concentration differences with isobaric and isothermal conditions is expressed as:

$$J = D \frac{\Delta C}{\Delta x} \qquad (1)$$

where,

J   = radon flux through the concrete cross-sectional area
D   = diffusion coefficient of radon gas through the concrete sample
ΔC = radon gas concentration difference across the concrete sample
Δx = thickness of the concrete sample

The method employed by Maas and Renken (1997) was used to determine the time necessary for steady state to be achieved prior to the initial sampling of the chambers. Sixteen and twenty-four hour diffusion test runs were made. Details of the experimental procedures and calculations can be found in Lambert (1999).

Air Permeability Apparatus

The air permeability coefficients of the concrete samples were measured by the apparatus diagrammed in Figure 2. Here. the concrete samples in their holders were firmly bolted between the High and Low Pressure Chambers. each containing a release valve and port. A low pressure differential was applied via a linear actuator constructed from a fine-threaded rod pushing on the plunger of a 10 ml syringe bracketed in place. To keep the pressure differential constant. a hand crank was manually operated to turn the rod. A PC-data acquisition system was used to measure. monitor and record the sensor readings (pressure. temperature and relative humidity). Air permeability coefficients were measured at pressure differentials of approximately 10 Pa.

The permeability coefficient like the diffusion coefficient is a proportionality constant characterizing the dynamics of the physical properties of the media and substances involved. The permeability coefficient quantifies the ability of a fluid to flow through a porous media when subjected to a pressure difference. This transport process known as advection is modeled by Darcy's Law:

$$Q = -\frac{-KA\Delta p}{\mu L} \qquad (2)$$

where.

Q   = volumetric flow rate of the fluid
K   = permeability coefficient
A   = cross-sectional area permeated
Δp = pressure difference across the porous medium
μ = viscosity of the permeating fluid

L   =   length of porous medium

The rate of fluid flow through the porous medium is directly proportional to the pressure difference and the cross sectional area and inversely proportional to the viscosity of the permeating fluid and the distance permeated. The permeability coefficient "factors in" the combining dynamics of physical properties of the porous medium and the permeating fluid.

<u>Porosity Apparatus</u>
Figure 3 is a schematic of the experimental system used to measure the porosity of each concrete sample. A gas expansion method as described by Renken and Rosenberg (1993) and Maas and Renken (1997) was used to calculate the pore volume. This method employs the Conservation of Mass and the Boyle-Marriotte Gas Law (Balmer 1990) to calculate the solid volume of the concrete sample. This solid concrete volume is determined by placing the concrete sample in the Sample Chamber of known volume. This chamber is then pressurized and allowed to come to equilibrium conditions. The chamber is then opened to the Secondary "Exhaust" Chamber and again allowed to come to equilibrium. By using the Boyle-Marriotte Gas Law for constant temperature conditions, a mass balance states that the mass of air present before and after expansion of the Sample Chamber volume is the same. By simple algebraic manipulation, the volume of solid concrete in the sample is solved for and the percent porosity of the concrete can be calculated. Details can be found in Lambert (1999).

EXPERIMENTAL RESULTS

<u>Radon Gas Diffusion Coefficient</u>
Table 11 and Figure 4 display the average radon gas diffusion coefficients of the 16 concrete samples as well as the statistically identified optimal concrete mixtures (E1, E2 and E3). The experimental uncertainty of the diffusion coefficient was estimated to be approximately $\pm 10\%$ (Lambert 1999). The results range in value from 1.94×10^{-4} cm^2/s for sample 7 to 4.85×10^{-4} cm^2/s for sample 11. Nine samples showed larger diffusion coefficients than the traditional mix (sample 1), while six samples showed superior resistance to radon gas diffusion transport.

The mean diffusion coefficients were applied in the FFED analysis to suggest and prepare the "best" formulation from among the 128 possible combinations of seven factors taken at two different levels. Two other formulations were suggested by using the mean values of the 16 hour runs and the 24 hour runs taken separately. The three samples were prepared using the FFED formulations that were suggested. These statistically generated concrete samples were designated E1, E2 and E3 and were based on the 16 hour mean, 24 hour mean and mathematical mean of all runs, respectively.

To ascertain the statistically generated formulations from the mean results of the samples tested the average responses of the factors and levels based on the FFED design matrix of Table 1 was calculated. A spreadsheet was constructed from the format of the response table shown in Table 2 to aid in computing the response values statistically attributable to each factor and level. The three sets of mean diffusion coefficient values were inserted into three separate spreadsheets to

obtain three distinct sets of factor responses. The resulting spreadsheets, average responses and factor levels that produced the lowest diffusive responses are summarized in Table 12. The suggested sample formulations as shown in Table 13 were prepared, cured and tested in the same manner as samples 1 - 16.

The statistically generated concrete mixtures (E1, E2 and E3) showed various outcomes. Sample E2 produced a 34% reduction in the radon gas diffusion coefficient from that of sample 7, the least diffusive sample and a 56.6% reduction when compared to the traditional concrete formulation represented by sample 1. Sample E3 also displayed a reduced diffusive property with reduction percentages of 26.2% and 51.5%, respectively. Sample E1 showed a significantly increased diffusion coefficient as compared to any of the other samples. This was due to incomplete hydration of the very "dry" wet mix that was observed while mixing this formulation and preparing the sample. Sample E1 was not tested any further except for compressive strength.

Air Permeability Coefficient
Table 14 and Figure 5 display the experimental results of the air permeability coefficients of the original 16 samples and the two FFED suggested concrete samples (E2 and E3). The experimental uncertainty of the air permeability results was approximately ±1.0% (Lambert 1999). The permeability coefficients ranged from 1.06×10^{-11} cm^2 for sample 8 to 1.98×10^{-9} cm^2 for sample 15. Sample E2 produced a significantly reduced permeability coefficient of 1.85×10^{-11} cm^2 (65.7%), while sample E3 produced a value of 5.45×10^{-11} cm^2 almost equivalent to the traditional mix of sample 1.

Porosity
Table 15 and Figure 6 display the results of the porosity measurements. The experimental uncertainty of the porosity results was approximately ±1.4% (Lambert 1999). Sample E2 produced a 31.3% reduction in porosity as compared to the traditional mix, sample 1. Sample E3 produced a porosity almost equivalent to sample 1.

Radon Gas Emanation
A cursory measurement of the emanation rate was made on samples 1 and 16 as shown in Table 16. Sample 1 depicts a traditional concrete formulation, while sample 16 contained all the waste products making it the most susceptible to additional radium content. The emanation rate of the samples was measured using the radon gas diffusion apparatus without supplying any radon. The results shown in Table 16 are attributable to the radon arising from within the entire bulk volume of the sample irrespective of the emanating surface side. The experimental uncertainty of the emanation rate was in line with that of the diffusion coefficient results, approximately ±10% (Lambert 1999).

The difference between the two values is statistically insignificant and within the range of experimental uncertainty. However, the lowered emanation rate of sample 16 may in fact be due to a decrease in the radium content from that of the traditional mix. This suggests that the waste products employed, which have replaced a portion of the sand of the traditional mix, are of a

lower radium content than the sand itself. The fact that sand has a fairly high radium content has been noted in the research of others (Poffijn et al. 1988; Ingersoll 1983).

<u>Compressive Strength</u>
Table 17 and Figure 7 list the compressive strength test results for each sample formulation. The compressive strength was measured with a commercial tester as per ASTM standards (ASTM. 1986). Sample E2 shows a 21.1% increase in compressive strength as compared to the traditional mix of sample 1. As expected, the concrete samples (2, 4, 5, 7, 9, 11, 14, 16, E1 and E3) containing crumb rubber showed reduced compressed strength when compared to sample 1.

CONCLUSIONS

This paper presented the experimental results of an investigation that utilized industrial by-products as a concrete admixture to reduce the radiological transport processes of radon gas through concrete. A *fractional factorial experimental design* was employed to identify three statistically optimal concrete mixes based on radon gas diffusion measurements. Of the three new mixtures. only one proved to be an extremely effective retardant to radon gas transport. This concrete sample formulation included fly ash and slag as its concrete admixtures and excluded bottom ash. silica fume, crumb rubber and a superplasticizer. A significant reduction in the radon gas diffusion coefficient (56.6%). air permeability coefficient (65.7%) and porosity (31.3%) and an increase in compressive strength (21.1%) was realized by this optimal concrete mixture as compared to a traditional concrete sample. It was also discovered that the radon gas emanation rates from the concrete test samples were insignificant.

The results of this investigation have indicated that *fractional factorial experimental design* can be used as a powerful tool in determining optimal concrete mixtures. It was shown that selective industrial by-products can be used successfully to retard radon gas transport in concrete while providing an environmentally friendly and simple recycling avenue for their disposal.

ACKNOWLEDGMENTS

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Fig. 1. Schematic diagram of diffusion apparatus.
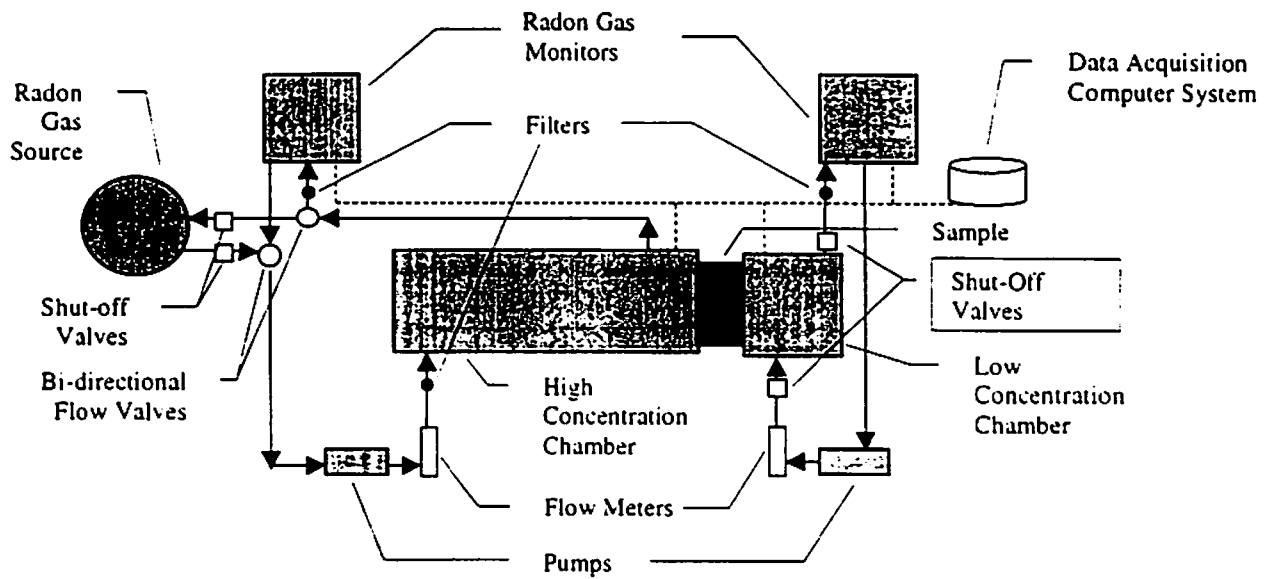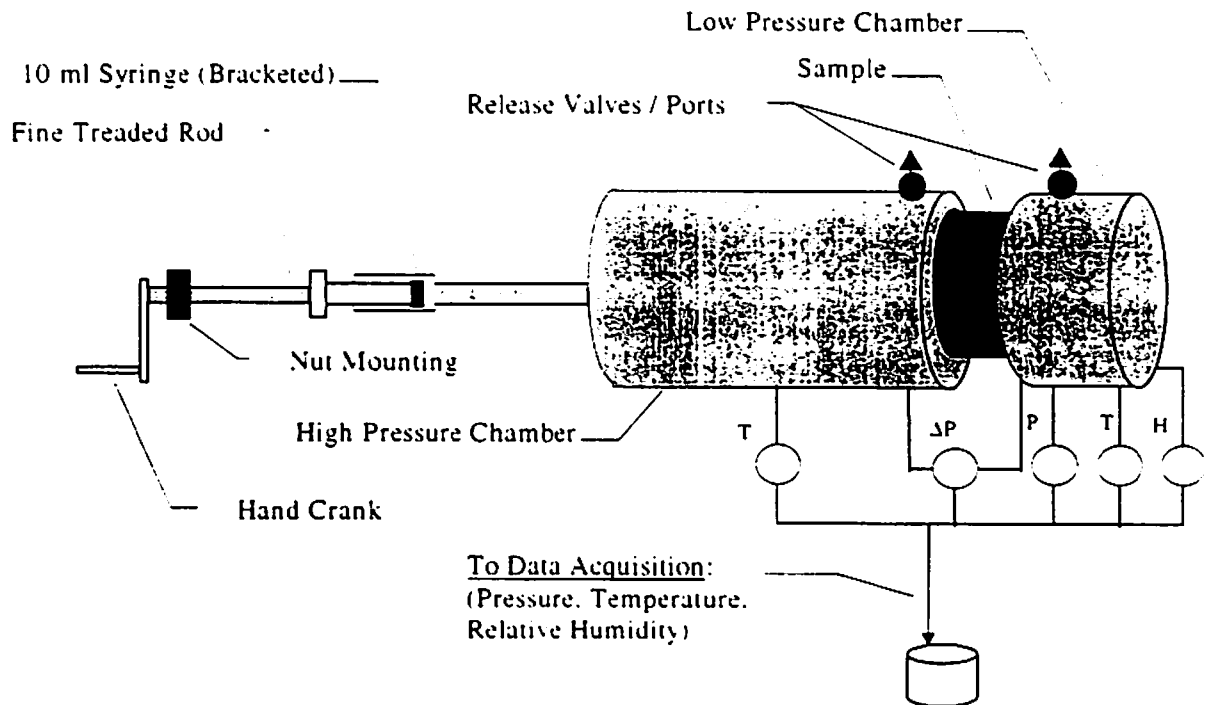

Fig. 2. Schematic diagram of air permeability apparatus.
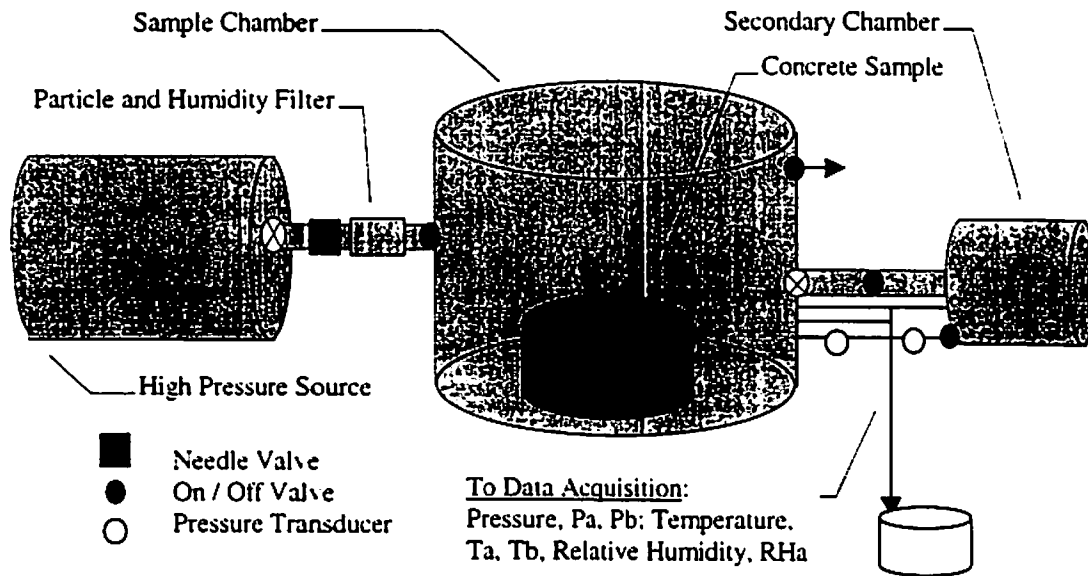
Fig. 3. Schematic diagram of porosity apparatus.
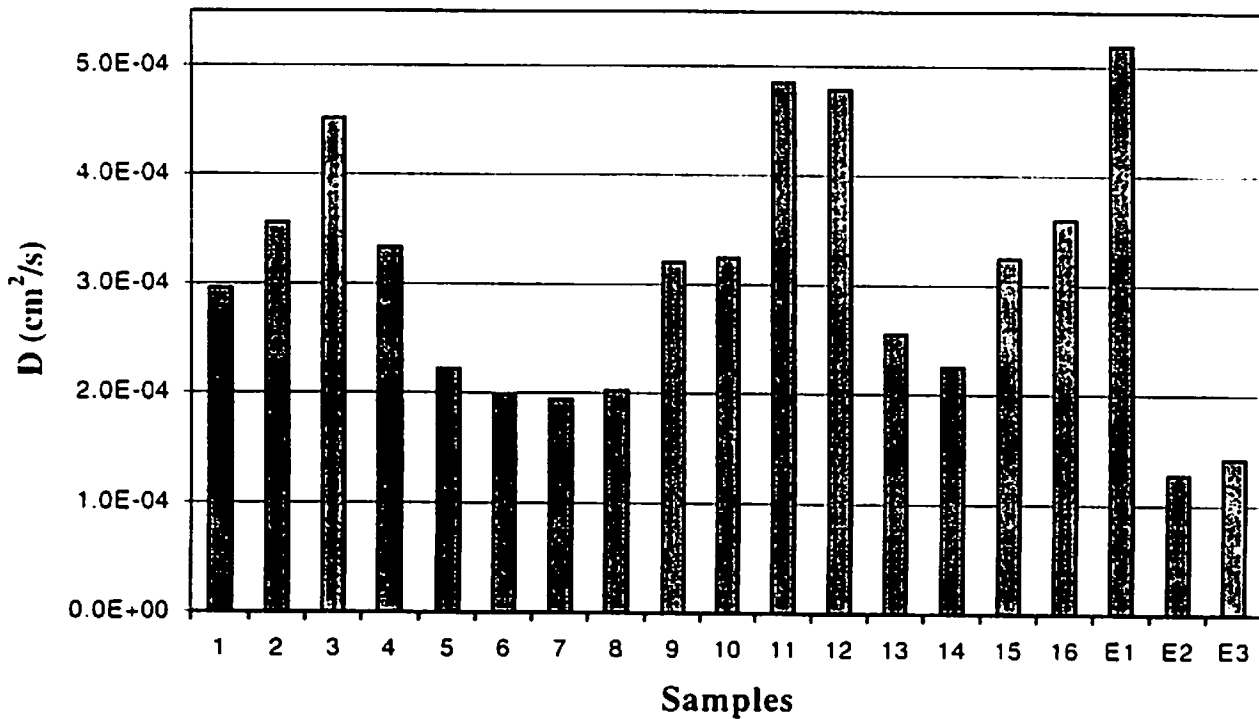
Fig. 4. Mean radon gas diffusion coefficients of FFED samples and statistically identified optimal concrete mixtures.
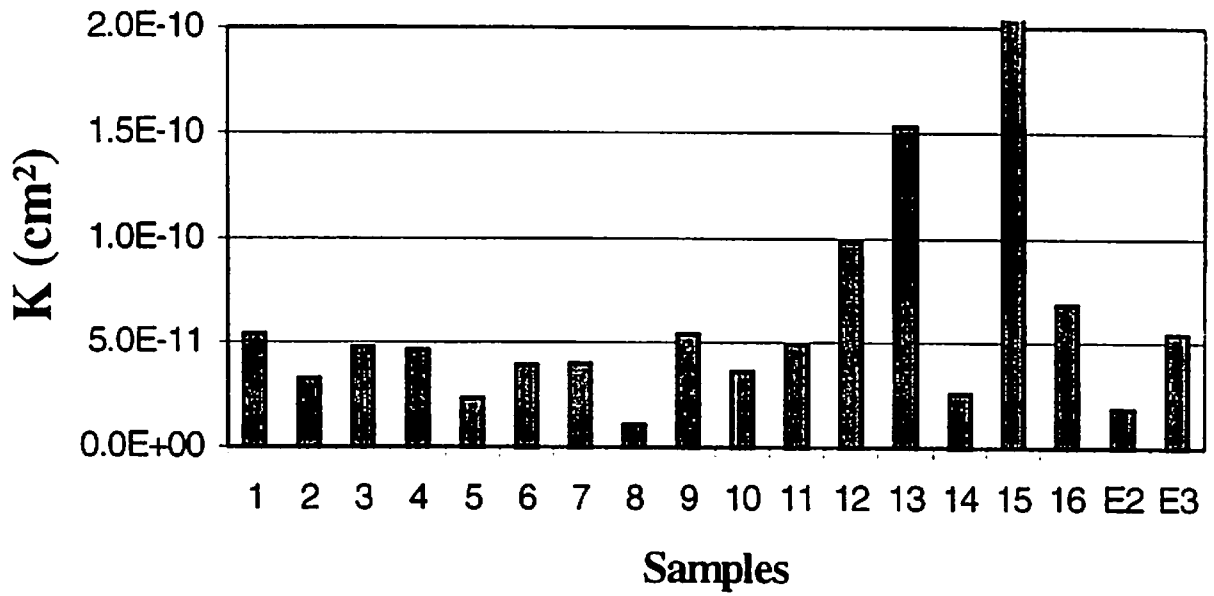
Fig. 5. Mean air permeability coefficients.
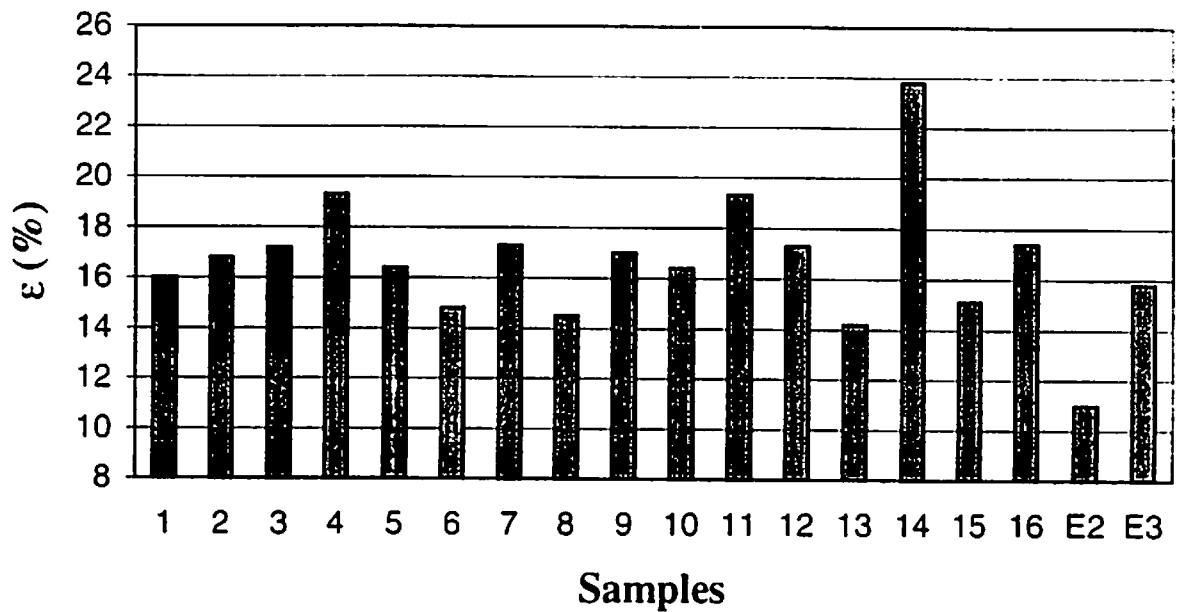
Fig. 6. Mean porosity measurements.
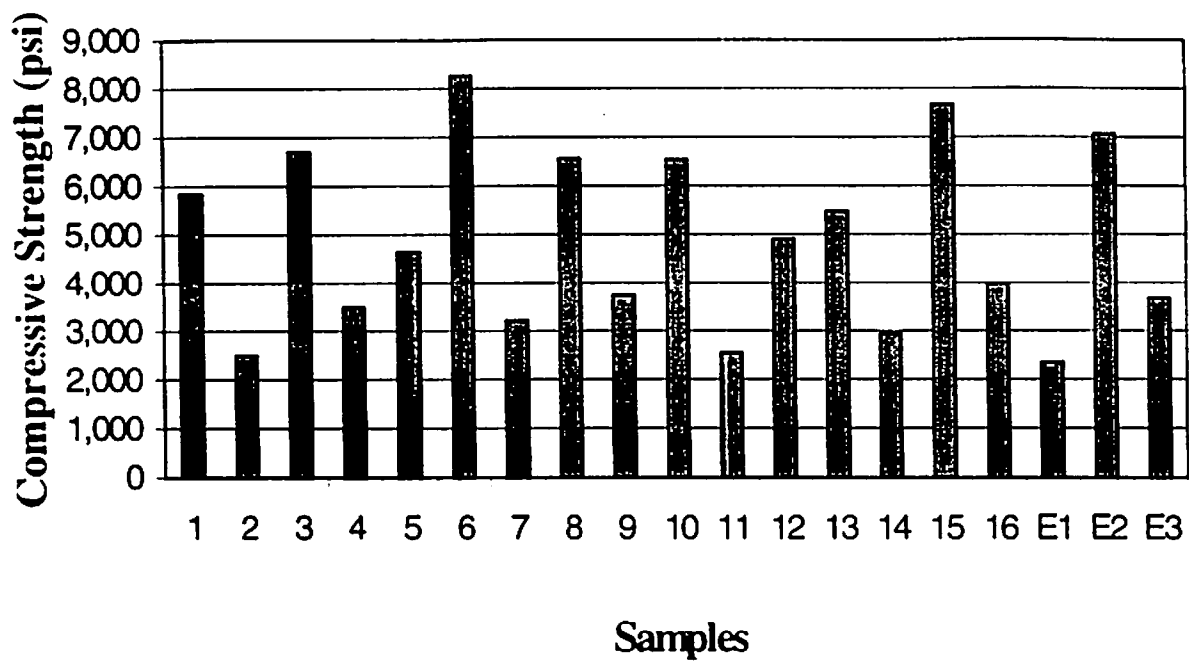
Fig. 7. Compressive strength measurements.

Table 1. Design level matrix for sixteen-run experiment (adapted from Lochner and Matar 1990).

Sample	Column Number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
5	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
6	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
7	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
8	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
9	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
11	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
12	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
13	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
14	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
15	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
16	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1

The intersecting coordinate values of 1 and 2 represent different constituent levels or sample conditions.

Table 2. Response table for sixteen-run experiment (adapted from Lochner and Matar 1990).

Table 3. Inherent interaction effects for design matrix (Lochner and Matar 1990).

2-Way Interactions	Column
AB CE DF	5
AC BE DG	6
AD BF CG	7
AE BC FG	8
AF BD EG	9
AG CD EF	10
BG CF DE	15
Three Factor Interactions	14

Table 4. Assignment of interaction rankings to factor constituents.

Factor Constituent	Interaction
Water	10
Superplasticizer	9
Fly Ash	8
Silica Fume	7
Bottom Ash	5
Slag	4
Crumb Rubber	3

Table 5. Factor constituent assignments to design matrix.

Column	Factor Designation	Factor Constituent
1	A	Water
2	B	Fly Ash
3	C	Bottom Ash
4	D	Slag
11	E	Silica Fume
12	F	Crumb Rubber
13	G	Superplasticizer

Table 6. FFED design level and interaction matrix.

Column # & Interactions	1	2	3	4	5 (AB CE DF)	6 (AC BE DG)	7 (AD BF CG)	8 (AE BC FG)	9 (AF BD EG)	10 (AG CD EF)	11	12	13	14 (3-Way)	15 (BG CF DE)
Designation	A	B	C	D							E	F	G		
Constituent	Water	Fly Ash	Bottom Ash	Slag							Silica Fume	Crumb Rubber	Super-plasticizer		
Sample 1	1	1	1	1							1	1	1		
2	1	1	1	2							1	2	2		
3	1	1	2	1							2	1	2		
4	1	1	2	2							2	2	1		
5	1	2	1	1							2	2	1		
6	1	2	1	2							2	1	2		
7	1	2	2	1							1	2	2		
8	2	2	2	2							2	1	1		
9	2	1	1	1							2	2	2		
10	2	1	1	2							2	1	1		
11	2	1	2	1							1	2	1		
12	2	2	2	2							1	1	2		
13	2	2	1	1							1	1	2		
14	2	2	1	2							2	2	1		
15	2	2	2	1							2	1	1		
16	2	2	2	2							2	2	2		

Level 1 = No Constituent Added or Lower Water Level
Level 2 = Constituent Added or Higher Water Level

Table 7. Waste material levels.

Waste Material	%*
Fly Ash (Type C)	3
Bottom Ash	5
Slag	5
Silica Fume	2
Crumb Rubber	5

* As a percentage of the conventional mix
sand and aggregate weight summed.

Table 8. Conventional interior concrete slab proportions (Concrete Construction 1994).

Cement (lbs.)	Sand (lbs.)	Aggregate (lbs.)	Water (lbs.)
580	1400	1800	320

Table 9. FFED concrete sample formulations.

Sample	Cement (lbs.)	Sand (lbs.)	Aggregate (lbs.)	Water (lbs.)	Fly Ash (lbs.)	Bottom Ash (lbs.)	Slag (lbs.)	Silica Fume (lbs.)	Crumb Rubber (lbs.)	Superplasticizer (ml)	Batch Weight (lbs.)
1	4.46	10.38	12.69	2.45	0.00	0.00	0.00	0.00	0.00	0.00	29.99
2	4.46	7.92	12.69	2.45	0.00	0.00	1.23	0.00	1.23	9.50	29.99
3	4.46	8.66	12.69	2.45	0.00	1.23	0.00	0.49	0.00	9.50	29.99
4	4.46	6.20	12.69	2.45	0.00	1.23	1.23	0.49	1.23	0.00	29.99
5	4.46	7.92	12.69	2.45	0.74	0.00	0.00	0.49	1.23	0.00	29.99
6	4.46	7.92	12.69	2.45	0.74	0.00	1.23	0.49	0.00	9.50	29.99
7	4.46	7.18	12.69	2.45	0.74	1.23	0.00	0.00	1.23	9.50	29.99
8	4.46	7.18	12.69	2.45	0.74	1.23	1.23	0.00	0.00	0.00	29.99
9	4.46	8.66	12.69	2.68	0.00	0.00	0.00	0.49	1.23	9.50	30.22
10	4.46	8.66	12.69	2.68	0.00	0.00	1.23	0.49	0.00	0.00	30.22
11	4.46	7.92	12.69	2.68	0.00	1.23	0.00	0.00	1.23	0.00	30.22
12	4.46	7.92	12.69	2.68	0.00	1.23	1.23	0.00	0.00	9.50	30.22
13	4.46	9.65	12.69	2.68	0.74	0.00	0.00	0.00	0.00	9.50	30.22
14	4.46	7.18	12.69	2.68	0.74	0.00	1.23	0.00	1.23	0.00	30.22
15	4.46	7.92	12.69	2.68	0.74	1.23	0.00	0.49	0.00	0.00	30.22
16	4.46	5.46	12.69	2.68	0.74	1.23	1.23	0.49	1.23	9.50	30.22

Table 10. Description of industrial by-products investigated.

Fly Ash	Type C fly ash produced at the Pleasant Prairie power plant operated by Wisconsin Electric Power Company. Light brown/tan color fine powder. Tested as highly cementitious when a small quantity was mixed alone with water and allowed to harden.
Bottom Ash	Produced at the Sheybogan power plant operated by Wisconsin Power and Light. Coarse sand-like in appearance with a very small amount of larger prune sized chunks scattered in between.
Slag	Produced at the Sheybogan power plant operated by Wisconsin Power and Light. Black glassine irregular shaped bits about 1mm x 1mm in size on average. A few larger marble sized chunks dispersed in between.
Silica Fume	Cormex Construction Chemicals commercially packaged microsilica. Grey very fine and light weight powder.
Crumb Rubber	Tires ground into 1-2 mm x 0.5 mm strings obtained from Tire Terminators. Inc., Waukesha. WI.

Table 11. Mean diffusion coefficients of FFED samples.

Sample	D (cm^2/s)
1	2.95E-04
2	3.56E-04
3	4.52E-04
4	3.34E-04
5	2.21E-04
6	1.99E-04
7	1.94E-04
8	2.02E-04
9	3.21E-04
10	3.25E-04
11	4.85E-04
12	4.78E-04
13	2.55E-04
14	2.25E-04
15	3.25E-04
16	3.60E-04
E1	5.19E-04
E2	1.28E-04
E3	1.43E-04

Table 12. Statistically identified optimal concrete sample factor levels.

Column	Constituent	E1 Level	E2 Level	E3 Level
1	**Water**	1	1	1
2	Fly Ash	2	2	2
3	Bottom Ash	1	1	1
4	Slag	2	2	2
11	Silica Fume	2	1	1
12	Crumb Rubber	2	1	2
13	Superplasticizer	1	1	1

Table 13. Statistically identified optimal concrete sample formulations.

Sample	Cement (lbs.)	Sand (lbs.)	Aggregate (lbs.)	Water (lbs.)	Fly Ash (lbs.)	Bottom Ash (lbs.)	Slag (lbs.)	Silica Fume (lbs.)	Crumb Rubber (lbs.)	Super-plasticizer (ml)	Batch Weight (lbs.)
E1	4.46	6.69	12.69	2.45	0.74	0.00	1.23	0.49	1.23	0.00	29.99
E2	4.46	8.42	12.69	2.45	0.74	0.00	1.23	0.00	0.00	0.00	29.99
E3	4.46	7.18	12.69	2.45	0.74	0.00	1.23	0.00	1.23	0.00	29.99

Table 14. Mean air permeability coefficients of FFED samples.

Sample	K (cm^2)
1	5.40E-11
2	3.27E-11
3	4.80E-11
4	4.65E-11
5	2.32E-11
6	3.90E-11
7	3.98E-11
8	1.06E-11
9	5.41E-11
10	3.63E-11
11	4.94E-11
12	9.84E-11
13	1.53E-10
14	2.58E-11
15	1.98E-09
16	6.88E-11
E2	1.85E-11
E3	5.45E-11

Table 15. Mean porosity values of FFED samples.

Sample	ε (%)
1	16.0
2	16.8
3	17.2
4	19.3
5	16.4
6	14.8
7	17.3
8	14.5
9	17.0
10	16.4
11	19.3
12	17.3
13	14.2
14	23.8
15	15.1
16	17.4
E2	11.0
E3	15.8

Table 16. Radon gas emanation rates from samples 1 and 16.

Sample	Emanation Rate (pCi Rn-222/min)
1	4.37E-03
16	3.60E-03

Table 17. Compressive strength measurements.

Sample	Compressive Strength (psi)
1	5,835
2	2,498
3	6,700
4	3,493
5	4,639
6	8,252
7	3,215
8	6,557
9	3,740
10	6,533
11	2,541
12	4,902
13	5,475
14	2,928
15	7,663
16	3,979
E1	2,340
E2	7,066
E3	3,684