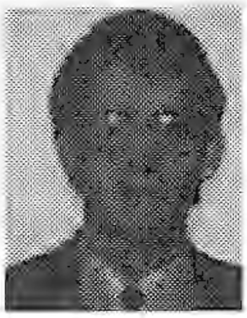

PERFORMANCE TAILORING OF STRUCTURAL CONCRETE

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ABSTRACT: The paper presents the acquired knowledge from the development and use of an expert system for the performance tailoring of concrete. The expert system combines a shell in the Windows-environment with a number of programs and applications, in an optimal constellation where the most suitable program, shell or application can be used for solving the problem. The system can design concretes according to Danish, Spanish and French codes for a specific strength, workability and durability according to the national codes. The system uses the local aggregates and cements, documented with the different national codes. The facilities enables a fast and optimal use of aggregates and cement, thus leading to a better use of the available types of aggregates and a reduced cost.

KEYWORDS: Performance Tailoring, Durability, Workability, Concrete Mix Design, Expert system.

1. INTRODUCTION

A European research project "Performance Tailoring of Structural Concrete" which has established guidelines for an optimal mix design has been completed. The project was funded by the European Commission as a BRITE/EURAM-project and carried out by the Spanish (ICCET), French (Bouygues) and Danish (AEC; RH&H; G.M.IDORN CONSULT) participants.

It has been shown that the strength and workability requirements and formulas are fairly similar, but that the durability requirements to concrete in constructions differs significantly from one country to another.

An effective optimization of concrete mix design to comply with the requirements will take quite a lot of time unless proper computer simulations are used. An evaluation of several alternative types of aggregates for the concrete mix design will thus be difficult, except with the use of an expert program.

The aim of the project has thus been to develop an expert program, with rules from the standards of different countries, their durability requirements and the necessary formulas and tables for designing the concrete for the requested strength and workability. The development of the prototype were carried out under the Windows-environment, using the NEXPERT expert shell, Visual Basic and EXCEL, which enabled a fast and simple prototyping, where even the report generation, optimization and testing could be carried out with the most suitable program or application.

This enables a fast performance tailored mix design of the concrete, leading to a price optimal concrete using the local materials and in compliance with the requirements for strength, workability and durability. The main results are presented in this paper. A commercial version will be developed during 1993.

2. THE DESIGN PHASES

The design of the concrete mix must be split into several main design phases:

- Identification and characterization of the requirements
- Selection of constituent materials
- Optimize design with selected materials
- Testing and evaluation of mix design

The user interface, program structure and design tools must follow those phases in order to be clear and consistent and enable a later, consistent expansion of the program by inclusion of further models or simulation tools.

3. SPECIFICATION OF REQUIREMENTS

The designer must start by specifying the requirements for the concrete mix, prior to the actual mix design process. The requirements can best be grouped in:

- Processing requirements
- Strength requirements
- Durability requirements

3.1. Processing Requirements

The processing requirements depends on the intended way of processing the concrete. This will lead to requirements to slump and precaution against bleeding and separation. It will result in requirements for:

- Ideal grain size distribution curve
- Filler and cement content
- Water content

which all depends on a number of items as reinforcement arrangement, casting method (pumping/flow) and on national traditions.

The reviews have shown that fairly different ideal curves are used in the European countries [1,2], which may be due to either traditions or the differences in the aggregate types used in the concrete production (sand and gravel deposits or crushed aggregates from quarries).

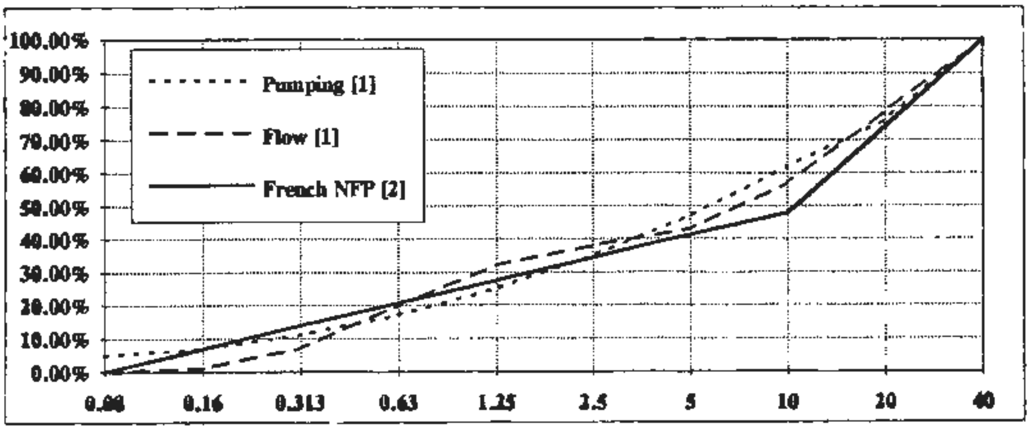

Figure 1. Ideal grain size distribution curves (sieve sizes in mm).

The differences between the ideal curves show that there is a large potential for introducing new ideal curves in the mix design. The ideal curve is an important aspect in the concrete mix design, since a correct ideal curve will increase the workability and reduce the cement consumption and the mix price.

3.2. Strength Requirements

The strength requirements covers all the requirements for strengths and stiffness at different maturities, abrasion resistances etc. The one used in the program and in ordinary practice is the compressive strength at 28 days age, but other values can easily be introduced in the design.

3.3. Durability Requirements

The relevant codes, handbooks and guidance documents such as for instance the Danish Concrete code [3] have been reviewed in the project for a number of countries (Denmark [3,4], France [5,6,7,8,9,10], Spain [11], Germany [12,13,14,15,16,17,18], USA [19] and the European Community [20,21]).

Significant differences between the different countries have been identified, ranging from the type of requirements, preventive measures against deterioration and definitions to the use of environmental classification. These differences are mainly due to the differences in environment (frost or not) and in the local geology (which types of aggregates are available, and the types of problems they may cause).

All the reviewed European standards use an environmental classification, which unfortunately differs from one country to another as shown in Table 1.

Country	Environmental Classes
Denmark	Passive, Moderate, Aggressive, Extremely Aggressive
France	0, 1, 2, 3, 4
Spain	I, II, IIf, IIh, III, IIIf, IIIh
Germany	1, 2, 3, 4
EEC	1,2a,2b,3,4a,4b,5a,5b,5c

Table 1. Possible environmental classes in reviewed European codes.

This makes a strict comparison impossible. It seems, however, that the most common requirements for producing a durable concrete are related to:

- Maximum water/cement ratio
- Minimum compressive strength
- Minimum cement content
- Aggregate parameters

However, since the three first parameters are interrelated many codes specify only two of them, and opinions differ as to which one - if any - that should be omitted from code specifications. The requirements for the minimum cement content seems however to be the one to remove since an increase of the cement content in a concrete with a fixed water-cement ratio, leads to an increase of the porosity and price of the concrete. The differences between the reviewed codes and their importance to the concrete construction industry will be further elaborated in a separate paper.

A comparison is possible since approximately 75% of all concrete produced in Europe [22] is intended for use in environments which are either dry or humid without risk of freezing or chloride attack (corresponding to indoor structures and some foundations), as shown in Table 2.

Requirements	Denmark	Germany	Spain	France	EEC	USA ACI
W/C Ratio, max	-	0.75	0.65	-	0.60	-
2Concrete Strength, min	15	-	-	-	-	-
Cement Content,min	-	240	250	-	260	-

Table 2. Requirements for 75% of European concrete consumption [22].

4. OPTIMAL CONCRETE MIX DESIGN

Within the project large number of test designs have been carried out, using local materials, with parameters provided by the participants. The models used in the expert program have been verified by batching and testing on Bouygues full-scale plant near Paris.

The mix design can thus be carried out in a number of steps:

1) the selection and combination of aggregates to comply with the durability requirements and to fit with an ideal curve
2) the selection and mix of cements, flyash and microsilica
3) the combination of the aggregate mix and the Cement/Flyash/Microsilica-mix with water and additives to comply with the requirements in an optimal approach.

This stepwise design enables the user to identify and replace the constituent material, which limits the design optimization. A full optimization will, however, often request the user to optimize all the steps at the same time, since e.g. some of the durability requirements be interrelated as e.g. the cement content and the chloride content in the aggregates.

The performance tailoring of the aggregates aim at a combination, where the aggregate mix respects the durability requirements and the mix curve fits the ideal curve best possible. An unsuitable choice of aggregates will, however, lead to an unsuitable mix curve which differs too much from the ideal curve, as illustrated in Figure 2.

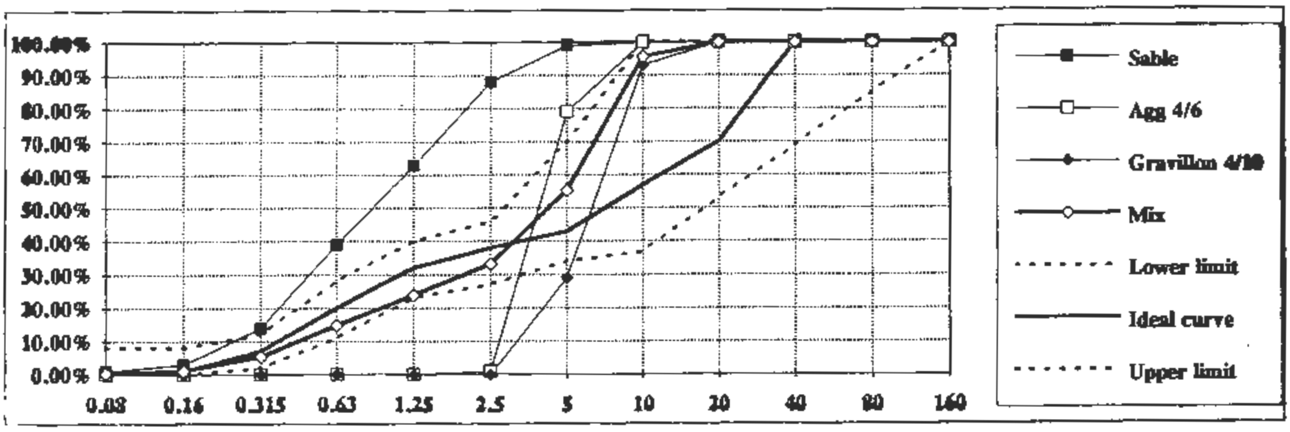

Figure 2. Unsuitable combination of aggregates (sieve sizes in mm).

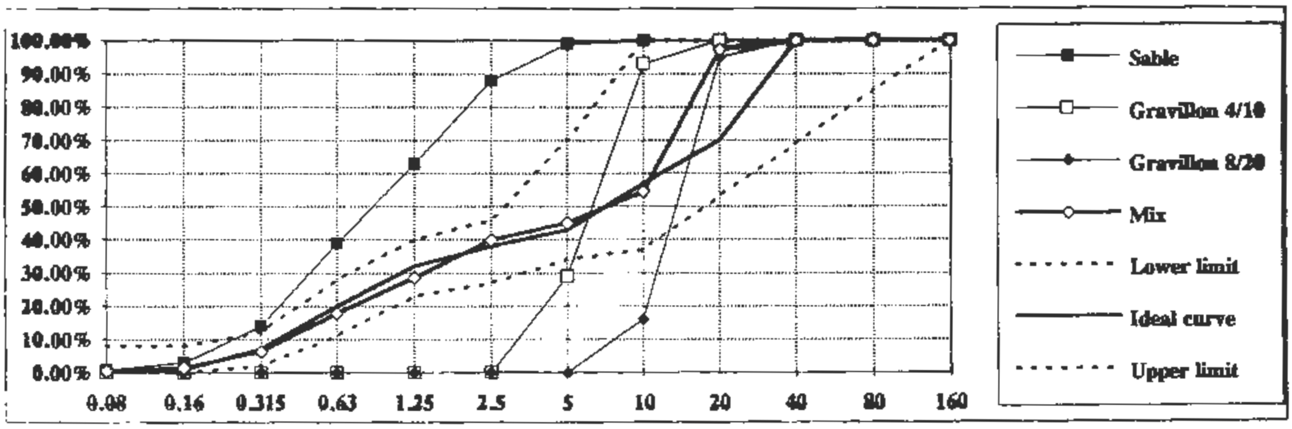

Figure 3. Acceptable combination of aggregates (sieve sizes in mm).

The aggregates should in such a situation be replaced by more suitable aggregates, leading to an improved aggregate mixing as indicated in Figure 3.

The different mix compositions show that two or three aggregates are usually sufficient to ensure a good fit to the required aggregate curve, (if the constituent aggregates are properly chosen).

A combination of the cement with flyash or microsilica is often an advantage, since these materials contributes to the strength as well as the workability of the concrete. The optimal ratios will always be dominated by the prices of the cements, flyash and microsilica.

The differences between the countries can best be illustrated through the use of case studies. The main results from those are shown in Table 3, where the main requirements for the strength and the durability (Equivalent cement content C_{eqv} including the flyash and microsilica, water-cement ratio W/C_{eqv} and compressive strength) are presented along with the values for the actual mix. The mixes were based on local materials from France, Spain and Denmark.

Casestudy	Country	Compressive strength [MPa]			C_{eqv} [kg]		W/C_{eqv}		Price [ECU/m^3]
		S	D	M	D	M	D	M	M
Foundation wall	France	10	15	15	-	200	-	0.91	38.7
	Denmark	10	30	33	-	290	0.55	0.54	30.5
	Spain	10	-	29	275	278	0.60	0.59	63.2
Indoor wall	France	25	-	25	-	200	-	0.85	37.8
	Denmark	25	15	33	-	291	-	0.55	28.3
	Spain	25	-	34	275	280	0.60	0.59	25.3
Outdoor wall in N. Europe	France	30	15	30	-	294	-	0.56	44.4
	Denmark	30	30	33	-	294	0.55	0.54	30.8
	Spain	30	-	33	300	303	0.55	0.54	65.9
Outdoor slab in C. Europe	France	30	30	40	384	389	0.50	0.49	45.9
	Denmark	30	35	41	-	307	0.45	0.45	38.1
	Spain	30	-	36	300	337	0.50	0.50	28.9
Column in the Mediterranean sea	France	40	30	40	384	388	0.50	0.43	50.9
	Denmark	40	35	41	-	359	0.45	0.45	36.9
	Spain	40	-	40	275	342	0.60	0.47	32.7

Table 3. Comparison between strength requirements, durability requirements and the actul mix. (S denotes strength requirements, D denotes durability requirements and M denotes estimated value in the mix).

Table 3 indicates fairly similar values of the main parameters (Cement content, Water/cement-ratio and compressive strength) for most of the examples. Some variations are, however, observed as expected from the code review.

The prices were expected to depict fairly constant ratios between the mix prices in Denmark, France and Spain. The case studies show, however, an unexpected high variation of the mix prices. This is due to the variations on the prices for different cement and aggregate types and to the variations in the durability requirements. This variation illustrates well the need for considering alternative cements and aggregates in the mix design.

5. CONCLUSIONS

The existing formulas and tables for strength and workability are generally applicable for all the countries, but the durability requirements differ significantly. The requirement for a minimum amount of cement in the concrete leads to higher prices as well as lower durability (for a fixed water-cement ratio).

The ideal aggregate gradation curves are important for the concrete design, but the traditional ideals differ much from one country to another. This suggests a need for further work and of opportunities for further cost reductions.

The case studies document the economical importance of considering alternative aggregates and cements for the concrete mix design.

The expert system is a good tool for designing concrete and it is necessary in order to test alternative constituent materials in the mix design. A lack of such programs prevents the designer and producer from obtaining the possible cost reductions or quality improvements.

6. ACKNOWLEDGEMENTS

The contents of this paper has benefited through valuable discussions with my colleagues in G.M.Idorn Consult, RH&H and Bouygues. The contents are based on work, partly sponsored by the BRITE 3469 project "Performance Tailoring of Structural Concrete".

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