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A systematic approach for the development of porous concrete based on axiomatic design theory

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Abstract. This paper presents a design framework developed using axiomatic design (AD) theory that can be applied in the design process of porous concrete. The main contribution of this paper is the definition of an AD framework based on the needs and functional requirements of porous concrete. The framework shows how AD theory can be used to provide guidelines for proportioning and manufacturing porous concrete. The advantage of the AD approach is that it systemizes the way to decouple design parameters and makes designers to think rationally between what we want to achieve and how we propose to satisfy the functional requirements of porous concrete. In this paper, test results of laboratory-size porous concrete specimens under compression were analyzed to evaluate the performance of the porous concrete based on the desired functional requirements.

Keywords: axiomatic design; porous concrete; mix proportioning; functional requirements; design parameters; process variables.

1. Introduction

Mix proportioning is one of the steps to designing of concrete structures with the desired performance characteristics. It is the process of determining the composition of cement, aggregates, water and admixtures for making concrete. This process is considered an art rather than a science due to the various conflicting requirements that influence the decision in arriving at the right mix proportions (Mehta and Monteiro 2006). For example, increasing the water content may improve the flowability of fresh concrete while at the same time decrease the strength. Another important factor is the fine-coarse aggregate ratio. Many researchers have shown that particle size distribution of aggregates could affect performance of concrete (Amirjanov and Sobolev 2005). For a fixed volume of aggregates, the use of less fine aggregates compared to coarse aggregates reduces the water requirement due to decrease in the surface area of the aggregates. However, the porosity of the concrete may be increased since there is lack of fine aggregates to fill up the void spaces in between coarse aggregates. Due to many constraints that mix designers need to consider in order to obtain a functional mix proportion, clearly a systematic framework for this process is needed. Parichatprecha and Nimityongskul (2009) suggested that an integrated approach using artificial

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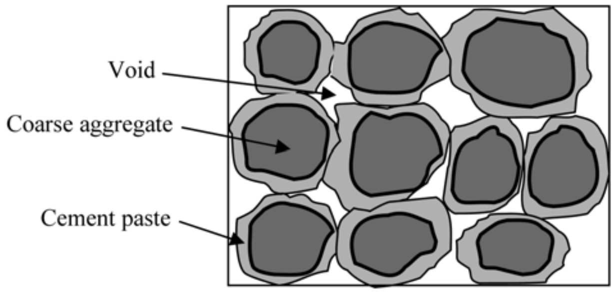

Fig. 1 A schematic model of porous concrete (redrawn from Yang and Jiang 2003)

neural networks and genetic algorithms would be able to overcome these constraints in achieving optimum solution.

Porous concrete is a special concrete with high porosity and continuous voids, which readily allow water to pass through. Porous concrete can be produced using narrowly graded coarse aggregate, low paste content and admixtures. The most notable advantage of porous concrete is its ability to allow percolation of water into the ground and minimize stormwater runoff. Thus, it is commonly used as a pavement material for parking lots and walkways. Porous concrete is also effective for sound absorption and it can be used as sound barrier to reduce the impact of highway noise (BRITE/EURAM 1994). The potential problem for porous concrete is clogging. However, studies have shown that pressure washing can restore the porosity of clogged porous concrete to nearly new conditions (NRMCA 2009a).

Compared to normal concrete that usually contains from 3 to 5% voids, the total void content in porous concrete ranges from 15 to 40% depending on its application, and its compressive strength and density are much lower than that of normal concrete (Chopra *et al*. 2006). Since little or no fine aggregates are used, it is also called as no-fines concrete (Meininger 1988). Fig. 1 shows the schematic model of the porous concrete. Coarse aggregates form the concrete framework and they are bounded together by cement paste layer while the interstitial void spaces are left unfilled. The fundamental factors influencing performance of porous concrete such as aggregate size and volume, paste-aggregate ratio, admixture types and dosage have been investigated by many researchers (Zhang *et al*. 1997, Yang and Jiang 2003, Park and Tia 2004, Park *et al*. 2005, Schaefer *et al*. 2006, Haselbach *et al*. 2006, Neithalath 2007, Chindaprasirt *et al*. 2008). Although the typical range of material proportions for porous concrete are available in the literatures (e.g. NRMCA 2009b), there is still lacking of guidelines for a proper proportioning of materials for meeting the performance requirements.

This paper is an attempt to show how AD theory can be used to guide designers through the process of design of porous concrete. Functional requirements, design parameters and process variables for the development of functional porous concrete can be determined by a systematic decomposition technique proposed by Suh (2001). Based on the Independence Axiom (Suh 2001), rational sequence of the mix proportioning process is proposed with the aim of reducing the trial-and-error effort to obtain the desired properties of concrete.

2. Recapitulation of axiomatic design theory

The AD theory was developed by Suh in 1970s as a general design framework that can be applied to all design activities. Suh (2001) defines design as the interplay between “what we want to achieve” and “how we want to achieve it”. A good design can be achieved by considering two important axioms: 1) the Independence Axiom states that the chosen functional requirements must always be independent of each other, and 2) the Information Axiom states that the information content must be minimized in order to maximize the probability of success of the design (Suh 2001).

Suh (2001) illustrates that the world of design is consisted of four different domains as shown in Fig. 2. The customer domain characterized by the attributes that the customers or end users are looking for is the first domain to be specified, the customer attributes (CAs) are then translated in terms of functional requirements (FRs) in the functional domain, the FRs are mapped in terms of design parameters (DPs) in the physical domain, and finally, the process is characterized by process variables (PVs) in the process domain (Suh 2001).

In order to assess the Independence Axiom, the FRs and DPs are expressed mathematically as follows (Suh 2001):

$$\{FR\} = [A]\{DP\} \tag{1}$$

where [A] is known as the design matrix. The design matrix will determine whether the design is uncoupled, coupled or decoupled. Suppose we have three FRs and DPs. The design equation will be as follows (Suh 2001):

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{2}$$

If the design matrix is diagonal as shown in Fig. 3(a), each FR is satisfied independently by the corresponding DP. It is called an uncoupled design, which perfectly satisfies the Independence

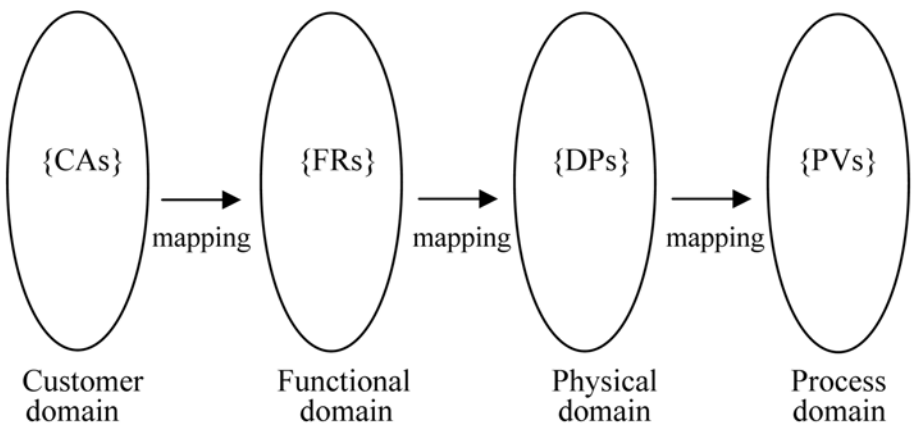

Fig. 2 The four domains of the design world (Suh 2001)

$$\begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \quad \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \quad \begin{bmatrix} X & 0 & 0 \\ X & X & X \\ X & 0 & X \end{bmatrix}$$

(a) (b) (c)

Fig. 3 Uncoupled, decoupled and coupled design matrices defined by Suh (2001)

Axiom. The symbol 'X' indicates the relationship between FRs and DPs and the mathematical expression can be written as follows (Suh 2001):

$$FR_1 = A_{11}\, DP_1 \tag{3a}$$

$$FR_2 = A_{22}\, DP_2 \tag{3b}$$

$$FR_3 = A_{33}\, DP_3 \tag{3c}$$

When the matrix is triangular as shown in Fig. 3(b), the independence of FRs can be guaranteed if and only if the DPs are determined in a proper sequence. Such a design is called a decoupled design (Suh 2001). The process for the decoupled design is as follows (Suh 2001):

$$FR_1 = A_{11}\, DP_1 \tag{4a}$$

$$FR_2 = A_{21}\, DP_1 + A_{22}\, DP_2 \tag{4b}$$

$$FR_3 = A_{31}\, DP_1 + A_{32}\, DP_2 + A_{33}\, DP_3 \tag{4c}$$

From Eq. (4a), DP_1 is first determined for FR_1 and fixed. FR_2 in Eq. (4b) is satisfied by the selection of DP_2 and DP_1 and finally DP_3 in Eq. (4c) is obtained the same way as DP_1 and DP_2. Any form of the design matrix other than the diagonal or triangular design matrix is called a coupled design. In a coupled design shown in Fig. 3(c), the FRs cannot be satisfied independently by any sequence of DPs as shown below (Suh 2001):

$$FR_1 = A_{11}\, DP_1 + A_{12}\, DP_2 + A_{13}\, DP_3 \tag{4a}$$

$$FR_2 = A_{21}\, DP_1 + A_{22}\, DP_2 + A_{23}\, DP_3 \tag{4b}$$

$$FR_3 = A_{31}\, DP_1 + A_{32}\, DP_2 + A_{33}\, DP_3 \tag{4c}$$

Defining the FRs and the corresponding DPs as above may not be sufficient in a complicated case. Suh (2001) proposes that the design process be established by a systematic decomposition technique as illustrated in Fig. 4. Beginning at the top level, the design process is carried out from the functional to the physical domain. In Fig. 4, FR_1 and FR_2 are the FRs that characterize the top level DP and must collectively satisfy the top level FR. By zig-zagging between the two domains, the decomposition process continues level by level until the FR can be satisfied without further decomposition when all of the branches reach their final state (Suh 2001). It is noted that the axiomatic design process is not quite like the iterative process since the goal of the whole mapping process as explained above is to systematically identify the corresponding DPs based on the desired FRs. The basis of the AD theory is that an ideal design could be achieved if we can satisfy each FR independently by the corresponding DP.

The advantage of applying AD theory in a design process is that designers can think rationally

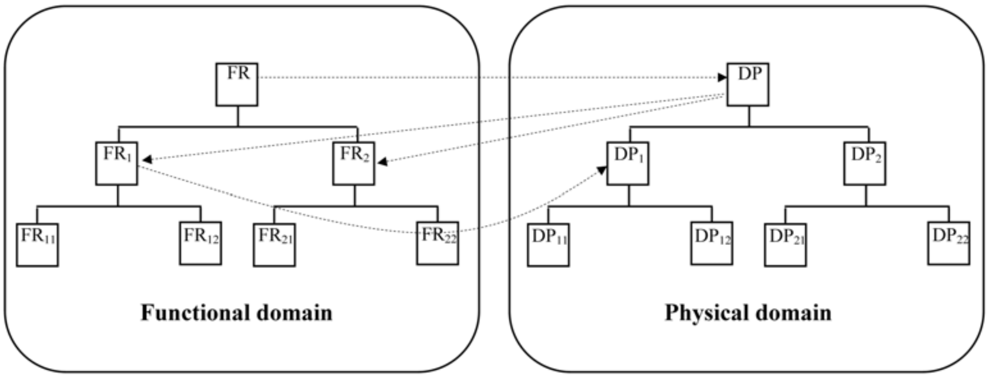

Fig. 4 The process of mapping from functional to physical domain (redrawn from Suh 2001)

about what they want to achieve and how they propose to achieve it. Defining the FRs properly and understanding the FR-DP relationship provides a systematic guideline to go through the high level design to the low level design activities. Hence, AD theory provides us with a useful tool to develop a useful framework for understanding a complex design (Suh 2001).

3. Design framework of porous concrete

In this section, the AD theory is used to propose a framework for proportioning porous concrete and to systemize the design process to achieve the functional requirements of porous concrete.

3.1. Mapping from functional domain to physical domain

Herein, the mapping process from the functional to the physical domain is carried out. Designers must first define the essential needs and what they want to achieve. By considering the attributes that the customers or end users are looking for, the desired performance characteristics of porous concrete are identified. Based on the various applications of porous concrete, the FRs may be stated as

FR_1=Provide suitable porosity and permeability
FR_2=Provide acceptable strength

Porosity can be defined as a function of void content. If void content increases, porosity increases. Thus, void content and pore structure are chosen as DP_1. To satisfy the second FR, we propose DP_2: Additives. Therefore,

DP_1 =Void content and pore structure
DP_2 = Additives

The relationship between FRs and DPs at this level may be written as follows:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{5}$$

As explained in Section 2, the symbol ‘X’ indicates the relationship between FRs and DPs, while ‘0’ indicates that there is no relationship between them. If the effect of a particular DP is small, we can assume there is no relationship (symbol 0). The design matrix in Eq. (5) is triangular, i.e., decouple design.

The top-down zig-zagging decomposition is carried out to decompose the design hierarchy. Since the void content of porous concrete is equal to the difference between one and the sum of volume fractions of aggregate and hardening paste, the FR_1 and DP_1 are decomposed according to this relation as follows:

FR_{11} = Provide suitable volume of aggregate
DP_{11} = Unit aggregate content
FR_{12} = Provide suitable volume of paste
DP_{12} = Unit paste content
FR_{13} = Provide good hydraulic conductivity
DP_{13} = Aggregate size distribution

In matrix form, they can be written as follows:

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{Bmatrix} \tag{6}$$

Eq. (6) suggests that we can determine unit aggregate content and unit paste content prior to deciding on the other detail of aggregate component. Since volume of paste is made up of volume of cement and water, FR_{12} and DP_{12} can be further decomposed as

FR_{121} = Suitable volume of cement
DP_{121} = Cement content
FR_{122} = Suitable amount of water
DP_{122} = Water/ Cement ratio

In matrix form, they can be written as follows:

$$\begin{Bmatrix} FR_{121} \\ FR_{122} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{121} \\ DP_{122} \end{Bmatrix} \tag{7}$$

The suggested decomposition for FR_2 and DP_2 are as follows:

FR_{21} = Use suitable type of additives
DP_{21} = Type of additives
FR_{22} = Provide suitable amount of additives
DP_{22} = Amount of additives

In matrix form, they can be written as follows:

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \end{Bmatrix} \tag{8}$$

	DP1	1.1	1.2	1.2.1	1.2.2	1.3	DP2	2.1	2.2
FR1	X						0	0	0
1.1		X	0	0	0	0	0	0	0
1.2		0	X			0	0	0	0
1.2.1		0		X	0	0	0	0	0
1.2.2		0		X	X	0	0	0	0
1.3		0	X	X	X	X	0	0	0
FR2	X	X	X	X	X	X	X		
2.1	0	0	X	0	0	0		X	0
2.2	0	0	X	0	0	0		0	X

Fig. 5 The design matrix of the proposed design framework

After determining DP_{11}, DP_{12} and DP_{13}, and their sublevels, the (initial) strength of porous concrete can be estimated based on designers' experience and previous researches. DP_2 is an option for improving the strength of porous concrete depending on individual case. In the case that the strength of porous concrete is below the requirement after using DP_{11}, DP_{12} and DP_{13}, DP_2 should be used to improve the strength. But, in the case that the strength satisfies the requirement, additives (DP_2) may also be used to provide for higher strength of porous concrete.

Fig. 5 shows the design matrix of the proposed design framework. For checking the Independence Axiom, here the matrix is triangular. Even though the matrix does not show an ideal design, the independence of FRs can still be guaranteed by determining the DPs in a proper sequence. The FRs and DPs provide guidelines in the mix proportioning of porous concrete. The main factor for each corresponding functional requirement can be clearly identified based on the framework. The proposed framework could help to minimize the iterative trial and error process and maximize the probability of success of manufacturing good porous concrete.

3.2. Mapping from physical domain to process domain

After completing the mapping process between functional domain and physical domain, a suitable set of PVs are defined that can generate the DPs. Porous concrete can be manufactured by various techniques. In general, the manufacturing of porous concrete involves three processes: preparation, mixing, and placement and compaction. In the preparation process, aggregate, cement, admixture, water and all the necessary equipment are readily prepared before mixing. The mixing speed and time in the mixing process have a strong influence on the characteristic of cement (binder) paste. After placing concrete mixes into the molds or formworks, vibrators or other compaction equipment are used to compact the fresh concrete. The type of compaction equipment and compaction time play an important role in the final void content, pore structure and strength of porous concrete. Based on the AD theory, the zig-zagging process is carried out to decompose PVs and to map from the physical to the process domain. The suggested PVs are given in Table 1. For the laboratory investigation presented in the following section, the manufacturing processes related to the PVs

Table 1 FRs, DPs and PVs

FRs	DPs	PVs
FR_1: Provide suitable porosity and permeability	DP_1: Void content and pore structure	PV_1: Manufacturing process
1.1 Provide suitable volume of aggregate	1.1 Unit aggregate content	1.1 Compaction
1.2 Provide suitable volume of paste	1.2 Unit paste content	1.2 Mixing
1.2.1 Suitable volume of cement	1.2.1 Cement content	1.2.1 Prepare cement
1.2.2 Suitable amount of water	1.2.2 W/C ratio	1.2.2 Prepare water
1.3 Provide good hydraulic conductivity	1.3 Aggregate size distribution	1.3 Selection of appropriate sieve size
FR_2: Provide acceptable strength	DP_2: Additives	PV_2: Appropriate usage of additives
2.1 Use suitable type of additives	2.1 Type of additives	
2.2 Provide suitable amount of additives	2.2 Amount of additives	

were studied from the literature survey to understand their influence on properties of porous concrete. Subsequently, the proposed framework presented in Fig. 5 was used to suggest ways to improve the mix proportion of porous concrete.

4. Laboratory investigation

Several porous concrete mixes were prepared in the laboratory to illustrate how we may apply the conceptual AD framework. The design objective is to make porous concrete with porosity from 20 to 30% and compressive strength above 10 MPa. The design process follows the computational procedure as shown in Fig. 6. In the mix proportioning of porous concrete, target void content is selected as the first variable in order to calculate absolute volume of materials. The functional requirement FR_{11} can be determined based on mass of aggregates divided by the total volume they occupy. The FR_{12} and paste to aggregate volume (P/G) ratio can be calculated from target void content and FR_{11}. In addition, FR_{122} can be obtained based on the suitable flow of cement paste to make porous concrete and subsequently, the water to cement (W/C) ratio was calculated based on unit paste content and FR_{122}. The remaining design variable DP_{121} can be determined from unit paste content and W/C ratio. Three mix proportions were designed with varying P/G ratio and 5 specimens were made for each mix proportion. Paste to aggregate (P/G) volume ratio for each mix was selected as 0.3, 0.4 and 0.5, respectively. Normal Portland cement was used in this investigation. W/C ratio of 0.27 was chosen for all the mixes. To achieve FR_{13}, coarse aggregates made of crushed stones with 13 to 19 mm particle size were used. To improve the strength of porous concrete, two types of additives were used. In each mix, 1% superplasticizer (SP) by the weight of cement and 10% silica fume (SF) by the weight of the binder (cement plus SF) were added. Details of the three mix proportions are given in Table 2.

In the process domain, the mixing speed was set at 45 rpm. The materials were mixed in accordance with the following separate charging method (Park and Tia 2004): coarse aggregates, cement and SF were added first and mixed in a dry state for 1 min. After that water containing SP was added and mixed for another 3 min. Cylindrical specimens (ϕ100×200 mm) were made by rodding 25 times in two layers to consolidate the fresh concrete and to provide strong bond between the paste and coarse aggregate. Vibration was also applied on the top surface for 10 s. During the first 24 hours, the cylinders were covered with plastic sheet to avoid moisture loss. After 24 hours,

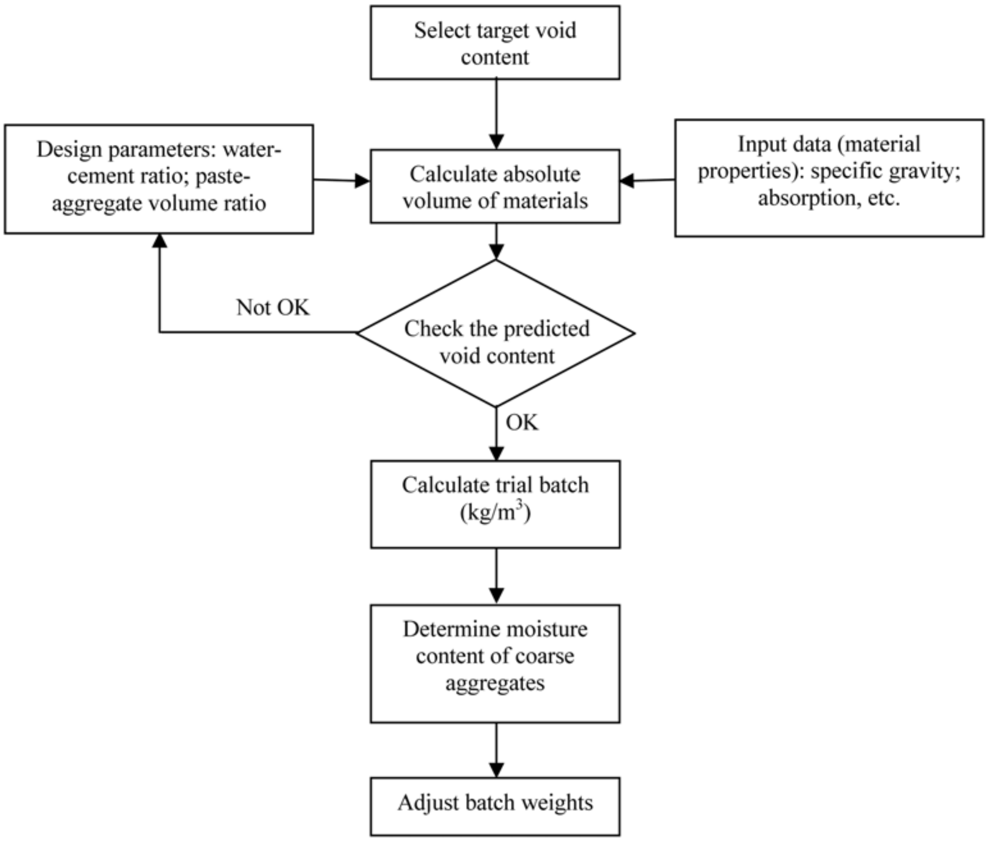

Fig. 6 Computational procedure for mix proportioning

Table 2 Mix proportions

Mix proportion	Aggregate (kg/m^3)	Water (kg/m^3)	Cement (kg/m^3)	SP (1%) (kg/m^3)	SF (10%) (kg/m^3)
1	1600	73.55	275.8	2.758	30.65
2	1487	91.14	341.77	3.418	37.97
3	1388	106.34	398.77	3.988	44.31

the specimens were removed from the molds. For the remaining period until testing, the specimens were cured under water at 20°C to allow them to continue to hydrate. Without water, hydration of cement would not occur. The existing practice for acceptance of concrete quality is usually based on the strength of specimens prepared and cured under ideal conditions in laboratory. The methodology in this study did not address the quality of the construction and/or the adequacy of the field curing process. Strength tests can be performed on specimens extracted from the completed structure. However, this issue is beyond the scope of this study.

The compressive strength and void content of specimens were determined at 28 days. Compressive strength of concrete was determined in accordance with ASTM C39. Cylindrical specimens were placed in a universal hydraulic testing machine (UTM) as shown in Fig. 7. The

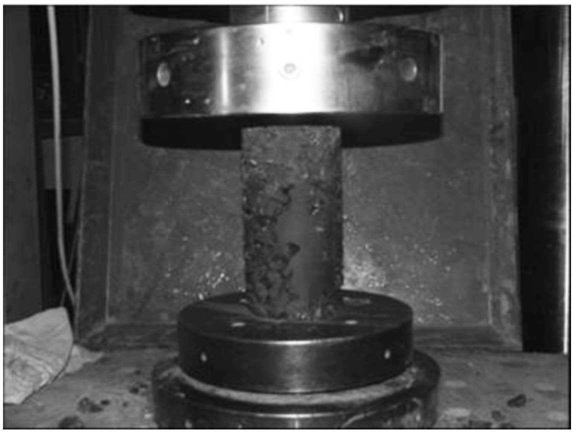

Fig. 7 Compression test

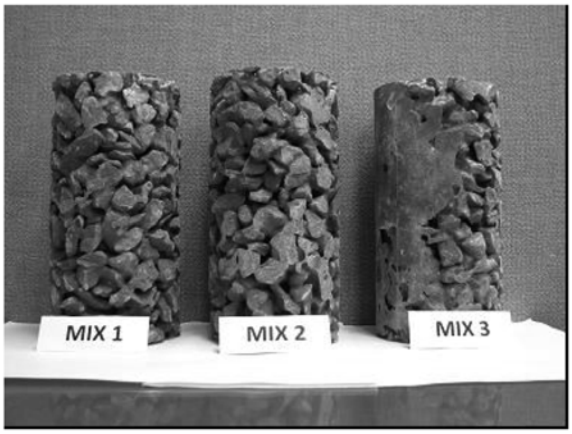

Fig. 8 Typical specimens

Table 3 Experimental results

Mix proportion	Specimen	Void content (%)			Compressive strength (MPa)		
		Individual value	Average value	Standard deviation	Individual value	Average value	Standard deviation
1	1-1	30.93	30.37	0.88	9.17	8.12	1.10
	1-2	31.53			7.45		
	1-3	30.11			6.59		
	1-4	29.26			9.07		
	1-5	30.00			8.31		
2	2-1	27.58	26.64	1.09	10.50	12.61	1.62
	2-2	25.41			14.99		
	2-3	25.68			12.99		
	2-4	27.83			12.22		
	2-5	26.69			12.32		
3	3-1	22.20	20.72	2.17	12.80	14.07	1.79
	3-2	23.02			14.23		
	3-3	21.38			12.61		
	3-4	17.79			17.06		
	3-5	19.19			13.66		

UTM was operated at a constant loading rate of 0.015 mm/s until the specimens failed.

The void content of porous concrete was calculated by the following equation (Park and Tia 2004):

$$A = \left(1 - \frac{(W_2 - W_1)/\rho_w}{V_1}\right) \times 100\ (\%) \tag{9}$$

where W_1 = Weight of specimen under water, kg;
W_2 = Weight of specimen dried in air for 24 hours, kg;

V_1 = Volume of specimen, mm^3;
ρ_w = Density of water, kg/mm^3.

The test results are presented in Table 3 and the typical specimen for each of the mix proportion are shown in Fig. 8. In Table 3, the statistical analysis for each mix with respect to void content and compressive strength was obtained in terms of average value and standard deviation. Based on the test results, mix 1 is considered as a failure due to its low compressive strength (below 10 MPa). Using the AD framework, we can suggest the way to correct this mix proportion. FR_2, which is the function of DP_1 and DP_2, can be used to improve strength of porous concrete. To achieve FR_2, we can change both DPs or just one of them. However, in this case the cause of the problem could be DP_1 because the void content was rather high. Thus, based on the AD framework, the most effective way is probably to change DP_1 (reduce void content). The void content can be reduced by changing DP_{11} (increase unit aggregate content) or DP_{12} (increase unit paste content). This can be done by controlling the volume of paste against the volume of aggregate. Therefore, changing DP_{12} (increase unit paste content) would have higher probability of success to increase porous concrete strength.

Both mixes 2 and 3 are of acceptable strength and the difference between compressive strength of mixes 2 and 3 was only 1.46 MPa. However, the distribution of void content and strength of specimens of mix 2 around the average value is smaller and more stable than that of mix 3, as shown in Table 3. This means that we are likely to achieve higher probability of success if we make porous concrete using mix 2. Consequently, mix 2 is considered the best design. It is noted that the above findings were reached based on limited number of mix designs with varying paste-aggregate volume ratio only. Other design parameters such as water-cement ratio, aggregate grading, aggregate size, amount of additives, etc. may also be considered in the actual production of porous concrete.

5. Conclusions

In this paper, AD theory was used to define the design framework for the development of porous concrete with the desired functional requirements. AD theory provides designers with a standardized design procedure based on a top-down decomposition process. It helps designers carry out design activities in a well-organized manner.

The FRs, DPs and PVs were determined to provide guidelines for proportioning and manufacturing porous concrete. Based on the mapping between the functional and the physical domain, and the physical and the process domain, designers can clearly classify and determine the main factors for each corresponding functional requirement that the designers want to achieve. Therefore, if the designers make mistakes, they can easily detect the cause of their mistakes and make suitable corrections. That is, the application of AD theory in this case helps to minimize the iterative trial and error process and maximize the probability of success.

A laboratory investigation was carried out to illustrate the application of the AD framework. Three mix proportions were designed and 5 specimens for each mix proportion were tested to determine their compressive strength and void content. The test results showed that all specimens made with mix proportion 1 have low compressive strength than the target strength. An analysis was made based on the AD framework to suggest a way to correct mix 1. Finally, mix 2 was chosen as the best design with the highest possible probability of success for making good porous concrete with the desired functional requirements.

The proposed framework was an initial attempt by the authors to show the applicability of AD theory in the design process of porous concrete to achieve the desired functional requirements with high probability of success. In specific applications, porous concrete may have special functional requirements (e.g. acoustic absorption, heat insulation, provide hard surface, etc.). In future, researches on the development of design framework based on AD theory would be focused on these applications.

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References

Amirjanov, A. and Sobolev, K. (2005), "Optimal proportioning of concrete aggregates using a self-adaptive genetic algorithm", *Comput. Concrete,* **2**(5), 411-421.

ASTM C39 (2005), "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens", *IHS Specs & Standards, American Society for Testing and Materials*, Philadelphia.

BRITE-EURAM (1994), "Surface properties of concrete roads in accordance with traffic safety and reduction of noise", *State-of-the-Art Report, Recommendations for Practice and Further Developments and Final Technical Report*, Intron, Sittard, Netherlands.

Chindaprasirt, P., Hatanaka, S., Chareerat, T., Mishima, N. and Yuasa, Y. (2008), "Cement paste characteristics and porous concrete properties", *Constr. Build. Mater.*, **22**, 894-901.

Chopra, M., Wanielista, M. and Mulligan, A.M. (2006), *Compressive strength of pervious concrete pavements*, Final Report FDOT Project BD521-02, June, Stormwater Management Academy, University of Central Florida, Orlando.

Haselbach, M.L., Valavala, S. and Montes, F. (2006), "Permeability predictions for sand-clogged Portland cement pervious concrete pavement systems", *J. Environ. Manage*., **84**(1), 42-49.

Mehta, P.K. and Monteiro, P.J.M. (2006), *Concrete: microstructure, properties, and materials*, 3rd Edition, McGraw-Hill, NY.

Meininger, R.C. (1988), "No-Fines Pervious Concrete for Paving", *Concrete Int.*, **10**(8), 20-27.

Neithalath, N. (2007), "Extracting the performance predictors of Enhanced Porosity Concretes from electrical conductivity spectra", *Cement Concrete Res.*, **37**, 796-804.

NRMCA (2009a), "FAQ" (available at http://www.perviouspavement.org/FAQ.htm)

NRMCA (2009b), "Mix Design and Materials, Pervious concrete" (available at http://www.perviouspavement.org/mixture%20proportioning.htm)

Park, S.B. and Tia, M. (2004), "An experimental study on the water-purification properties of porous concrete", *Cement Concrete Res.*, **34**, 177-184.

Park, S.B., Seo, D.S. and Lee, J. (2005), "Studies on the sound absorption characteristics of porous concrete based on the content of recycled aggregate and target void ratio", *Cement Concrete Res.,* **35**, 1846-1854.

Parichatprecha, R. and Nimityongskul, P. (2009), "An integrated approach for optimum design of HPC mix proportion using genetic algorithm and artificial neural networks", *Comput. Concrete*, **6**(3), 253-268.

Schaefer, V., Wang, K., Suleiman, M. and Kevern, J. (2006), *Mix design development for pervious concrete in* *cold weather climates*, Final Report, Feb 2006, Center for Transportation Research and Education, Iowa State University.

Suh, N.P. (2001), *Axiomatic Design: advances and applications*, Oxford University Press, NY.

Yang, J. and Jiang, G. (2003), "Experimental study on properties of pervious concrete pavement materials", *Cement Concrete Res.*, **33**, 381-386.

Zhang, R., Nakazawa, T., Imai, F. and Shinnishi, N. (1997), "Void content of no-fines concrete", *JCA Proc. Cement Concrete*, **19**(1), 1051-1056.

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