Diffusion of Innovation in the Construction Industry : High Strength Concretes

by

Laurent A. Combier

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Author ....
Department of Civil Engineering
February, 1993

Certified by ....
Fred Moavenzadeh
Professor of Civil Engineering
Thesis Supervisor

Accepted by ....
Eduardo Kausel
Chairman, Departmental Committee on Graduate Studies

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Abstract

Construction industry today is slowly adopting high strength concrete (HSC) innovation, though it could take advantage of the many opportunities it provides for lower construction and maintenance costs, innovative designs or applications. More durable and better quality construction, but also economical construction when appropriate design is specified could be achieved through better use of currently available knowledge. A number of technical and institutional factors have led to this situation and are studied through six different steps suggested by Everett Rogers research on innovation diffusion.

Those deemed more important are the technology push pattern of the process which brought HSC on to market, the lack of interdisciplinary communication, short-term rather than long-term economic approach of the industry, and a strong risk aversion due to institutional barriers.

They are illustrated with actual examples drawn from HSC realizations in which implementation difficulties were faced and innovative solutions worked out. The role played by key individuals in HSC project has been identified, as well as the need for more formal centralized organization in charge of diffusing HSC innovation (change agencies).

Thus, several opportunities for improvement were suggested, of which some have already been implemented in some places, whereas others are recommendations for change agencies as well as construction industry professionals. They are based on improved communication and the central role played by trials to prove the feasibility of HSC, test its properties, and speed up code modification procedures.

Thesis Supervisor: Fred Moavenzadeh
Title: Professor of Civil Engineering

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Part I

Introduction

Chapter 1

Introduction

1.1 Description of the General Problem

Not only construction industries in most countries are not commonly viewed as very technologically innovative industries, but also they exhibit some slowness to develop and incorporate new technologies. There is usually a long delay, a couple of decades, from the time when a new product or process is available for users to the time when it is actually widely used. Even when those new ideas have great advantages, potential users might have difficulties perceiving them, or some structures might prevent them from putting into use what is known.

Therefore, it should be a concern for members of the construction industry to understand and analyze the reasons for the slow diffusion of innovation, and to suggest mechanisms for successfully and rapidly introducing innovations in the industry, when they represent a better alternative to the previous method they might replace.

Innovation and diffusion of innovation are commonly studied in many fields, mostly in manufacturing. Some specific characteristics of the products and the technological constraints of construction yet significantly differentiate it from manufacturing, in the innovation process, and the factors governing its diffusion. Diffusion of innovation in the construction industry has been a neglected field of innovation studies for decades, as documented by C.B. Tatum [NT89], in spite of the importance of technological advancement in a industry vital for the world's economy.

In the field of concrete, new technologies and processes allow today to achieve high strength in the order of 8,000 psi, the maximum attainable for commercial use being in the region of 15,000 to 20,000 psi [Bau88].

This new type of construction material appeared, most people agree, in the 1970's in the Chicago area, where they were used for the construction of high rise buildings, in which they yield cost savings, increased floor space, enhanced occupant comfort and many other advantages described later in section 3.4.1. Kenneth L. Saucier reported [Sau80] that in the American Concrete Institute seminar on high strength concrete (HSC) in Pittsburgh in 1977, skepticism was expressed that producers and users in New York City would ever consider using concrete with a compressive strength higher than 6,000 psi. Yet, one year later, inspired by the need to conserve space, a fifty story office tower, the Palace, was under construction using 8,000 psi concrete. Through a survey sent to professionals in the construction industry for this research (see appendix) it appeared again that those people are still wondering if there is a real need and market for HSC. They are reluctant to use HSC because of the adverse reports they have heard. Better information about what is achievable with HSC is needed in order to brake the barriers impeding the diffusion of this new material. Nevertheless, it is likely that in the near future it will gain wider and wider acceptance and finally be commonly used. Some change agencies, organizations in charge of promoting the diffusion of innovations, keep on struggling to show how HSC properties should be used.

This case is an obvious example of slow diffusion in the construction industry but it is all the more dramatic as the potential savings associated with a wider use of HSC could be huge, and especially due to an increased concrete durability, "a multibillion dollar opportunity" [oCDNO87].

1.2 Thesis

In order to implement actions aiming at increasing the rate of adoption of HSC, to get a better understanding of HSC innovation diffusion in the construction industry is a preliminary and necessary step. The thesis objectives are to analyze this process and to propose some alternatives to better diffuse HSC innovation.

In part two of this thesis, a general presentation of diffusion theories is introduced (chapter two), based on models developed by Everett Rogers in his book "Diffusion of Innovation" [Rog83]. A definition of this social science will be given, as well as a description of the many factors influencing diffusion of new concepts. At last, the importance of this type of research will be pointed out, with a stress put on the specific issues raised by HSC innovation.

Then the second half of part two (chapter three), will introduce the reader to some basic knowledge of concrete and HSC, first of all through a brief historic of their use, and then through definitions of concrete, HSC and high performance concrete (HPC), as well as a description of their properties. Part two will end with a presentation of the concrete industry.

Part three will put together the knowledge gained in chapters two and three in an analysis of HSC diffusion. At the light of a framework suggested by Everett Rogers, six different aspects of this process will be examined, with the objective to understand the interests of individuals, companies and organizations involved in HSC activities.

Part four is the logical outcome of part three, in the sense that its findings are used to evaluate strategies for a better diffusion of HSC innovation.

Part II

Diffusion and High Strength Concrete

Chapter 2

Diffusion of Innovation

2.1 Lack of Diffusion Studies in Construction Innovation and the Importance of Product Innovation

Though many papers emphasize the technical issues raised by HSC, very little research has been done so far on the actual application and use of those new concretes in the construction industry. As a matter of fact, the whole study of construction innovation has been neglected for a long time, partly because it is very different from manufacturing innovation. C.B. Tatum of Stanford University led many interesting researches in this field, but still remained marginal. He showed notably, the importance in the long run of product innovation as opposed to process innovation. A process innovation, such as improvement in crane technology, produces a greater volume of output per volume of input resources, whereas a product innovation, such as HSC, produces qualitatively superior output from a given amount of input resources. He argued that product innovation played a central role in long term economic growth, because, as Schumpeter said, "it gives a fundamental impulse that keeps capitalism going".

And C.B. Tatum pointed out that in the neglected field of construction innovation, product innovation is the most neglected.

2.2 Pro-Innovation Bias

Change agencies, which are the sponsors of diffusion activities, described in chapter 8, are convinced that it will provide beneficial results for the construction industry, but this is a pro-innovation bias which has to be discussed. They tacitly assume, since they foster HSC implementation, that this new material is needed by the construction industry and that its adoption would represent "success". Jean Chapon, in his opening remarks to the symposium on high performance concrete (HPC) held in Cachan in September 1989 [Mal0], said that "to be able to make HPC does not consist only in establishing new records, but above all in designing the concrete which will fit best the needs, keeping in mind economic considerations involved both in construction and in maintenance".

As we will show later on using a comparison between plastics and HSC innovation diffusion, an all-important reason for the success of the latter was the clear cut economic advantage it provided : less labor intensive, less expensive raw material, easy to install. The economical solution provided by HSC in some structures is not obvious because of the higher cost per unit volume of concrete : the savings are due to the good quality and performance of the construction material. The obstacle that change agencies have to face is to convince a "poor" industry with low mark-ups to adopt a "luxurious", high quality product. This is not a natural behavior.

Consequently, it is not only attributes of HSC which have to be considered to assess its profitability to the construction industry, from structural concrete properties to organizational patterns of the industry, and mentalities. Despite the idea of progress and growth associated with innovation, it might be that HSC does not suit the industry because it takes to much effort to implement.

2.3 The innovation diffusion process

In the complex process of technological change, the diffusion of innovation is only one particular step. Three main stages can be distinguished : first of all, basic research is conducted either by R&D programs or by the users themselves [Hip88], resulting in a new idea, an invention, possible solution to a perceived problem or need. It takes the form of a prototype, or in the case of HSC, some experimented chemical and structural properties of new admixtures experimented in laboratories. Then an invention becomes an innovation when enough improvements have been realized to make it feasible on site and economically viable, and therefore usable by potential users. This step may involve innovations in parallel technologies, such as the development of special admixtures, or the improvement of the basic components of concrete (Portland cement, aggregates of higher quality). Then at least, some potential users become aware of the existence of the innovation, start collecting information about it from suppliers, competitors, trade and research associations, or even the company's own R&D department, commission a study, and finally after they have tried it, decide to adopt or reject the innovation. This final phase is the diffusion of innovation.

2.3.1 Four elements in diffusion

Everett Rogers defines it as "the process by which an innovation is communicated through certain channels over time among the members of a social system".[Rog83]

An innovation is characterized by its expected degree of benefit for potential adopters ; however this possible advantage remains to be proved and the uncertainty about its expected positive consequences to be reduced by potential adopters. This uncertainty reduction process is discussed further in section 2.4 and is the core of the message transmitted through communication channels.

Two dimensions affect the effectiveness and the type of communication. The first one consists in communication channel type. Whereas mass-media channels diffuse a knowledge of the new idea, rapidly, but do not change attitudes, interpersonal channels are slower, but more effective in influencing decisions. The second one is the degree of similarity between the people who interact (education, social status) which have an all important impact on communication. Though homophilous relationships [1] are easier, in a vertical diffusion of innovation, heterophilous relationships are more necessary and are a barrier to effective communication.

Time is also of major concern, as far as economic growth is concerned as developed in section 2.5.1, both at the micro analysis level [2] (rapidity of the innovation-decision process), and at the macro-analysis level (rate of adoption among a social system). Time is associated with the capacity of the social system to exchange information rapidly. Nevertheless, the success of diffusion of innovation will not depend only on the efficiency of the communication system, but also on the attributes of the new ideas as perceived by the potential user (relative advantage, compatibility, complexity, triability and observability) and on the management qualities.

At least, the study of the innovation's diffusion should also take into account the structure of the social system in which it takes place. A social system is characterized by problems and objectives shared by its members, which imply some cooperation. Actors with different responsibilities play different roles, and norms define the scope of their action. "It is as unthinkable to study diffusion without some knowledge of the social structures in which potential adopters are located as it is to study blood circulation without adequate knowledge of the structure of the veins and arteries", according to Katz.[Kat63]

[1] People are homophilous when they are alike as regard parameters such as education, social status. On the opposite case, people are heterophilous.

[2] Micro and macro analysis of diffusion are defined in the following section.

2.3.2 Micro and macro analysis of diffusion

The diffusion of innovation is implemented at two different levels. The first one, which we will call the micro analysis of diffusion, involves the behavior and reasoning of an individual user, which will lead him from the knowledge of the innovation to the final decision to reject or adopt it, through the innovation-decision process. (figure 2.1)

The second one, macro analysis of diffusion, focuses on how the number of users fluctuates over time, on the factors which influence such variations and on the consequences occurred to the social system and its individuals. (figure 2.2)

2.3.3 Incremental innovation

Nevertheless, neither technological improvement nor its implementation are so radical, and the boundaries around a technical innovation are often unclear. Innovation seems to go much more by baby steps then by leaps as shown by the table recording records of strength of concretes since 1962 (Table 1.1).

What was called a HSC ten years ago is regarded today as a regular concrete, thanks to a series of incremental improvements in cements, admixtures, proportionning methods or quality control. And the new records are set benefitting from the experience gained in previous HSC projects. Furthermore, for a given innovation the process of diffusion itself is incremental, involving several steps at which the potential adopters can decide to reject the innovation or to carry on his innovation-decision process, deciding that the new product is worth being put into practice or not, or even reshaping it according to his actual needs [Hip88]

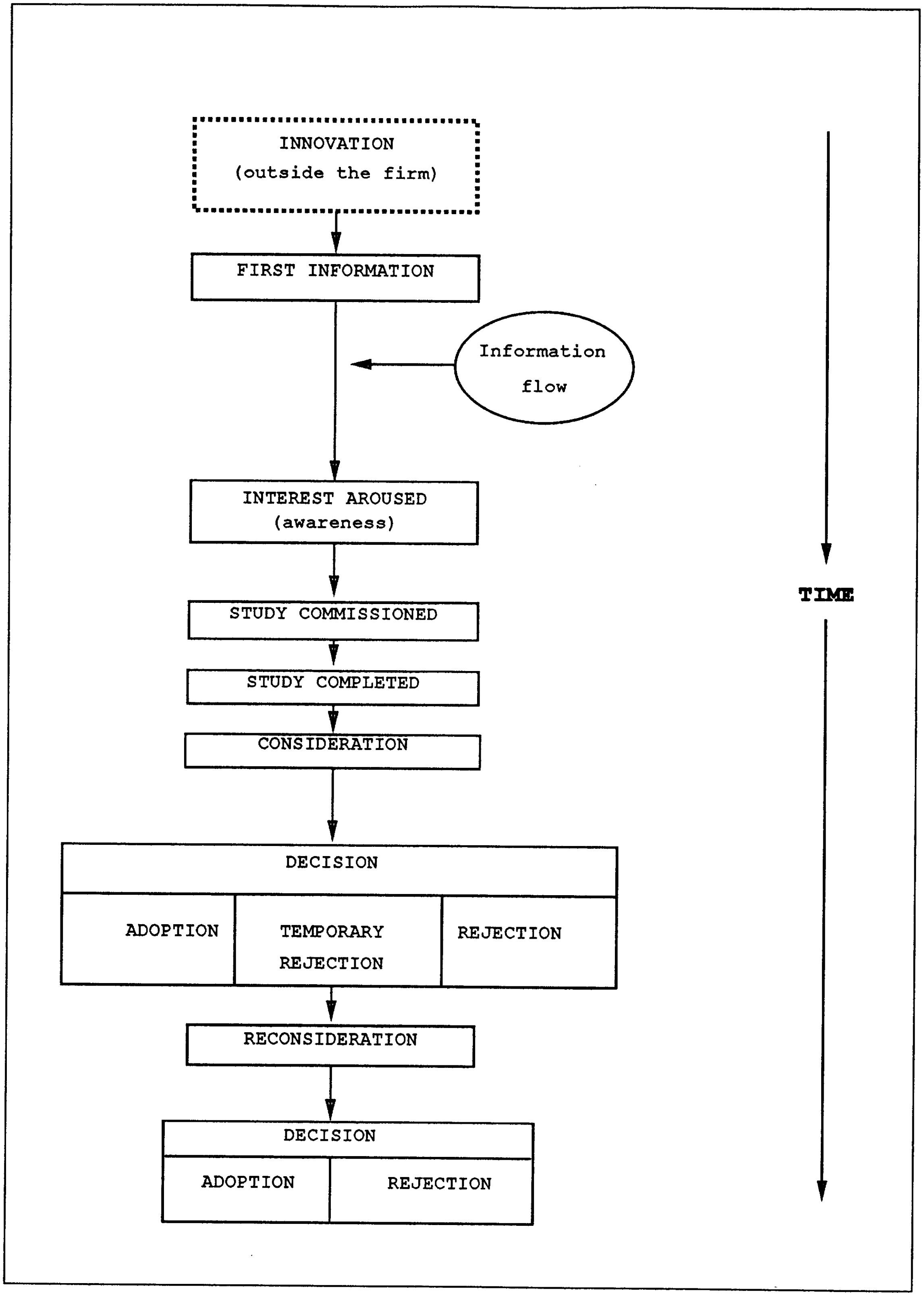

Figure 2-1: Micro analysis of diffusion
[NR74]

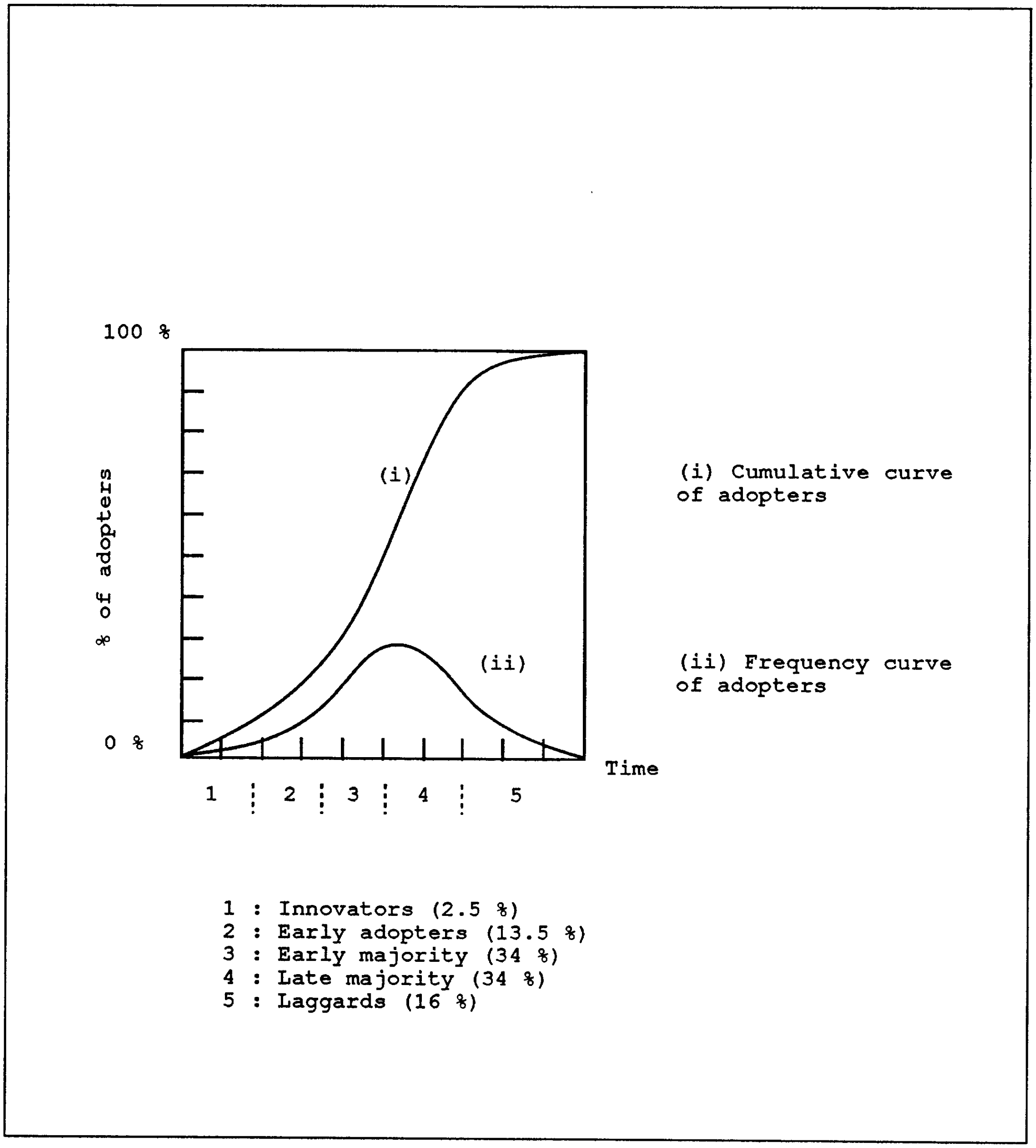

Figure 2-2: Macro analysis of diffusion
[Rog83]

Table 2.1: High Strength Concrete Realizations

Year	Structure	Location	Concrete Strength	Remarks
1962	Building	1,000 Shore Plaza, Chicago, Ill	6,000 psi	640 feet
1965	Building	Lake Point Tower, Chicago, Ill	7,000 psi	
1972	Building	Mid Continental Plaza, Chicago, Ill	8,700 psi	
1976	Building	Water Tower Place	9,000 psi	
	Building	River Plaza , Chicago, Ill	11,000 psi	Exper.
1982	Building	Columbia Center, Seattle	11,000 psi	76 stories
1986	Building	Toronto, Canada	11,000	
	Building	Montreal, Canada	10,000 psi	
	Building	Chicago, Ill	14,000 psi	
	Building	MLC Center, Sydney, Australia		68 st, 808 ft
	Building	Trump Tower, N.Y.	8,000 psi	68 st
	Building	Palace Hotel, N.Y.	8,000 psi	53 st
	Building	101, Park Avenue, N.Y.	8,000 psi	50 st
	Building	499, Park Avenue, N.Y.	7,000 psi	27 st
	Building	535, Madison Avenue, N.Y.	8,500 psi	36 st
1988	Building	Tete Defense, Paris, France	9,000 psi	
	Bridge	Viaduc de Sylans, France	9,700 psi	
	Bridge	Pont de Pertuiset, France	9,000 psi	
	Bridge	Pont de l'Ile de Ré, France	9,000 psi	
	Bridge	Pont de Joigny, France	10,000 psi	

2.4 Uncertainty, Risk and Information in Diffusion

A technological innovation is supposed to, and at least it is the change agency's objective [3], improve the satisfaction of the user. On the other hand, the incentive for the potential adopter is a process improvement (more units of output per unit of input, which means higher productivity), or a product improvement (increased competitivity of the product due to its qualities). In the case of HSC, it is both, as Tchang said about the Two Union Square Building in Seattle "we use these innovative ideas not for the sake of innovation, but because they result in the least-cost building", and he could have added, a building which would had not be born without the contribution of HSC.[Bau88]

However, the probability of the new alternatives being superior to previous practice is not obvious to the potential adopter, because of the risk involved in the newness. Therefore, knowledge and information gathering is necessary in order to reduce uncertainty. Two solutions are available to the potential adopter.

The first one consists in collecting information about the innovation either from near-peers, journals, or other communication channels. On the one hand, this information has the major drawback of being subjective, since the problems and the needs may differ from one potential user to another. In this trading of information, two kinds of sources, or partners should be distinguished, since they reduce uncertainty in different manners. The change agent is knowledgeable and expert about the technical innovation and has competence credibility, whereas colleagues or near-peers will not be suspected of having some selfish motives or manipulation intentions, and are perceived as safety credible. On the other hand, the information collected through various formal or unformal communication channels is low cost and does not imply any substantial investment. Both sources will give, by nature, biased information.

[3] A change agent is an individual who influences clients' innovation in a direction deemed desirable by a change agency [Rog83].

The second solution available to a potential user to reduce uncertainty consists in trials, or personal research. Preceding a large scale implementation of the innovation, some trials will be undertaken on a limited basis. This method, contrary to the previous one, has the advantage of its reliability, but the disadvantage of its (relative) high cost. Triability belongs to the eight perceived attributes of innovation which influence its rate of adoption. New ideas that can be tried easily will generally be adopted more quickly than innovations that are not divisible

Diffusion of innovation is basically an uncertainty reduction process, for both analysis, at the micro and the macro level. When potential adopters pass through the innovation decision process, their goal is to determine the relative advantage of the new product compared with current methods. This relative advantage is then the most important information transfered through the communication channels. And at the macro-analysis level, the difference of behaviors of different individuals is explained by the way they deal with risk : whereas the earlier adopters are more likely to trust the change agent, and have a broader view of risk (they are able to deal with technical, financial and commercial risks), the following adopters do not have this ability to understand the risks involved and consequently can not cope with the degree of uncertainty as the same time as innovators (and early adopters). They will seek more information from sources they trust, such as their peers who are likely to have faced the same challenges, and therefore will subtantially reduce their risk by giving relevant data.

Everett Rogers distinguishes two different kinds of information that are needed by potential adopters of technological innovation. The software information [4] describes what the innovation consists in and how it reduces uncertainty as regards the product itself. The innovation-evaluation information is more related to the links between the innovation and its particular user : the potential adopter wants to reduce uncertainty of the degree to which the innovation is applicable in his particular case, and is likely

[4]The hardware of a technology is its physical body, its software is the knowledge base for the use of the hardware

to yield some benefit.

2.5 Impact of rapid diffusion

There is often a difficult step to reach between the moment when a new idea is born and when it is finally adopted. And even in the case when it offers obvious advantages, some obstacles inherent to the people, the organization or the innovation itself make it long for the innovation to be adopted. What is newly used is often what was known years ago and there is a wide gap between what is achieved in laboratories, and what is actually realized on site in the case of the construction industry. How to speed up this transition (which is one of the issues tackled by diffusion of innovation) is a major concern for industrials. And any kind of management should involve some innovation management in order to stay in business and to provide clients with the most up to date service or product.

2.5.1 Diffusion and economic growth

The interest of economists in the diffusion of innovation lies in its links with economic growth. Many studies have been conducted to find out what part the advance in technology plays in the economic development. It is generally accepted that the growth depends mainly on two factors : the increase of natural resources, and the improvement in the way those resources are combined in the industry (and this is precisely a definition of productivity in engineering). But what R. M. Sollow showed is that more than 85 % of the United States national output increase between 1920 and 1950 is due to technical progress[Sol57]. And it is likely today, with more resource constraints that this figure has not decreased.

Even if those figures and others computed with the same method were criticized by other authors arguing that an unquantifiable parameter such as technological advance is difficult to evaluate, and is mixed with factors like management skill or improvement of productivity due learning by doing, no one can disagree with the capital role played by innovation in an industry performance.

Therefore, the diffusion of innovation becomes an all-important factor in the rate of growth of an economy or an industry, and at a smaller scale in the competitive advantage that a company can get vis-à-vis its competitors. The ability for an organization to absorb rapidly an innovation (we are assuming in this discussion that the innovation is good), and to incorporate it in its production systems result in a higher growth rate.

However, the rate of inventions is with no doubt another factor which can speed up growth, but this thesis will not study this issue since it assumes a given invention (how to make HSC) and focuses on the process of diffusion within the construction industry. Nevertheless this limitation does not really narrow the scope of the thesis. In most countries (the most important for the study of HSC development seem to be the United States, Canada, Japan, Norway and France) basic research, which product is what we call an invention or an innovation is made by public agencies whereas the private sector is more involved in applied research, which deals primarily with the implementation of the innovation and its diffusion. Therefore, the whole industry has theoretically access to the same information in terms of invention and innovation, and what makes a difference is the extent to which its members are going to have the knowledge of it and are going to implement the process of adoption or rejection. Moreover, it seems to have little barriers (except the language) to the communication of technical information on HSC research at a world scale.

As a conclusion, the picture of the situation is a follows : an international source of information on HSC, coming mainly from public research organizations, is available for individual companies on the innovation of HSC. They will compete on the way they are reached by those organizations (and we will see in chapter 8 that appropriate communication networks have been set up in some countries) or on their ability to catch and use the information. And this is precisely diffusion of innovation.

2.5.2 Synergistic Effect of Innovation

The rewards a company can get from a successful innovation are not limited to the technological change itself. There are dynamic effects of innovation that can be approached at two levels : social and technological.

Social Synergy

A innovative state of mind creates within a company a positive, creative and entrepreuneurial atmosphere. This point was developed by D. Teese, a professor at the University of California at Berkeley's School of Business and Administration. He demonstrated that the social rate of return of a fully developed innovation is four times greater than its direct rate of return. Innovation seems to be more than merely technological changes, and are therefore positively associated with improvement.

Technical Synergy

The construction technology involves the materials and the way to put them together, using appropriate methods. In all fields of the construction process opportunities for innovation exist in the development of new construction methods or sequences, application or extension of techniques originally developed to meet other requirements, development or application of new equipment or tool and scale-up or refinement of existing methods. C. B. Tatum showed how the correlations between those fields can make an innovation very successful and yield large project benefits if there is a efficient integration of the different disciplines involved. "The synergistic effect of considering combined innovations in engineering and construction frequently offers very large project benefits. These activities are highly related : minor changes in one can produce substantial changes in the other".

However, in spite of many innovations compiled by various authors, the construction industry is commonly said not to be very innovative and this statement is partially true : R&D exist, but suffer from a poor coordination which entail a low level of development. It seems that the industry does not take advantage of synergistic effects.

2.5.3 Cost of Poor Diffusion of Innovation

Many factors, such as inadequate education, low levels of research funding, poor coordination and a lack of efficient technology transfer mechanisms have led to an under use of currently available knowledge. In concrete terms, what is the impact of the low ability of the industry to take advantage of the many opportunities to incorporate new technologies ?

Concrete is one of the most important concrete material used in a five hundred billion dollar industry. Therefore, its qualities and the improvement of its performance can have a significant impact on the economy. HSC has two qualities relevant for this computation : its higher strength, implying lower quantities of concrete put in place, and despite its higher price, lower total concrete costs (short-term savings); and, more important, its higher durability due to its lower porosity (long-term savings). Even if concrete structures are very efficient in harsh conditions, many people reproach them for their poor aspect and performance when deteriorated (and this is a main difference with stone) which entails a need for expensive facility maintenance. This argument is commonly understated, and further developments will be given in section 3.4.1.

One must acknowledge that so far in the construction industry, maintenance has been a laggard, and that people are thinking short-term rather than long-term investments. An explanation of this behavior lies probably in the relatively long durability of concrete structures, which are commonly in good shape after at least ten years of service. One thinks more than ten years ahead with difficulty, especially in an industry which is used to separated budgets for construction and for operation and maintenance. Also pushing this attitude is the contract system which usually awards the job to the lower bid, somehow in competition with durability and quality. At least, funds are usually easier to raise for construction than for reparation.

We have described two attributes of HSC, and the one which plays in its favor in the owner's mind is its higher strength because of its promise of quick reward. This short-term approach is a weakness of the industry in terms of innovation. In the competitive bidding process, innovative ideas are commonly generated as possible answers to perceived needs or problems, but their viability depends on the immediacy of rewards. The construction industry allows little time and money to refine the innovation, all the more so since it is required at the start of the job. Weston Hester (University of California) recognizes that "in virtually all parts of the United States, strengths on the order of 15,000 to 19,000 psi can be achieved by almost all concrete producers[Bau88]. It does take a willingness to see that it is done consistently and properly, as well as a recognition that initially it will cost more". Small contractors cannot afford such overcost on a single project. Contractors are often people reluctant to take risks, and are used to solving problems by themselves right on the site (which by the way creates even more innovations).

2.6 Current mechanisms of innovation in the construction industry

Many factors lead today to an increased need for innovation in the construction industry. The design of new facilities become more complex, not only using already mastered technological advances but also requiring new technologies. Owners' requirements for more cost effective solutions is another challenge, and they are more ambitious in the design. At least international competition makes innovation a requirement for firms to stay in business, mainly because of the globalization of R&D, new ideas being available at the same time regardless of national boundaries. Construction industry must be considered at world scale level.

Innovation in the construction industry is different from the one in other industries for many reasons which help understand its strengths, weaknesses, and a need for a particular focused study.

First of all, unlike in many other industries, most research is done outside the construction itself, and even if good new ideas were born in laboratories, they are carried out to the industry itself with difficulty.

Besides, a construction project consists in the work of many participants, resulting in a unique product, which lifetime is long (typically more than ten years), and is on an open shelf, revealed to anybody through site visits or other means of communication. This short description embodies the main reasons for the current patterns of innovation in the construction industry. The number of participants is not a concern for large japanese vertically integrated companies, this organization resulting in a better coordination of R&D efforts. However, in other countries, the unfavorable structure of a fragmented industry can explain a lack of R&D activities for two reasons. Firstly, all the people involved in successful HSC projects have emphasized the all-important role of coordination during the project between, among others, owner, designer, contractor, ready-mix concrete maker, and code officials. An increased number of parties involved makes the organization heavier, decision becoming more difficult to take, and risks likely to be avoided. Besides, efforts are segmented, and no synergistic effect can be expected if the coordination is not efficient. Secondly, a cooperative state of mind is less likely to be seen in a structure in which other participants can take advantage of your own investments. This is all the more a constraint than innovations are put on an open shelf, and not only the investments will yield a benefit to the industry in its vertical dimension, but also in its horizontal dimension : the rewards of innovation efforts are protected with difficulty.

Along with this lack of interest and money of the industry for research, very few investigation has been made so far to find out how this research is used, and how its rate of implementation could be speeded up. Information about what the technical aspects of HSC are is currently available, but a question is usually put aside : how was this innovation diffused in the construction industry ?

For instance, how can HSC become available on site (chapter 4) ? How can owners, designers and contractors cooperate to make its use feasible practically (chapter 5) ? What are the key advantages of HSC as regard its rate of adoption (chapter 6) ? How can uncertainty and risk be reduced, and the limitation imposed by the codes overcome (chapters 6 and 7) ? What could be a better diffusion system (change agencies, chapter 8) ? What is the role of individuals and what are the diffusion networks(chapter 7) ? What consequences can be foreseen in the diffusion of HSC (chapter 9) ?

The following part will propose answers to these questions, as regard to HSC. Even if a study of a given innovation in a given industry cannot lead to general results, we will extract some lessons from this particular study to suggest several propositions for a better use of technological innovation, in the case of HSC, and more broadly for the construction industry in general.

Chapter 3

High Strength Concrete

3.1 Description of Concrete

A concrete is a composite construction material, made basically of a mixture of water, cement, and fine and coarse aggregates. In actual, current applications, solid or liquid admixtures are often added in order to modify the plastic or hardened concrete paste properties. Typically, concrete is produced one hour before it is placed, at the construction site or at a central plant. It is not an "off-the-shelf" finished product. It will gain its structural strength within a month of its production, though this duration can vary greatly (and particularly for HSC).

The most common used cement is Portland cement, sometimes in combination with cementitious admixtures such as fly ash. Aggregates are made up of natural or manufactured sand, gravel or crushed stones. Chemical admixtures include air entrainment admixtures, which enhance strength, resistance to freeze-thaw cycles and durability, water reducing admixtures, which allow to reduce excess water necessary for workability purposes, but affecting concrete qualities, super plasticizers, which increase the water-reduction and workability of concrete, set-retarding or accelerating admixtures. Mineral admixtures will be detailed in section 3.3.3. Typical compositions of concrete and HSC are provided in table 3.1.

3.2 A Brief History of Concrete

3.2.1 Concrete

It were the Romans who first extensively produced and used a composite construction material similar to our concrete. For centuries, it has been used in a large variety of compositions and forms, but it is not before the twentieth century that it became a recognized material for construction purposes because of its workability and compressive strength. A major improvement had been made in 1824 when Portland cement was patented by Joseph Aspdin. Tests conducted in 1974 on a building concrete made by Joseph Aspdin's son in 1841, probably using the 1824 patent concrete design, revealed a compressive strength of 4,200 psi.

Nevertheless, concrete has really been considered a standard construction material along with wood, steel, brick and stone when in 1905, the National Association of Cement Users was founded. A professional corps since then has worked to direct energy and talent toward concrete improvement, and those early efforts are illustrated by the publication in 1906 of the first textbook on concrete[1]. Reinforced concrete had become a composite material of interest : since concrete itself is weak in tension, it was realized that steel could provide tensile resistance.

However, those who accepted to use concrete as a construction material at the beginning of the century rejected its coarse appearance, and seldom was it exposed to view in surfaces where good looking was a concern. This attitude changed little by little, as a result of incremental actions directed by influent people, in many disciplines within the construction industry, concrete suppliers, architects, and in different places.

[1] "Reinforced Concrete", Buel and Hill.

Even if relatively high strength was achieved at the very beginning (around 4,200 psi in the 1840's), no consensus was reached on a recipe to make a good concrete. Even if the importance of the water-cement ratio was discovered in 1910, a controversy subsisted on the content of cement a concrete mix required. It is only recently that an article entitled "Use Less Cement" was published. The lack of understanding between researchers and professionals in the concrete industry seems to have been a constant in the concrete industry.

A major achievement in the improvement realized in the concrete technology during this century consists in the reliability of the material produced. Since no exact recipe existed, especially as regards the aggregate quality, which depends on so many unquantifiable factors such as size, shape, type of mineral, the quality control of concrete production had to become much more efficient. Machineries used in mixing, transporting, placing, vibrating concretes as well as a careful selection of aggregates and cement blend have played an all-important role in the evolution of concrete to a reliable material.

Nowadays, its qualities, such as fire resistance, elimination of painting and minimum requirements for maintenance, as well as its economical production and structural properties have made concrete a dominant material in the construction industry. Further more, it promises to become even more dominant in the future thanks to recent innovations which can reduce construction costs (rapidity of construction, precast construction, reduced quantities of concrete placed, and especially improved durability), or enhance its qualities for specific applications (porosity, strength, stiffness). Innovative use of the most modern concrete technology should create a new positive opinion for the concrete industry among owners, designers and contractors. This would entail a new state of mind within the industry, including R&D with progressive thinking, and a will from the ready mix concrete industry to accept the responsibility for the performance of their product. Unfortunately, it conflicts with the lawsuit environment that prevails in the United States, and which prevents innovators from using not well known, well proven technologies.

Among those major improvements in the concrete industry, HSC represents one of the greatest hopes.

3.2.2 High Strength Concrete

The interest for higher strength concrete is not new since in 1932, Thomas T. Towles wrote [Tow32] : "...let us make the assumption that it would be possible to manufacture satisfactorily concrete of 28 day strength of 7,000 psi. While concrete of this strength has so far been produced only under laboratory test conditions, the effective realization in practical work of concrete of this quality is not in my opinion merely a remote possibility." For purposes of comparison, concrete of strength greater than 87,000 psi are nowadays experimented in laboratories.

Since this period, the evolution of HSC, which should be understood as concrete with a strength greater than current standards, has been gradual. Historically, the production of concrete had to meet two incompatible requirements. On the one hand, the construction industry needed highly fluid concrete pastes which could be placed easily. But on the other hand, a low water-cement ratio was recommended in order to achieve good mechanical performances, and this entailed a low workable concrete.

Hopefully, technological improvements have made possible the realization of workable HSC, using chemical such as high range water reducing, and mineral admixtures such as silica fume. Nevertheless, the composition of this kind of mix becomes very different from a regular concrete, implying a need for extensive research and a reluctance from potential users.

Some records and main achievements are presented in table 1. For instance, in 1954, a strength of 5,000 psi was considered a standard for HSC, and 8,000 psi concrete was used in Cuba. In 1972, the first 9,000 psi concrete was produced for use in a fifty story building located in Chicago, the Mid Continental Plaza Building, and since then, HSC has shown a growth in its usage, especially in the Chicago area.

Why Chicago more than other American city ? Firstly because Chicago has always been an innovator in architecture and construction design. Secondly, because the headquarters of the Portland Cement Association are located in the Chicago area. Thirdly, because of the interaction between two innovators, willing to explore new ways in the concrete technology : William Schmidt, a designer, and John Albinger, a concrete supplier, working for Materials Services Company, and as we shall see further, the role played by "champions" in the diffusion of innovation is all important. And fourthly, because raw materials of the required quality were available in the Chicago area.

Use of 10,000 to 12,000 psi concrete could become common in a near future, and some put forward predictions of concrete with a compressive strength greater than 20,000 psi in a few decades.

3.3 A Definition for High Strength Concrete ?

3.3.1 High Strength or High Performance Concrete

High strength is only one of the qualities that can be achieved by a HPC. From a structural point of view, HSC is the form of HPC which has gained the most widespread interest, notably for columns of very tall reinforced concrete buildings (see table 3.1, 3.3 and 3.5). Most properties of HPC (durability, low porosity, early strength at early age,etc... See table 3.3) are a consequence of a low water/cement ratio or of admixture addition such as fly ash or silica fume. And it happens that this new mix can achieve very high compressive strength. Therefore, most of the time, HPC are also HSC, and in many minds those terms are synonymous.

The boundary between HPC and HSC is not clear, and definitions not yet precise. The most common ones are given below as concerns HSC.

3.3.2 Definitions of High Strength Concrete

A common and simple definition of HSC is "a concrete with a uniaxiale compressive strength greater than or equal to 8,000 psi for normal weight aggregates". This limit was suggested by the literature [lim83, Day81] and used in the survey mailed to 200 professionals in the American construction industry, mainly designers (see appendix). A similar, but more sophisticated definition has been adopted by the French researcher Lucien Pliskin [Mal0] who classifies regular concretes in the range 2,900-7,300 psi, HSC in the range 7,300-14500 psi, very HSC in the range 14,500-21,700 psi, and exceptional concretes with a strength above 21,700 psi.

With conventional methods of production and raw materials, a ready-mix concrete supplier can typically deliver concrete in the range of 3,000 to 7,000 psi. But, in order to produce concrete above 7,000 or 8,000 psi, more rigorous quality control procedures, use of admixtures (superplasticizers, fly ash, silica fume, etc...) and careful selection of the blends of cement and of the type and size of aggregates are required.[Heu83]

This constatation was a basis for the definition given by a NIST-ACI workshop held in Gaithersburg, MD in 1990 : "A HSC is a concrete having desired properties and uniformity which cannot be obtained routinely using only conventional constituents and normal mixing, placing, and curing practices. As examples, these properties may include :

- Ease of placement and compaction without segregation,

- Enhanced long term mechanical properties,

- High early age strength,

- High toughness,

- Volume stability,

- Long life in severe environments."[CC90]

Some other definitions have been given also by research committees on HSC which are more quantitative than the former, and more precise than the latter. For instance, Project C-205 of the strategic Highway Research Program has defined HSC (or HPC) as a concrete that meets the following criteria :

- It shall have one of the following characteristics :

* 28 day (after placement) compressive strength greater than 10,000 psi , or

* 4 hour (after placement) compressive strength greater than 3,000 psi , or

* 24 hour (after placement) compressive strength greater than 5,000 psi.

- It shall have a durability factor greater than 80

- It shall have a water-cementitious materials [2] ratio lower than 0.35.

At least, researchers at the University of Tokyo have taken another approach in defining HPC as a "forgiving concrete" which compensates for poor construction practices and structures detailing, such as :

- Sufficient long term strength and low permeability,

- Minimum of cracking at early ages due to schrinkage and thermal strains,

- Cohesive mixture with low segregation,

- Ability to fill forms with little or no external compactive efforts.

This short survey of HSC definitions shows how no consensus is reached on the term, and that it embodies more a new concept of material than an actual unique innovative mix. Rather, several ways to achieve high strength are currently available, from traditional methods like compaction, vibration along with a severe quality control and rigorous choice of aggregates, to innovative and very promising ones such as the use of mineral admixtures. The following section aims to present this kind of raw material which use is now spreading within the concrete industry.

[2] Including cement and mineral admixtures such as fly ash, silica fume or other pozzolans.

3.3.3 High Strength Concretes Made With Mineral Admixtures

Mineral Admixtures

Mineral admixtures include finely divided materials that fall into four types : those are cementitious, pozzolanic, both cementitious and pozzolanic, and those that are nominally inert chemically. Mineral admixtures have been produced for decades, and their use in the concrete industry began in the 1920's. Experimentation and research on concrete proportioning and use of appropriate and new raw materials have been going on since the beginning of the century. Many new admixtures are tested, and while some prove to be still unrealistic from a technical or economic point of view, some seem to have a brilliant future, and especially, those having cementitious and pozzolanic properties.

They are basically made up of particulate matter cleaned from industrial emissions. Thus, fly ash, which is the most common one, is a by-product of combustion of coal or other fuels when producing heat for generating electricity ; rice husk ash results from the use of rice husks as power plant fuel ; silica fume, the most promising one, is a waste in the production of metallic silicon and ferro silicon alloys in electric arc furnaces. However, those products are wastes (and their use by the concrete industry might be a solution to some environmental problems, and is encouraged by the EPA [Env83] in some public contracts) and are not especially manufactured for their use as mineral admixtures. Therefore, a careful attention should be paid to their selection and control.

Chemistry of Mineral Admixtures

Mineral admixtures are partners of cement in the concrete paste. When cement is combined with water, a chemical reaction occurs, called hydration [3]. The mix turns

[3]The chemical equations of the reaction are : $2C_3S + 6H \longrightarrow C_3S_2H_3 + 3Ca(OH)_2$, and

into a glue which hardens through a slow and complex process. During this process, a waste product, calcium hydroxyde ($Ca(OH)_2$), is generated. Mineral admixtures will then act as pozzolans, defined by ASTM C 595 as "siliceous or siliceous and aluminous material which in themselves possess little or no cementitious value, but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxyde at ordinary temperature to form compounds possessing cementitious properties." Therefore, pozzolans can behave as cement when combined with a concrete mix, as well as as very fine aggregates.

Fly Ash

Fly ash is a by-product of burning powdered coal at electric power plants and is collected by mechanical means or electrostatic precipitation before discharge of the gases into the atmosphere. When combined with Portland cement in a concrete mix, it produces additional amounts of hydration by reacting with the calcium hydroxyde liberated by the cement-water reaction, and therefore beneficially modifies the structure of the cement paste formed. The first large use of fly ash as a mineral admixture was in 1948 - 1953 at Hungry Horse Dam, Montana. Fly ash is now the most common used admixture in the U.S.. Surveys conducted in 1979 indicated that it is used in about 37% of the ready-mixed concrete produced in the United States, and that in that year, about 1,900,000 tons of fly ash were used as a partial replacement of Portland cement, which represents almost 10% of the total cement used in the U.S.. Some researchers consider this ratio could increase to 30% to 50%, in the areas where fly ash is available. Nevertheless, even if fly ash is much cheaper than silica fume, it does not have its extraordinary performances.[Mie83]

$2C_2S + 4H \longrightarrow C_3S_2H_3 + Ca(OH)_2$

Silica Fume

Silica fume is the most promising mineral admixture, because it improves considerably concrete properties. It is a by-product of the smelting process used to produce silicon metal and ferro-silicon alloys. It contains more than 80% of silicon dioxide (SiO_2) and acts as a very active pozzolan which could replace 5 to 10 % of the cement. It is usually used in combination with regular or high range water reducing admixtures. The particules are very small (0.1μm average diameter which is about the size of cigarette smoke particules and two orders of magnitude finer than particles of Portland cement) and therefore have a very large surface area available for chemical and physical reactions. The fine particules are able to fill or reduce the size of pores in the concrete, minimizing voids, and leading to a very dense concrete with a higher compressive strength. Also it reduces the opportunity for foreign materials to enter the concrete and attack its materials by chemical or mechanical processes, and this lower permeability increases its durability.

At least, the pozzolanic character of silica fume leads to a high consumption of calcium hydroxyde and gives a high efficiency factor to the process. This, combined with the reduction of waste materials within the concrete structure explains a higher strength at early ages.

More than with any other raw material, a precise quality control program is required for silica fume. Tests such as chemical reactivity and fineness are necessary.

Although the first recorded use of the material as a pozzolan goes back to early 1950's, it was in the 1970's that major R&D efforts towards its utilization in the Portland cement industry were undertaken. In 1981, the world production of silica fume was estimated to be about one million tons, with Norway and the United States as leading producers responsible for 120,000 tons each. In 1983, the U.S., Norway, France, Switzerland and West Germany produced 140, 113, 75, 50, and 42 thousand tons respectively. Interest in silica fume is currently increasing, but other similar fine silica sources may become available in the future, since production rates of silica fume in the world are heavily dependent upon the status of the steel industry. It is impossible to give exact figures regarding pricing of silica fume. However, as a general rule the price is higher than that of cement, and might be as high as fifteen times the price of cement.

3.3.4 High Strength Concrete Prepared With Regular Raw Materials

No new technology is absolutely essential to produce adequately uniform concrete with a strength between 8,000 and 10,000 psi. It is necessary to control the water-cement ratio of the concrete vigilantly, and to use efficient mixers, thorough consolidation by vibration, and forms designed to resist the pressures developed by the fresh concrete. Superplasicizers can be very useful from a workability point of view, since the water-cement ratio is very low. While no new technology is required, careful adherence to every aspect of the best practices in production and control is of primordial importance. And the single greatest cause for the difference in cost between concrete of normal strength and a HSC made with regular methods, is the excellent construction practice and rigorous control required to achieve HSC performance.

3.4 High Strength Concrete : Strengths and Weaknesses

The material is available in the concrete industry, which uses several means to achieve high strengths (pozzolans, low water-cement ratio, compaction, vibration, etc...). But there is some resistance from the construction industry itself and the innovation has been perching on the horizon for several years. Researchers love it, and make a good deal of efforts to have a better understanding of its properties. Engineers and designers, as indicated by the survey, like the concept but are waiting for an opportunity

Table 3.1: Examples of concrete and HSC mixes

Water	Cement	Fly Ash	Sil Fume	Fine agg.	Coarse agg.	Comp. Strength
266	657			1248	1872	4,500 psi at 28days
300	846	100		1025	1800	9,000 psi
345	623		62	1322	1634	10,600 at 56 days

Table 3.2: Estimated production and use of Condensed Silica Fume in 1984. Source : [Tel88]

Country	Total quantity produced (Mt)	Utilized in cement and concrete products (Mt)
Norway	140	40
United States	100	2
France	60	0
Australia	60	20
South Africa	43	0
Japan	25	0
West Germany	25	0
Canada	23	11
Sweden	14	5

to use it : ignoring some of its most important properties (notably durability), they think its use is limited to very specific applications. Contractors shy away because the problem of aggregates and raw material supplying, handling, placing and quality control have been exagerated. And codes are lagging behind the technological improvements and the equations of ACI 318 and AASHTO may not be applicable for high range of concrete strength.

3.4.1 Attributes of High Strength Concrete

A comprehensive list of the main attributes achievable using HSC was worked out by a workshop on HSC [oCDNO87]. This committee classified them in three general categories : properties which benefit the construction process, enhanced mechanical properties, enhanced durability properties. They are given in table 3.3.

Basically, they are due to the increased homogeneity of the material, batched at very low water contents, with high cement content, high dosages of both silica fume and high range water reducers, and which develop very impermeable pore structures that have completely eliminated most coarse, connected, porosity. Extremely good performances, including high compressive and tensile strength , far better than those of conventional concretes, can readily be obtained.

Further more, tests indicate that in addition to these properties achieved with such concretes, nearly all of the conventional durability problems can be avoided, due to this impermeable structure isolated from the external environment and some see in durability the best reason to use HSC. The main explanations why it has been used so sparingly to date are cost, difficult handling and placing, and constraint of quality control. But one should consider that the typical cost of concrete is only 2 to 5% of the total cost of the structure, and even doubling the concrete cost is not significant compared with a a service life that might be doubled. However, the issue raised at this point is the adequacy of such a concrete life time in a structure which might become obsolete earlier, because of other structural failures, or architectural

Table 3.3: Exploitable Attributes of High Performance Concretes. Source : National Inst. of Standards and Technology[CC90]

Attribute	Abbreviation
Adhesion to hardened concrete	AD
Abrasion resistance	AR
Corrosion protection	CP
Chemical resistance	CR
Ductibility	DUC
Durability	DUR
Energy absorption (toughness)	EA
Early strength	ES
High elastic modulus	EM
High compressive strength	CS
High modulus of rupture	MOR
High tensile strength	TS
High strength/density ratio (lightweight concrete)	S/D
High workability and cohesiveness	WRK
Low permeability	IMP
Resistance to washout	WSH
Volume stability	VS

or economic considerations.

3.4.2 Applications of High Strength Concrete

Many applications can benefit from the enhanced qualities of HSC. Those identified by the workshop cited previously [oCDNO87] are given in table 3.4. The principal ones are detailed in the following sections.

Buildings

High Rise Buildings Most applications of HSC to date have been in high rise buildings, especially in North America. HSC has already been used in columns, shear walls, and foundations of high-rise buildings in cities such as Houston, Dallas, Chicago, New York, Toronto and abroad. Tall structures whose construction using normal strength concrete would not have been feasible have been successfully completed using HSC. For a long time, building height did not improve because then-current codes required large columns that took up too much rentable floor. When in 1959, Chicago's Executive House Hotel became the United States' highest concrete building (371 ft), it beated a record established 37 years before (1922, Medical Arts Building, Dallas, Texas, 230 ft). Then, in ten years, from 1959 to 1969, the height of the tallest buildings nearly doubled, from 371 ft (Executive House Hotel, Chicago, Illinois) to 714 ft (One Shell Plaza, Houston, Texas). Column and beams dimensions could be reduced resulting in decreased dead weight of the structure, and result in a increase in the amount of rentable floor space in the lower stories. It has been showed that using 8,000 psi concrete instead of 4,000 psi concrete in a fifty story building could result in a reduction of 33 % in column diameters. At least, reduced dead weight can substancially lessen the design requirements for the building's foundation.

Low or Medium Rise Buildings Some studies have showed that the benefits of HSC can be used not only in high rise buildings, but also in low or medium rise build-

Table 3.4: Opportunities for Exploitation of High Performance Concretes. Source : National Inst. of Standards and technology

Application	Existing/ New	Needed Attributes
Buildings		
Columns	E	WRK,CS,EM,Predictable deform.
Post-tensioned slabs	N	CS,EM
Foundations	N	CS
Bridges		
Decks	E	CP, DUR, AR, S/D
Long spans	E	EM, S/D
Pavements		
Fast-track construction	E	ES, MOR
Repair	E	WRK, ES
Heavy traffic zones	E	AR
Precast/Prestressed concrete	N	WRK, CS, MOR, ES, CP, S/D
Repair		
Emergency	E	WRK, ES, AD
Underwater	N	WSH
Offshore structures		
Gravity structures	N	CS, TS, EM, DUR
Floating structures	E	CS, TS, EM, DUR, S/D
New transportation systems		
High-speed rail, mag-lev	N	VS, CP, CS, EM
Cold weather construction	N	ES
Chemical and food processing plants	N	IMP, CR, AR
Fast-track construction	N	WRK, ES, MOR
Hazardous waste containment	N	IMP, DUR
Parking garages	E	CP, DUR
Long-term	N	DUR, CS, AD
Use of fiber concrete	N	EA, WRK
Military structures	N	EA, TS, CS
Security structures	N	IMP, ES, CS, TS, DUR
Tunnel linings	N	IMP, ES, CS, TS, DUR
Lunar concrete	?	WRK
Automated construction	?	WRK

ings and proved the economic feasibility of using HSC in this type of construction, based on cost advantages of the reduction in reinforcing steel and other cost items outweighting the additional cost of using HSC [SR89]. Nevertheless, it has also been suggested that thirty stories is the minimum height for a building for which HSC is beneficial.

Concrete durability An important fraction of GNP is invested in new construction [4]. A healthy, well maintained infrastructure is a condition for extending and developing new facilities. This issue is closely related to the problem of concrete durability, and therefore linked with a greater use of HSC [C.D86]. It is a new challenge for the construction industry to be able to catch the opportunity offered by the availability of HSC to build more durable structures.

Volume of Reinforcement The Material Service Corporation in Chicago, Illinois, conducted a study in 1983 in which it showed cost savings in using HSC in columns. The percentage of reinforcing steel was reduced while a concrete with a greater strength was used. The most economical design proved to be a minimum percentage of reinforcing steel, with a HSC. Other studies [MZ85, Col86] found the same type of results.

Volume of Concrete HSC with strengths up to 10,000 psi was developed to keep volumes small while buildings grew higher. An increased concrete strength is used by engineers in conceiving smaller member size to carry the same loads (or even lighter if upper floors are also made of HSC, therefore themselves lighter) as a larger member of regular concrete would do. This reduction in member size increases the amount of rentable space. Unfortunately, this is accompanied by higher material costs, at least per unit volume of concrete.

[4] According to the U.S. Bureau of Census, the value of construction put in place in 1990 in the U.S. was $435 billion.

Formworks Costs Variations in the compressive strengths of concretes used in River Plaza Building in Chicago (See Figure)show how a clever conception can save formwork costs. The use of concrete of various strengths allows the designer to maintain constant column dimensions throughout several stories of a structure. The same precast formworks are used during the building construction, but the compressive strength of the poured concrete changes and decreases while the building is rising. Since the lower floors will carry their final loads several months after they are completed, their concrete has time to reach its final strength, and therefore this method is well founded.

In the tower itself, from the foundation to the 25th floor, a 9,000 psi concrete was used ; above the 25th floor, columns were made of concrete which strength gradually decreased from 7,500 to 4,000 psi.

Rapidity of Construction The early high strength of HSC allows to strip construction forms sooner. For instance, during the construction of Commerce Tower in Houston, Texas, a 24 hour strength of 4,000 psi was reached (from a 28 day design strength of 7,500 psi), which permitted to reuse the forms daily.

This entails a better productivity and a reduction in the total amount of rental time on construction equipment over the period of the construction project, and with the possibility of earlier occupation by tenants, an increased benefit for the owner.

Foundation Costs HSC used in combination with light weight concrete for slabs reduce considerably dead loads carried by the foundations. Without this saving, Water Tower Place foundations would have had to go much deeper than they actually do to reach bedrock and be anchoraged in it. This represented a saving of 120 ft in the upper layer, and 5 to 6 ft in the bedrock.

Stability and Comfort of Top Floors Occupants A stiff building is attractive to landlords and tenants alike because the elasticity of a structure has a direct relationship to the safety and comfort of the occupants. The stiffer the structure, the less it sways or "drifts", and the less the occupants feel as though they are sitting inside a moving object. There have been cases reported where the drift in commercial buildings was so noticeable that some occupants left the building complaining of motion sickness.

Bridges

Many attributes which buildings beneficiated from are also of great interest for bridges, for similar reasons. Thus, durability, volume of concrete and rapidity of construction are as many factors in favor of a greater use of HSC in bridge construction. The rapidity of construction allowed by HSC can be a major incentive for the use of HSC in bridge construction and is well documented by the bridge of the Ré Island (France) [Ile88].

As suggested earlier in the case of building construction, one advantage of HSC is its higher compressive strength which, when evaluated in relation to the weight and volume required by the structure, might make it the least expensive means of carrying compressive force in bridges [Car80].

Further more, it allows lighter and slender members in the structure, due to reduced dead loads, providing improved horizontal clearances, and possible longer spans, with greater load capacity. This also can be a "plus" if, like in the Bridge of Joigny, the prestressing tendons are external and can easily be replaced, all-important precaution, given the longer durability of HSC. It seems that the factor governing the obsolescence of the structure is no longer concrete deterioration.

Also, increased stiffness, due to an increased modulus of elasticity is advantageous when deflections or stability govern the bridge design.

Other Applications

Offshore platforms, developed mainly by the Norwegian concrete industry, cryogenic storage vessels, high pressure, high temperature process vessels, and even lunar bases are among the many other possible applications foreseen in the future for HSC and very HSC.

3.4.3 Profitability and High Strength Concrete

A premium price has to be paid for HSC, but in many cases reduced construction costs, increased rentable space or greater durability more than compensate for the increased cost of raw material and quality control and should become a tremendous factor in the decision to use HSC.

Basically, HSC will carry a compression load at less cost than any lower strength concrete. Chicago based structural engineers William Schmidt and Edward S. Hoffman compiled charts indicating the cost of supporting 100,000 lb of service load comes to $5.02 per story with 6,000 psi concrete, $4.21 with 7,500 psi, and drops to $3.65 with 9,000 psi concrete which the authors report they had no difficulty obtaining in the Chicago area [SH75]. While the figures reflect 1975 costs, the ratio should remain similar. The reason for these economies is that, although the concrete itself is more expensive than lower strength mixtures, the cost differential is offset by significant reduction in the given member size, especially in columns. Their results are given in table 3.5.

Another study was conducted by Gregory J. Smith and Franz N. Rad, who showed in a very detailed cost analysis of HSC in building columns that it was evident that more economy could be obtained with the use of HSC than with normal strength concrete. They proposed figures of relative reduction in the column construction cost in the order of 26% for 8,000 psi concrete and 42% for 12,000 psi.

Many other examples could be found in the literature and Henry Russel noted that in every instance he had seen higher strength concrete used, it had been to reduce the total cost of the building [Bau88]. This was illustrated with the concrete used in Two Union Square building in Seattle, project which will be cited often in the following chapters, that cost approximately $125 a cubic yard. If a standard, more conventional mix had been specified, it would have cost approximately $60 a cubic yard. Nevertheless, use of the new innovative construction material reduced the cost of the $30 million structure by about 30%.

Extensive design evaluation and cost studies including material costs, rental benefits and increased durability should be conducted for projects in which HSC is used. The analysis given in table 3.6 is interesting because it includes rental benefits. It was conducted for Bourke Place core walls in Australia, and led to the use of HSC because an effective extra cost of $99,000 would have been incurred if 5,800 psi concrete was used rather than 8,700 psi [Bur89].

Those analysis generally do not include durability considerations, though it may the major reward of HSC. This drawback is the object of section 6.2.

3.4.4 Disadvantages of High Strength Concrete

Cost and Availability of Raw Materials

Availability of raw materials for HSC is a major drawback. Firstly, the choice of aggregates must be made carefully, since very high strength cannot be supported by ordinary aggregates. Commercially available aggregates are expected to achieve a concrete strength of near 15,000 psi but strength higher than 20,000 psi might require selected aggregates such as calcined bauxite[LC84]. An important step in the next few decades might be to select raw materials able to complement silica fume and sustain very high strengths. Nevertheless, one should keep in mind that the solution should satisfy the requirements of workability, mechanical properties, but over all, remain economically feasible.

Table 3.5: Cost of Supporting 100,000 lbs of service load. Source : [SH75]

Material	Area required	Material per story	Cost per story
Steel	4.39 sq in	167.92 lbs	$50.38
f'c = 6,000 psi	52.08 sq in	3.16 cu ft	$5.02
f'c = 7,500 psi	41.49sq in	2.52 cu ft	$4.21
f'c = 9,000 psi	34.48 sq in	2.10 cu ft	$3.65

Table 3.6: Core Cost Study Based on Bourke Place per Floor. Source : [Bur89]

Concrete Strength (psi)	8,700	7,250	5,900
Loss in rentable space, m^2		11	27
Cost of Rentable space based on $3,500 per m^2		38,500	94,500
Extra concrete, m^3		41	100
Approximate price per m^2	130	115	105
Total concrete per floor, m^3	240	281	340
Concrete cost, $	31,200	32,300	35,700
Effective extra cost, $		39,600	99,000

In the case when silica fume is used, its supply might be difficult since the world-wide production of this substance is thought to be only about one million tons per year. Besides, it has some serious transportation and handling problems due to its fineness : it has a very low density (and therefore takes a lot of room), it is sticky and bulks easily, and escapes all but the tightest fitting systems. This entails a cost two to ten times (including transportation) as much as cement and fly ash.

Quality Control

Silica fume cannot simply be added to ordinary concrete. Mixes must be redesigned, and the proportions of stone, sand and admixtures varied to produce HSC with required performance characteristics. Since HSC is very sensible to variations in mix proportions, a series of extensive laboratory tests has to be carried out before the appropriate mix can be worked out, its properties determined, in order to be used at a larger scale. Therefore, not only raw materials are more expensive, but additional expenses are incurred because of a more stringent production and quality control.

Brittleness

There are significant differences between the failure processes in HSC and conventional concretes. HSC fails in a more brittle fashion, and it has raised concern about its applicability in special structures, such as seismic-resistant construction, where energy absorbance is of importance [CC91].

Steel required

Its higher strength along with its brittleness may require a greater volume of reinforcing steel, making cross section dimensions governed by factors such as minimum cover or thickness, so that the full strength capability of the concrete might not be used[Car80].

Other Drawbacks

It is also pointed out in the literature that curing might be more difficult, and that allowable stresses in codes may discourage the use of HSC. Administration and code reluctance is illustrated further in section 6.3.2.

3.5 The Concrete Industry

The concrete construction industry is diverse and fragmented, and is involved in the construction of almost every kind of structure. This characteristic pattern affects the efficiency of the technology transfer and diffusion of innovation. It is made up of a very large number of contractors, 95,000 in 1982 according to the Bureau of the Census' 1982 Census of Construction Industries.

Components making up concrete must be selected carefully, according to its performance requirements. Different types of cement and cementitious materials are available, aggregates of acceptable quality can be found, even if locally available sources must be tapped first, because of high transportation costs. Admixtures, mineral or chemical are playing an increasingly important role in the industry.

3.5.1 The Cement and Cementitious Materials Industry

This industry produces cements such as Portland cement, the most widespread hydraulic cement, and other types called blended hydraulic cements, like granulated iron blast-furnace slag cement or Portland-pozzolans cement, much more used in Europe and Japan. The list is obviously not exhaustive.

In 1990, about 90 million tons of Portland cement were used in the United States, more than 80% of this quantity being produced domestically. Different kinds of Portland cement are available, even if not in all parts of the U.S., fitting different performance requirements. Their use is regulated by ASTM Designation C 150.

Two tables are provided which indicate the Portland cement shipments to specific customers, and their apparent use by different markets (Tables 3.7 and 3.8).

More details about cementitious materials are given in section 3.3.3 since they usually provide higher strength and durability to the concrete. The market is today dominated by the use of fly ash, which properties are much less interesting than the silica fume's ones, but which is still much cheaper and more available.

The U.S. cement industry invests very little in R&D : it is almost completely unfunded and spending on basic research on cement and concrete in the U.S. is minimal. The cement industry's figures show expenditures of less than 0.03% of gross sales on research in 1987. However, it is probable that greater spending on basic studies, even to the extent of only 0.1% of sales, could quickly pay for itself in a better and more controllable product and lower processing costs [oCDNO87]. Similarly, it is estimated that concrete producers spend less than 0.01% of sales on research. Here again, greater effort could lead in the long term to better control methods and a more performing product.

But few developments are expected to be generated by this sector. Rather, it counts on public research agencies or specialized chemical producers to transfer technology. In this context, Portland cement will probably continue to be the most widely used cement in the construction market, but with an increasing role played by silica fume, especially in the domain of specialty concretes.

3.5.2 The Aggregate Industry

It is characterized by the volume and the diversity of its production. Since aggregates are not necessarily inert components of concrete, their quality has a crucial effect on concrete performances. Their friability, size, chemical composition, modulus of elasticity or thermal properties are so many factors influencing the structure.

Table 3.7: Percent of Portland Cement Shipments by Type of Customer, 1985. Source : U.S. Bureau of Mines, 1986, Cement in 1985, Annual Advance Summary

Customer	Percent
Buildings materials dealers	5.5
Concrete product manufacturers	12.2
Ready-mixed concrete plants	70.1
Highway contractors	4.6
Other contractors (including oil well)	5.8
Federal, state, and other government agencies	0.3
Miscellaneous and own use	1.5

Table 3.8: Apparent use of Portland cement by market, 1981-1985. Source : Portland Cement Association, 1986

Market	Percent distribution
Building construction	
Residential building	29.5
Public building	7.1
Commercial building	24.3
Farm construction	3.9
Total building	64.8
Public works construction	
Streets and highways	19.4
Water and waste	6.7
Utilities	1.3
Other public works	2.0
Total public works	29.4
Nonconstruction	
Oil wells, mining, miscellaneous	5.8

Nevertheless, the producer generally does not have a broad choice of aggregate types, because of high transportation costs, and is limited to locally available sources, with the challenge of not impairing concrete properties.

The bulk of the productive capacity is managed by a small portion of operators, since 63% of the total production is made by 15% of the owners. The industry is concentrated in large urban areas, and on a transitory scale, in areas where highways, dams, or other large scale projects are under construction. Aggregates are produced in every state and the resources are virtually not exhaustible. However the geographic distribution often does not match market partners requirements, and the quality of available material varies from one deposit to another. The most commonly cited specification for concrete aggregates is ASTM C 33, but the knowledge seems to be incorporated very slowly to current standards. This industry is not expected to change significantly in the next few decades.

Part III

Analysis of High Strength Concrete Diffusion

The framework of the following analysis is inspired by Everett Rogers [Rog83] who proposed eight different steps in studying an innovation diffusion. His theoretical structure has been slightly modified to fit more closely the needs of HSC diffusion analysis and resulted in the following six chapters.

Three main sources of information have been tapped to collect the information necessary to an understanding of HSC diffusion.

Firstly, an extensive bibliographical survey was conducted, which focused on books, technical reports, theses and articles dealing with topics related to HSC innovation : description of projects in which HSC was used as an innovative construction material, technical research on HSC performance and evaluation of its potential applications, and finally innovation studies, and more precisely, though this field is neglected, innovation in the construction industry. An extensive bibliography is proposed at the end of this research.

Secondly, a survey was mailed to two hundred professionals in the construction industry, mostly designers. They were chosen among the top three hundred designers identified by Engineering News Record in 1992. The objective of this survey was to gain a better comprehension of what professionals' opinion about HSC is. The questionnaire was designed for both companies which have had an experience in the use of HSC, and those which have not. The rate of response was 19 %. Their interest lay not only in the questionnaire answers, but also in the various comments made. Both results are given in the appendix.

Thirdly, three telephone interviews were conducted with researchers working on HSC, in France , Canada and the U.S.. The findings of these interviews are incorporated in the following study. The key idea was to find out where the needs, the obstacles and incentives, and the interests of the construction industry are, as far as HSC is concerned.

Chapter 4

Generation of High Strength Concrete Innovation

This chapter is concerned with where HSC innovation comes from, and what the consequences of the specific patterns of its generation on its diffusion are. HSC will be defined mostly as a technology push innovation, with nevertheless a contribution of users in the applied research stage. It will be pointed out that the innovation is incremental rather than revolutionary, and that codes, imposing safety regulations, retard recent improvements diffusion.

4.1 A Technology Push Innovation With Incremental Users' Innovation

The innovation of HSC was not a response to a perceived, well defined need, or a problem that had to be solved. The relatively low concrete strength limited building height, was the cause of large columns and slow construction; concrete bridge spans were shorter. However, higher strength was not a requirement of the construction industry. Rather, it had a pattern of innovations in organizations, as J.G. March noted, which "often seem to be driven less by problems than by solutions. Answers often precede questions"[Mar81]. HSC appears more as a way open to improvements in the concrete and construction industry through incremental users' innovation. This point is well documented by the workshop on HSC held in Gaithersburg [oCDNO87] which shows how the participants listed the qualities of HSC (table 3.3), then the different applications which could fit those attributes (table 3.4) and not the other way round.

Therefore the new product does not come out in a market ready to use it, and a technology push innovation, as opposed to a market pull innovation, is likely to have to convince potential users of the superior alternative it represents to the previous product that it might replace. The issue is then, assuming that HSC is really superior to regular concrete (and one may wonder what the meaning of superior is), whether potential adopters have access to information and are able to understand it. In this context, the quality of communication becomes crucial. It will be studied in more detail in the following chapters.

Researchers have long debated the relative importance of "market pull" as contrasted with "technology push" in producing innovations. Holt argued that radical innovations are the result of technological impetus, whereas minor innovations that follow arise in response to market demand [Hol83]. This analysis applies to HSC innovation, which major concepts come from basic research with little feed back from the industry, whereas users are in charge of incremental improvements through applied research conducted for field application. However, Myers and Marquis [MM69] found that the market is the driving force in the great majority of successful innovations. This characteristic of the generation of HSC innovation might partly explain its slow diffusion, and some change agencies have tried recently to undercome this obstacle (chapter 8).

4.2 Software and Hardware Components or High Strength Concrete : Role of Basic and Applied Research

HSC is an innovation which has very distinct aspects. As most technologies, it can be divided in two different components : a material aspect, called the hardware (the equipment, the raw materials, the products used, etc...), and a software aspect, consisting in knowledge, skills, procedures, and principles that are an information base for the tool.

HSC as we see it in this study is composed with the general new concepts that can lead to an improvement in the concrete performance, such as improved curing, vibrating or compacting methods, and new efficient raw materials (fly ash, silica fume, chemical admixtures). This is the knowledge base of the innovation, its software aspect, which derives from basic research, defined by Everett Rogers [Rog83] as "original investigations for the advancement of scientific knowledge that do not have the specific objective of applying this knowledge to practical problems".

It is generally the first step in the innovation process in a technology push type of innovation.

Then, applied research represents the next step, in which the results of basic research are put into practice to solve a problem in a particular practical application. This all-important stage in the generation of innovation is well described by Claude J. Bauer [Bau88] in a real case (construction of Two Union Square Building in Seattle). In this particular application, the structural designer worked with the local concrete supplier for two years prior to using HSC in the project. The designer defined what he wanted to achieved, and then had to select the right materials to meet his requirements. Therefore, experiments were conducted with different aggregates and components by a technician in the quality control department of the concrete supplier who was assigned the side duty of performing more prejob experiments than normal to develop a mix design for HSC. This example is typical of the way applied research is conducted on HSC. Since each locality and project is unique, producers and users must usually conduct a number of laboratory and full-scale evaluations of alternate concrete materials and proportions in order to establish commercial concrete mixes, according to each particular project specifications. Initially, the producer may use general guidelines such as those published by ACI and others to select materials and proportions, but substantial attention must be given to the availability and prior performance of locally available materials and concrete production equipments. In Seattle, for example, the local availability of an extremely hard gravel and excellent cement allows local producers to readily achieve 28 day strengths in excess of 16,000 psi. In other parts of the country, however, exceptional coarse aggregates are not readily available and producers must use combinations of higher cement contents and special admixtures to achieve high strengths. In all cases, applied and specific research has to be conducted by users themselves.

4.3 Incremental or Revolutionary Innovation : Role of Users' Innovation

Consequently, this type of innovation in the construction industry, and more precisely in the concrete industry, is not generated only by a formal or institutionalized R&D program, as opposed to manufacturing. In the previous example, except its technician assigned to the development of the HSC mix, no separate groups or budget existed for this activity. Trial and error method was used with an existing quality control equipment. C. H. Nam and C. B. tatum define this type of R&D by "informal R&D, a consequence of everyday activities deliberately aimed to incrementally improve the existing technology" [C. 91].

Many researches conducted on innovations in the construction industry have showed how crucial was the role played by users' innovation. For instance, E.S.

Slaughter [Sla91] explained the importance of builders-users innovation in the residential construction industry.. The case of HSC is hybrid, provided that on the one hand basic research is conducted by structured R&D based programs performed by highly trained professionals with scientific methodology, public organizations or universities, whereas on the other hand, the applied research is on charge of the user itself who has to adapt the results of basic research to his particular problem, or differently stated, to reinvente a HSC which fits his needs. Consequently,incremental improvements are made in the methods of proportioning, batching, mixing, placing, curing and finishing. E. Braun and S. MacDonald noted that "a technological innovation is like a river, its growth and development depending on its tributaries and on the conditions it encounters on its way" [BM78]. Basic research should take advantage of this incremental users' innovation ; and it was a major objective of the French project "Voies Nouvelles du Béton" (New ways for Concrete) which aims on the one hand to focus on basic research, but on th other hand to involve directly professionals of the construction industry in the program. This strategy makes easier research projects evaluation by those who are the potential users, and, with more input from the construction industry itself, moves closer to a market pull innovation process.

4.4 Codes Restrictions

There is a close relationship between the diffusion of HSC innovation, and the diffusion of medical innovations. In both cases, there is an imperative need for a severe "quality control" over the technology that diffuses, so that the innovations that spread have desirable consequences and are used according to precise guidelines, for instance codes. This concern with regulating the diffusion of those new technologies is understandable given the possible threat to human life that may be involved. Therefore, a technology brought on to the market place should be safe and effective.

As noted Boris Bresler in the 1982 Davis lecture [Bre83], identifying lessons to be learnt from Raymond E. Davis' experience, "the important lesson in this case is the sequence : solution before innovation ... Innovations without verification is a sure way to get into trouble and to create more new problems rather than solve existing one... before using new materials or new techniques in service environments, let us make sure they are properly tested in the laboratory or on the field". Codes usually impose safety provisions to ensure that the probability of structural distress or failure is made "acceptably small". Nevertheless, as Jacob Feld objected in a printed discussion to the published draft version of the 1962 National Building Code for Reinforced Concrete, "the only acceptable failure probability is zero Probability". This statement wrongly assumed the possibility of a design with a zero failure probability. Rather, structural design codes and calculation methods should aim to provide a mean to assess quantitatively failure probability. However, the multiplicity of local codes and regulations, the inerty of revision procedures as well as the conservatism of officials represent a real constraint on innovators.

4.5 Conclusion

This chapter has emphasized that HSC innovation was a technology push innovation with incremental progress made by users, and that the construction regulation system impedes innovation : it had in it the seeds of a slow diffusion. Main results are presented in table 4.1.

Table 4.1: Generation of High Strength Concrete Innovation.

Patterns of HSC relative to innovation generation	Retard diffusion	Speed up diffusion	Remarks
Mostly technology push	Does not correspond to a market need Little feed back from users Have to convince potential users of superiority		
Applied research conducted by users	Using the innovation requires more involvement of the users	Innovation will closely fit users' needs	
Codes are lagging behind the innovation	Reluctance to extrapolate codes equations		Safe practice Improvement in quant assess of failure prob See section 6.3.2 for further information

Chapter 5

The Innovation-Decision Process

In the previous chapter, we have focused on how HSC innovation was generated, that is to say the process which made HSC available for potential users through basic and applied research, despite users' reluctance and obstacles.

This chapter is emphasizing the role played by the user in the diffusion of innovation, called by Everett Rogers [Rog83] the innovation-decision process, from first knowledge of HSC, to forming an attitude toward its possible applications and benefits, to a decision to adopt or reject it, and eventually to implementation.

5.1 Different Stages in the Innovation-Decision Process

5.1.1 Knowledge

The availability of HSC in the concrete industry is well known by professionals in the construction industry, because it has been experimented for several decades, used in spectacular realizations (Water Tower Place, Chicago, Ill.) and its properties and applications are well documented by journals. Unfortunately, much of the knowledge has not been passed on to the construction industry in a usable form, leaving the specifier, the contractor and the concrete producer wondering what is fact and what is fiction. Some experimentation indicate that certain products or processes are impractical or uneconomical while other researches point the way to previously unimagined new products. This point is illustrated by the controversy on the use of HSC for low or medium rise buildings, developed in section 3.2.2. More over, codes which can be considered as an official confirmation of unformal existing knowledge are lagging behind.

Everett Rogers splits user's knowledge about an innovation in three different types of knowledge : awareness knowledge, how-to knowledge, which contains information necessary to use the innovation properly, and principles knowledge, consisting of "information dealing with functioning principles underlying how the innovation works". Principles knowledge is acquired through applied research which intends to understand the chemical and physical properties explaining concrete qualities. The objective is to make concrete technology less empirical and closer to a structural science, with more predictable results.

Consequently, because a concrete mix depends on so many, yet badly understood, parameters, how-to knowledge is crucial for users. What designers need is to know on what equations they can rely for design purposes, which extrapolations from existing codes are safe, which are not. The ready mix concrete industry needs to be able to make a reliable, consistent material, and do its marketing (see section 9.2.2). Contractors have to learn how to place HSC (see section 9.2.4). THis type of knowledge can be gained by experience and good communication within the industry.

Therefore, in the light of this analysis, it appears that though the construction industry has reached a good awareness knowledge of HSC, there is still a need for better principles knowledge and above all how-to knowledge, which has to be fulfilled by potential users themselves through applied research.

5.1.2 Persuasion

At this stage of the innovation-decision process, a user is going to develop a feeling toward HSC. He will seek to reduce his uncertainty as regard the main attributes of HSC described in the following chapter, in order to develop a positive or negative perception of HSC, using communication channels available to him and described in sections 2.3, 5.2 and chapter 7.

The lack of relevant information available for practical applications (in his response to the survey, one person pointed out a need for further information about HSC in the private industry) entails a very subjective opinion of construction professionals toward HSC. Further more, even if no case of unsuccessful HSC project is reported in the literature, 18% of survey responses cited examples where concrete requirements were not met.

At least, typical construction firms rarely include individuals responsible for advanced technology, though satisfactorily performing the technical "gatekeeping" role to keep the firm aware of new technical developments and how to put them into practice is a key factor in the diffusion of innovation. Therefore, the decision stage is messed up and the opinion of potential users on HSC is often biased, not accurate because based on incomplete information.

5.1.3 Decision

A major drawback of HSC innovation is the difficulty of a small scale trial prior to use in an actual project. A HSC mix is designed for each particular application and the decision to use it or not is made on the basis of (and often prior to) an extensive and detailed program, but still limited in volume, and in laboratory conditions, whereas most difficulties are likely to appear because of the specific patterns of a construction site : large volumes, handling and placing problems, and fragmentation of responsibilities, with a widespread use of subcontractors leading to an overwhelming number of disparate supervisory often taking priority over field supervision. It has been showed [Rog83] that innovations that are not appropriate for trials are generally adopted less rapidly.

Nevertheless, as documented by the survey, companies which have had an experience with HSC were rather enthusiastic before its use (80%) and after the project (100%). This enthusiasm after the completion of the project might be an explanation of the confidence before its start, since some individuals might consider that the trial of HSC by a peer can substitute, at least in part, for their own trial of HSC, even if it is in a slightly different case. As a matter of fact, change agents, who will be described in more detail in chapter 8, can seek to speed up the innovation-decision process of companies by sponsoring or promoting a demonstration of the availability of HSC, and feasibility of its application. For instance, the French project "Voies Nouvelles du Béton" (New Ways for Concrete) was at the root of the realization of the Bridge of Joigny, which aimed to prove that a regular bridge using HSC could be built economically, with well known, well proven construction methods.

5.1.4 Implementation

The implementation stage occurs when HSC is put into application in a real project, because the user has an opportunity and is willing to use it, and able to do so, because he feels that uncertainty is reduced enough. About 28% of surveyed companies had an experience with HSC, but this figure is somewhat biased, given that this kind of firm was more likely to be interested in such a questionnaire. As a matter of fact, and illustrating the positive attitude of most corporations toward HSC, question 10b clearly points out that many of them are ready to use HSC, but are waiting for an opportunity. Thus the rate of diffusion of HSC itself is slowed down by the still limited number of practical applications. Owners are reluctant to implement a new idea and the potential of HSC may not be as broad as expected : a response to question 2 was "a realistic need for HSC". It is probably a consequence of the "technology push" aspect of HSC innovation. Many difficulties are encountered at that time, which should have be weighed up at the decision stage. The availability of suitable raw material is the first one, and trial batches have to be prepared to test concrete strength and performance achievable. The design itself of the structure itself is another one if the range of concrete strength used is not covered by local codes. At last, placing problems might occur, and very detailed schedule, quality control and assurance must be worked out since HSC is very sensitive to any variation of its parameters, much more than regular concrete.

5.2 Role of Communication Channels

During the innovation-decision process, potential adopters of HSC will pass through an uncertainty reduction process in order to evaluate the possible benefits of the innovation to their specific case. Therefore, collection of information is a major concern for them, and this efficiency and availability of communication channels will affect largely the success of innovation decision.

Question 5 of the survey shows that colleagues within or outside the company as well as journals are sources often tapped. Professionals are also exposed to new ideas at a lesser degree through seminars, conferences, continuing education lectures, and representatives of concrete additive producers or large concrete mix producers. However, few communication between researchers and professionals exist (vertical communication). This point will be developed largely in section 7.2.

Other sources of importance, such as R&D programs within a company or contacts with universities are not well developed, as showed by question 7.

5.3 Role of Competition

Such a technology is very difficult to protect by legal means, or through a control of major suppliers of a key raw material and it is not easy to keep a competitive advantage provided by a good knowledge of HSC. What makes a HSC project successful lies in a series of details in the organization, enabling a good coordination among the participants in the project, and a well designed mix. The latter is accessible through site visits when potential adopters travel to see HSC in operation, and address their questions directly to their peers who have actually struggled with similar implementation problems they themselves will face if they decide to adopt the innovation. No exact recipe exist for the former, or as stated P.C. Aitcin [Ait87] "it does not exist, or nobody has yet accepted to publish it". The importance of information exchange is addressed by the French project "Voies Nouvelles du Béton" : every participant should cooperate and share his knowledge to increase the global expertise, and can hope in return to collect some elements to achieve new improvements. Nevertheless, this program does not underestimate the necessity to find the happy medium between quickly diffusing knowledge, and keeping its benefits for those who accepted to finance research. At least, playing in favor of a competitive advantage gain, the use of HSC in a project increases the reputation of a firm, and constitutes a good publicity (cited by survey respondents).

5.4 Conclusion

This chapter has put the stress on the innovation-decision process, which is at the root of the micro-analysis of innovation diffusion. It has been showed how the transfer of information was incomplete, and had therefore to be improved by applied research led by potential users themselves. Though for years, information was diffused by decentralized systems, there is now a tendency toward centralized systems of technology transfer, illustrated by the French program, and other similar projects in the

United States, Canada, Norway, England and Japan to overcome the difficulties and the failures of the previous decentralized system. These programs will be described in chapter 8 (change agents), and the appropriateness of centralized versus decentralized system, and of vertical versus horizontal strategy will be developed in chapter 7 (diffusion networks).

Table 5.1: The Innovation Decision Process.

Patterns of HSC relative to the innovation decision processs	Retard diffusion	Speed up diffusion	Remarks
HSC properties well documented in technical papers		Good awareness knowledge	
Spectacular realizations		Good awareness knowledge	
Many controversies and uncertainties remain	Professionals wonder what is reality and what is fiction		Illustrated by the lack of codes provisions
Need for full-scale trials	Unappropriability of small-scale trials	Possibility of using HSC trials by a peer	See Bridge of Joigny [Yve91]
Limited number of practical applications	Lack of actual opportunities		Consequence of technology push process
Sources of information used	Lack of R&D Lack of joint programs university-industry	Good communication inside the industry Use of technical papers	
Competition Competitive advantage	Innovation difficult to protect	Publicity Reputation of firm	

Chapter 6

Attributes of High Strength Concrete Explaining its Rate of Diffusion

In the previous two chapters, we have studied how HSC innovation has become available to the construction industry, and by what processes potential users passed from the first exposure to HSC to the decision to use it or not in an actual application.

This coming chapter aims to describe characteristics of HSC affecting the rate at which it is diffused and adopted. What will be proposed here is not a description of HSC attributes as classified by concrete experts, but rather potential users' perception of those attributes, because they are the variables of importance to understand what patterns of HSC should be modified, improved or explained to foster its implementation.

The set of attributes chosen to describe HSC from the user's point of view is suggested by Everett Rogers [Rog83] and includes relative advantage, observability, compatibility, triability and complexity.

6.1 Relative Advantage

The main advantages and disadvantages of HSC have been largely discussed in section 3.4. They have been drawn from highly specialized books on HSC, and from technical papers published in different journals such as ACI journal, Concrete International, etc. They are summarized in tables 3.3 and 3.4 with possible applications, and represent experts' point of view.

Question 12b of the survey, "what kind of rewards would you expect from the use of HSC" gives us the opinion of potential users. Their primary concern is clearly profitability: market forces are certainly the main factors in explaining the rate of adoption of HSC. Also, the publicity and increase of technical knowledge that such innovative construction method might yield is expected to give a competitive advantage for future projects. In France, thanks to successful, risky and spectacular HSC projects , like "la Tête Défense" or "le Pont de l'Ile de Ré" [Ile88], Bouygues has gained technical expertise in activities related to HSC. Bouygues is the French largest construction company, with R&D, design and construction departments, and is now the leader in the French HSC market. The Bouygues Group has been conducting intensive research work on HSC, both in laboratory and on construction sites, since 1985. The program is headed by Pierre Richard, and has been carried out under the control of various official French laboratories. These laboratories have controlled and tested the concrete produced by Bouygues in their plants and construction sites, and have issued reports on the tests performed. Most of the research conducted by Bouygues is applied research directed toward actual projects, but some basic research has also been carried out, and 87,000 psi concrete has been produced in Bouygues' laboratories.

For a recent project in Paris, 340 meter high building, "la Tour sans Fins", not yet started, HSC columns are needed, and Bouygues is likely to be awarded the job (provided that the financing of the project is available, which is still an unknown).

Nevertheless, the construction industry is a business of very low mark-ups, but high cash flows, and few companies can afford to lose money on a project based only on publicity rewards. This policy has been documented in some construction cases, but no such examples were found for HSC projects (and obviously are not publicized in construction journals). Tony Tschanz, of the structural firm that designed 19,000 psi concrete columns on Seattle's Two Union Square Building, explained that his firm used these innovative ideas "not for the sake of innovation, but because they resulted in the least-cost building" [Jr.87].

Also of major importance, as pointed out by the National Material Advisory Board's report on concrete durability [oCDNO87] are the long-term savings allowed by HSC performance. Quality of construction has been cited several times in terms of durability and more efficient structures. However, among the different subdivisions of relative advantage, the immediacy of rewards is crucial, and explains why preventive qualities of HSC are too often forgotten. This point will be developed further in the next section.

On the other hand, professionals are also concerned by HSC drawbacks, as they expressed in response to question 3. Though no risk seems really to be predominant in explaining a rejection of HSC, it has been commonly noticed by respondents that the main reason why they have never used HSC was simply the lack of opportunity of a job in which HSC would apply and be specified.

As a conclusion, HSC most expected reward consists in immediate economic profitability, and seems to be a very valuable material, but only for very specific applications in which the price of the risk premium, the raw material and other extra expenditures is justified.

6.2 Observability

How easily other potential HSC users can observe its relative advantage has an impact on their perception, and consequently on the rate of adotion of HSC.

Thus, the use of HSC to erect economically high rise buildings, to develop fast track construction or to enable innovative design is well understood by the construction industry since spectacular structures have been realized. But what might be considered as the most important of HSC attributes, durability, is still underestimated. Yet this stake has been called "a Multibillion dollar opportunity" [oCDNO87]. But the durability pattern of HSC is a preventive innovation, which enables to avoid the possibility of some future unwanted deterioration. However, such innovations, like auto seat belts or preventive medical care, have a slow diffusion because their relative advantage is difficult to demonstrate to potential users, since the rewards occur at a future unknown time : they suffer from a lack of observability. Question 11a in the survey illustrates this point, since 90% of the owners involved in HSC projects were concerned by short terms rewards, whereas only 40% sought long term profitability thanks to enhanced durability.

Therefore, this is the attribute that change agents like those described in chapter 8 should point out, in order to develop the awareness of potential users.

6.3 Compatibility With Codes and Construction Needs

The extent to which HSC is perceived by potential users as compatible with codes and with their own needs will have an impact on how HSC is diffused within the construction industry.

6.3.1 Compatibility With Users' Needs

It has been pointed out before, that a low level of compatibility with users' needs is a weakness of HSC innovation. Though HSC performances are superior to regular concrete ones, despite its higher cost, it has been brought on to the market by a technology push process, and its attributes did not necessarily meet market's requirements. Though construction professionals recognize its qualities, they are still waiting for opportunities to put this innovation into practise.

However, it has been said that the durability of HSC does fit users' needs, but because of the poor interest of the construction industry for maintenance, and because of the preventive pattern of this attribute, this need is not perceived by potential users.

6.3.2 Compatibility With Codes

Building Regulations Can Restrict High Strength Concrete Diffusion

Buildings codes are considered by many professionals to be an obstacle to HSC innovation. While serving the public role of safe construction, they can also "result in unnecessary added cost of construction, promote inefficiency in construction and retard the introduction of innovative products and construction methods", according to a study prepared by Charles G. Field, an attorney specializing in building code issues for the U.S. Federal Trade Commission's Office of Policy Planning. The concreting guidance documents are prepared for limited strengths, not including the range of very high strength, the revision process is very slow, and building codes specifications vary from city to city. Building codes are local regulations specifying materials or minimum standards that must be used in building in this juridiction. Although codes allow local officials to approve innovative products and building techniques, "few local construction-code officials choose to exercise this flexibility" said the study quoted previously. This alternative was successfully implemented when in 1988, Seattle's Two Union Square Building was erected, using a concrete three times as strong as the limits of local codes, as described in the following section. However, this case remains marginal, and the conservative nature of the design equations has been documented by many tests. There are concerns, nevertheless, about extrapolating the design equations to the HSC range. As a result there are restrictions on the maximum concrete strength that can be used in certain design equations. For example, in the ACI code, there are empirical design provisions that incorporate the square root of compressive strength as a factor. Chapters 11 and 12 of the 1989 version of the ACI code place a limit on this factor, which impedes the use of concrete in excess of 10,000 psi.

The effect of codes limitations on HSC innovation is double.

On the one hand, they really impede innovation diffusion. Field quoted estimates that said building codes can increase construction costs as much as 20% and can increase sales prices between 2 and 5%. According to the study, when a builder seeks to use an innovative product or new method of construction, the costs of securing the approval sometimes dissipate the cost advantage that motivated the use of the innovative product. Therefore, most professionals would rather go along, use inefficient methods and pass the costs on to the consumer than fight to get approvals.

Thus, building code regulations affect the price and quality of consumers' housing as well as affecting many groups in the industry.

On the other hand, they force new extensive research, so that code adjustments are made according to well proven scientific data and they put a brake on excessive applications of HSC. As said Arthur Nilson of cornell University "extrapolation of empirically based design equations, such as are found in most national codes, far beyond the limits of the original test data on which they are based, is not safe practise. A thorough review is necessary" [Jr.87].

Examples of Successful Approaches of Codes Officials

However, in describing the Two Union Square project, C.H. Nam, J.G. Gasiorowsky and C.B. Tatum showed howgood coordination and cohesion of the project team can lead to successful results [C. 91].

The city building code officials were involved in the project since its beginning as members of the design team. Consequently, they were not embarassed with finished design specifications they would have to ratify or reject. Rather, the process was a successful interaction between city officials and designers which resulted in a bilateral review of existing codes. As the authors pointed out, even if building codes have to be conservative since human lives are at stake, a good communication initiated by construction professionals can lead to a better mutual understanding, and to changing the usually unilateral regulatory process into an efficient revision procedure.

At least two groups, ACI and ASTM are now developing relevant standards and guidelines to practice. Designers of Two Union Square Building were members of those committees, so it would be no surprise if some of the procedures and quality assurance requirements developed for or used at Seattle found their way into national codes and recommended practices.

The involvement of a practical application of HSC in a review of codes was also an objective of the experimental bridge built in Joigny (France). The bridge had monitoring instruments built-in to follow its behavior and verify the validity of the conceptual approach. It played the important role of a trial in HSC diffusion in France.

High Strength Concrete and European Codification

In the U.S., the whole construction organization does not have unified reglementation and professionals have to deal with local rules, changing from city to city. It seems that a standardization is necessary and could improve significantly the diffusions of innovations of all types. Such a task is extremely complex, but still has been undertaken by the European Community.

How is the transition between national codes and a unique European code managed ?

It is ruled principally by acts 36 and 100 of the Rome Treaty. Though Act 36 allows a country to keep a different national legislation for safety and health reasons, this situation should only be temporary, and according to Act 100 be followed by a unified European legislation. Nevertheless, by using the expedient of Act 36, members of the European Community can avoid temporarily to comply with European Acts.

Different commissions now work on nine "Eurocodes", concerning civil engineering design, including Eurocode 2, focusing on concrete structures, and Eurocode 4 on composite material steel-concrete.

Unfortunately, there is a tendency to use, or abuse of Act 36, for two main reasons. Firstly, many professionals fear that the new Eurocode be very conservative, in a way adopting the position of the most conservative member in each field, trying to minimizing risks, but impeding innovation. Secondly, the definition of the European normalization is going slowly and the Eurocodes will probably not be finished in 1993. Meanwhile, national codes are recognized to be relevant, according to Act 36.

The ultimate goal seems to determine codes which are flexible enough from a composition point of view, but guaranteeing a minimum quality. A solution could be to have a performance more than a prescriptive approach : codes would emphasize compressive strength, porosity or durability rather that aggregate quality or proportionning. All well considered, such an approach would facilitate innovations, since an outstanding performance might be achieved outside the restrictive guidelines of prescriptive specifications.

However, performance standards and standard tests still have to be worked out and the different members of the European Community still have to agree on common evaluation procedures. For instance, porosity tests are not yet determined, and durability tests are in some cases a real challenge to concrete experts.

The European Community new code making procedure is interesting for two reasons. First because it shows how spontaneously national industries keep their own codes, using Act 36, because they are less conservative. Secondly, because it represents an opportunity to build a code based on performance, which would constitute a real improvement.

6.4 Triability of High Strength Concrete

HSC is often experimented on a limited basis but part of the uncertainty that potential adopters would like to reduce lies precisely in the large scale implementation. Four kinds of trials are documented in the literature.

Firstly, experiments are conducted in laboratories in order to have a better understanding of HSC properties; but this basic research is not done by potential users.

Secondly, applied research led by users occurs during actual projects, but only after HSC has been chosen as the perceived problem solution : this kind of trial is part of the implementation stage, and not of the decision one.

Thirdly, some researchers conduct small scale field experiments on real projects in order to evaluate HSC behavior in situ. This type of trial is documented by P.C. Aitcin[LB82][pp51–70] : during the summer 1984, a 13,000 psi at 91 days concrete was substituted for the originally specified 8,000 psi material in an experimental column that carried through the four subbasement floors of a 26 storey high rise building in Montreal. However, tests were conducted by researchers, not by users.

Lastly, an example of a large scale experiment is documented in France : after extensive R&D in French laboratories, the French Ministry of Public Works and the National Project on New Concretes team("Voies Nouvelles du Béton") agreed to build an experimental bridge using 8,700 concrete. The goal was to demonstrate the feasibility of building an average bridge with HSC, using simple construction methods, and to monitor the structure to verify the assumptions in the calculations, to check its long term behavior, and to assess its durability compared to ordinary bridges. The bridge construction was successfully completed in 1989.

This example is of primary importance since it proves how a good coordination of potential users, who commissioned the bridge, and researchers, who supervised the construction of the HSC structure, gave confidence to the French Road Direction which decided to extend the use of HSC to the construction of most bridges in the coming years.

6.5 Complexity of High Strength Concrete Implementation as an Obstacle to its Diffusion

Because of the lack of practical technical information available for construction professionals, extensive applied research programs and quality control procedures are necessary. Cooperation and coordination are of importance during the project. Further more the supply of adequate raw materials can be a problem, and if silica fume is used, its handling is difficult. Thus, a lot of new attitudes and skills are required for a successful use of HSC, and retard its diffusion.

6.6 A Comparison With a Successful Innovation : Plastics for Construction

In order to have a better understanding of the reasons explaining the rate of adoption of HSC in the construction industry, it might be useful to compare its attributes with those of plastics, a material which diffusion within the construction industry has been highly successful.

6.6.1 The Role Played by Plastics in the Construction Industry

The use of plastics in the construction industry has been on the rise in construction for many years. Since 1980, the building industry has emerged as the largest consumer of plastics worldwide. In 1982, builders used 29 pounds of plastic for every $1,000 of construction and in 1989 this figure had nearly doubled to 43 pounds [Mac90]. Total use of plastics in construction is rising about 5 to 6% per year (see table 6.1).

Plastics are increasingly replacing conventional natural materials such as wood, steel and other metals, paper and glass, for a wide variety of applications in residential construction, ranging from simple interior trims to basic structural parts. They are not yet widely used for structural applications in the U.S., but their use for frames and basic structures is expected to grow as builders continue to seek economical alternatives to existing materials [tSotPI82].

6.6.2 Plastics Attributes and why this Innovation Diffusion was Successful

A review of the available literature on plastics diffusion in the construction industry showed how their increasing use can be explained by a few attributes, some of which HSC does not have (see table 6.3).

First of all, they are characterized by heavy R&D efforts to develop new products for the construction industry, and testing laboratories or similar groups have been equally busy establishing product credibility [Bel88], leading to very fast technological advances and a lot of possible applications. Further more, plastic products are easy to install, require less skilled labor, give fine performance [1], can be produced and

[1]There is still a controversy concerning the fire resistance of some plastic materials, which retard codes changes. Professionals of the plastic industry say it is kept alive by industries which products plastics could replace because of their superior quality.

shipped quickly, and have a unit cost lower than old solutions. As a matter of fact, thanks to technological advances, their prices have risen much more slowly than prices of all construction materials (see table 6.2).

Those attributes are the main areas of difference between HSC and plastics innovation in the construction industry. At the light of this comparison, it seems that the difference in the rate of adoption can be explained by the broader range of applications available for plastics, their ease of use, the reduction of labor required, and above all, the potential savings per unit they represent. At last, even if the technology driven approach is not a major obstacle to the diffusion of plastics (because fortunately there was a market for a lot of applications), there is now an effort from the plastic industry to have a more market driven approach.

6.7 Conclusion

Through the study of HSC attributes, it becomes clear that a whole set of new behaviors is necessary such as being concerned with long term rewards (durability) and not only immediate profitability, improving coordination and communication with codes officials to undercome codes limitations, or researchers to conduct full scale trials, having more severe quality control procedures, etc. Though those obstacles are not unsurmountable, they require a fair amount of good will and efforts from professionals, and represent a real challenge for them.

Table 6.1: U.S. Plastics Demand in Construction (million pounds).Source : [New89]

Item	1972	1986	1991	1995	% Annual Growth	
					86/72	91/86
New construction (Expend bil 1982 $)	323.5	336.3	372	410	0.3	2.0
lbs/000$ const	14.3	29.0	32.0	33.7		
Plastics in construction	4617	9756	11900	13800	5.5	4.1
Markets						
Insulation	249	844	1067	1259	9.1	4.8
Plumbing	1734	4351	5360	6300	6.8	4.3
Decorative & Interior	275	248	275	297	-0.7	2.1
Structural & Exterior	2359	4313	5198	5944	4.4	3.8

Table 6.2: Increases of U.S. Construction Material Prices.
Source : [New85c]
Prices of All U.S. Construction Products Rising faster Than Plastics Products.

Year	All construction Materials	Plastics construction Materials
1976	7.9%	2.7%
1977	9.2%	4.7%
1978	11.4%	2.4%
1979	10.1%	8.1%
1976-9	44.5%	19.1%

Table 6.3: Plastics vs HSC attributes.

Attributes	Plastics Description		High Strength Concrete Description	
Ease of use	Assembly simplification	S	Tests by users	R
Design Flexibility	Innovative design	S	Innovative design	S
Availability of raw materials	No renewable, but available Wastes can be used	N	Low production of silica fume but not yet totally used	N
Technological advances	Fast, developed R&D	S	Slow, little R&D	R
Labor needs	Labor moved to the factory	S	Labor intensive	R
Codes requirements	Restrictive, slow modification procedures	R	Restrictive, slow modification procedures	R
Origin of Innovation	Technology push [Bel88]	R	Technology push	R
Performance	Very good : low mass, corrosion resistance	S	Very good : durability, strength, ...	S
Areas of uncertainty	Fire resistance	S	Many	S
Unit cost	Much cheaper than old materials	S	More expensive than regular concrete	R
Overall cost in an appropriate project	Much cheaper than old materials	S	Cheaper	S
Applicability	Many applications	S	Still few opportunities	R
Availability	Fast production Can be transported easily	S	Need for locally available materials	R

Speed up diffusion : S
Retard diffusion : R
Neutral : N

Table 6.4: Attributes of High Strength Concrete.

HSC Attributes	Retard diffusion	Speed up diffusion	Remarks
Profitability of HSC projects	Few applications Little compatibility with users' needs	Market forces drive the implementation of HSC innovation : economical solution in specific cases New possible applications Innovative design	Need for immediacy of rewards
Spectacular realizations		Observability Reputation Publicity	No cases documented of HSC projects undertaken only for publicity purposes
Durability			Could speed up, but not perceived need (preventive innovation)
Compatibility with codes	HSC not included in concreting guidance Slow revision Specification vary from city to city	Force extensive research	Safe practice Good communication with code officials can undercome this drawback [C. 91]
Need for trials	Difficult large scale trials		Examples of successful full scale trials are documented [Yve91]
	All set of new attitudes and skills required to use successfully HSC		

Chapter 7

Communication in High Strength Concrete Diffusion : Diffusion Networks and The Role of Individuals

It appeared several times during previous chapters that HSC adoption is not a matter of one particular group of professionals, such as owners, designers or concrete suppliers, but rather a problem which concerns the whole construction industry, and adopting HSC is a collective innovation decision. An organization can be defined as "a stable system of individuals who work together to achieve common goals through a hierarchy of ranks and a division of labor." [Hes89]. In this chapter, we will consider the whole construction industry as an organization which faces HSC innovation decision.

The innovation process in organizations is very complex, but yet is closer to the reality of technological change. It involves a large number of individuals, each of whom plays a different role in the innovation decision. At the light of the previous chapters, it appears that one of the main steps in the diffusion of HSC is to transmit the available scientific and technical knowledge in a usable form for the potential user.

7.1 A Structure Impeding Innovation : a Need for Better Communication

A continuing demand for more complex facilities, incorporating advancement of new technologies triggers the search for construction technology innovation. Nevertheless, a good communication between the project participants is all important and might decide of the success or failure of the implementation phase, and consequently of the innovation diffusion. This coordination pattern is specific of the construction industry, as opposed to manufacturing, and seems easy to achieve in a simple case where building techniques are well understood by all involved parties, and building performance is predictable. When complex innovations like HSC are at stake, it proves to be much more difficult.

Therefore, it is natural that there is an unwillingness to move away from well known situations. The client's needs can usually be summarized in a well-designed, well-constructed structure, at a reasonable cost, and rapidly built. He is not likely to undertake any further development if those requirements are met, especially if he cannot expect to benefit from the experience in following projects, and given that there is a greater chance of building failure with an unproven construction material.

The designer knows that using new techniques might entail new skills, which may take time to master, new developments that require expenses, undesirable in a low-bid process, and time when there is pressure to start site work as soon as possible. Further more, and a major concern in the U.S. law-suit environment, if the designer uses a new material that fails (and there are cases of HSC project failures), he will possibly be sued by his client for damages, and consequently lose his reputation.

Moreover, the lack of communication is a real problem since the design process is divorced from the construction process and there is little opportunity to exchange information at time the important design decisions are being made. And in public contracts, specific conservative standards have to be met.

In this context, the role played by the "coordination champion" described in section 7.2.3 is crucial.

7.2 Lack of Vertical Communication

Communications channels within the construction industry identified through the survey comprise, among others, technical publications, distribution of technical information by trade bodies (like cement or concrete association), continuing education lectures, seminar, conferences, symposia, sales forces, and even the day to day business of making contact with the man on site. However, it is seems that little "vertical" interdisciplinary communication exists in the construction industry, between individuals.

7.2.1 Interpersonal Communication

The best and most efficient method used to acquire new information is still to ask a peer who knows about utilization of HSC. Even if he does not know the exact answer, he can save a tremendous amount of time by giving the right source. The survey indicates that this source of information is often tapped by professionals. There can be consequently little doubt that conferences and meetings will remain one of the most important means of communication among engineers and scientists. However, what should be done is to refine organization methods and to improve international and interprofessional coordination of meetings.

P.C. Aitcin, in a telephone interview admitted that in spite of the quality of work in conferences on HSC, they usually gather together professionals of the same field of activities : designers, or researchers, etc. Researchers acknowledge that designers do not pay enough attention to technical papers, but due to the outstanding performance of HSC, and above all durability, think they will ultimately use it; and potential users wonder what the practical applications are in which HSC is economical, if any (this comment has been found many times in survey responses). But little effort has been made to help those groups to meet and exchange their point of views. As described in the section on change agencies, some steps in this direction have been made recently.

7.2.2 Homophily and Heterophily

Therefore, we have identified a language problem between researchers and users of HSC and this communication being crucial for the diffusion has to be established.

Everett Rogers [Rog83] explained how homophily can be a barrier to diffusion. Homophilous communication takes place between two individuals who share some attributes, such as objectives, technical competence, or language. Such a communication is easy, effective and rewarding. It occurs within the circle of researchers, the circle of designers, the circle of concrete suppliers, etc. However, in such a system, new ideas spread horizontally rather that vertically. Interpersonal heterophilous relationships, even if not as natural as homophilous ones, should be developed. "Homophilous communications may be frequent and easy, but may not be so crucial as the less frequent heterophilous communication in diffusion."

Here lies also the importance of a centralized system of diffusion (see chapter 8 on change agencies) because heterophilous relationships are not likely to be created spontaneously : there is a need for a central organization which creates links between people who have complementary information of diverse nature.

7.2.3 The Role of Champions

Question 1 pointed out the importance of key individuals. C.B. Tatum [NT89, C. 91] called them "the champions" an identified four types of champions relevant for successful innovation in the construction industry.

Three of them are drawn from the analysis of innovation in manufacturing : the "technical champion", who carries an idea from the original concept through development into a viable product; the "business champion" who provides a business framework for a technical idea; and the "executive champion" who sponsors an idea at the highest level, using his or her power to protect it, to move it along, and to seize the opportunity to exploit it.

However, even if C.B. Tatum identified precisely and named those three champions in Two Union Square project, above all he pointed out that the role played by those key actors was all important from an"integration" or "coordination" point of view. They orchestrated the efforts, including the appropriate participants, getting in touch with them at the right time, they improved communication. Thus, C.B. Tatum showed the existence of a fourth type of champion, specific of construction innovation, the "coordination champion".

I propose that for HSC diffusion purposes, a diffusion champion is needed. He is a kind of coordination champion at the concrete industry scale. His role is to foster communication, understand needs and problems of the industry and research and to reduce "language" obstacles. His action might be more efficient in the framework of a program. An example of such diffusion champions has been provided with the staff of the French program "New Ways for Concrete" (see section 8.2.7).

7.3 Conclusion

The main point discussed in this chapter is the difficulty of communication between people of different culture, such as researchers, contractors, or owners. Each project participant might encounter difficulties which could be solved by the participation of other parties. A striking example was the early involvement of code officials in the Two Union Square project. Structures to foster communication should be worked out (chapter 8) under the supervision of "diffusion champions".

Chapter 8

Change Agencies : Organizations Promoting the Use of High Strength Concrete

Between the organizations conducting research on HSC and professionals who have the opportunity to implement the innovation, a change agency might attempt to influence potential users' decisions to secure the use of HSC. Its role is to provide a communication link between those two groups of actors, and to facilitate the flow of information in both ways : providing the construction industry with relevant information issued from research, and forwarding the feed back so that researchers can make appropriate adjustments to their programs on the basis of users' needs.

Whereas for a long time the information flow about HSC was based on a decentralized system, the lack of coordination and a need for the "big picture", gave birth to several research programs aiming to diffuse HSC innovation. They are described below, with more emphasis on those directed towards both an increase of scientific knowledge and more efficient diffusion.

8.1 A Need for a More Centralized System of High Strength Concrete Diffusion

It has been noticed by some authors [Hig84] that research on cement and concrete was financed by a variety of industry and government sources. But the cement industry concentrated on Portland cement production, the construction industry on construction methods, and the aggregates industry on sand, gravel, and crushed stone. Not only none of the research efforts was of adequate scale (see section 3.5), but also their effectiveness was further limited by the absence of integration. Therefore, a coordinated effort was needed for research in cement and concrete in HSC.

The decentralized system that prevailed before the emergency of those programs described further had two major drawbacks : there was a lack of a coordinating role which made harsh the search of information about HSC for potential users; and though a very important attribute of HSC, durability was not perceived as a need and could not be without the intervention of a centralized change agency. However, on the other hand, HSC innovation diffused by a decentralized system was likely to fit users' needs and problems more closely.

It seems that a hybrid diffusion system in which certain elements of centralized and decentralized systems would be combined could be appropriate in the case of HSC. There would be a central agency, in charge of coordinating R&D, leading full scale trials on actual structures and comparative designs in order to develop how-to and attributes knowledge of potential users by informing designers, consultants, architects about the new material, convincing them of its economic interest and showing them how to use it. Adopters would still be responsible for conducting applied research in order to design a HSC mix according to their requirements. Most programs described in the following section are inspired by this theoretical model.

8.2 Examples of Current High Strength Concrete Change Agencies

8.2.1 Center for Science and Technology of Advanced Cement Based Materials

The center, headed by Pr. Surendra P. Shah, consists in a consortium of five organizations including Northwestern University, the University of Illinois, the University of Michigan, Purdue University, and the National Institute of Standards and Technology. It was created in 1989, and had four major goals : to carry out research advancing the fundamental science required for the design of new cement-based materials with enhanced properties; to improve the understanding of the science underlying cement-based materials processes and methodologies; to develop mathematical and computer based models to simulate the structure and the performance of cementitious materials; and to enhance the basic knowledge to improve the competitiveness of the U.S. construction industry. These activities are also intended to develop the scientific knowledge for designing the next generation of cement-based materials with improved properties.

8.2.2 Strategic Highway Research Program

This five year program encompasses a concrete subprogram including :

Project C-205 : High Performance Concrete

The objective of this project is to obtain information on the mechanical properties and durability characteristics of different HPC mixtures intended for highway specifications. The project is headed by researchers at North Carolina University, and includes others from the University of Michigan and the University of Arkansas. In addition to experimental work, a comprehensive literature review and state of the art report on HPC will be completed. Also, a database structure will be developed that will permit the incorporation of new research findings and allow query by users. The project is expected to be completed in late 1992.

Project C-206 : Optimization of Highway Concrete Technology

This project is intended to use the knowledge gained in the whole Strategic Highway Research Program on concrete and apply it to the development of new concretes and methodologies to increase the service life of highways. The project will include the evaluation of new materials and processes in concrete technology and establish plans for using them in highway applications.

8.2.3 Norwegian Project

The Royal Norwegian Council for Scientific and Industrial Research and the Norwegian concrete industry initiated a joint research program on HSC in 1986. Phase 1 of the program was completed in 1988, and Phase 2 in 1991. Its main objectives were to broaden the knowledge of HSC in the range of 9,000 to 15,000 psi, and to consider extensions to higher strengths; to determine the influence of variations in the major concrete constituents on the properties of fresh and hardened concrete; to determine the appropriateness and reproducibility of standard test methods when applied to HSC; and to transfer the technology on HSC to the Norwegian building industry.

8.2.4 Canada "Networks of Centers of Excellence" Program on High Performance Concrete

In 1988, the Canadian government initiated a competition for the creation of "Netwoks of Centers of Excellence" to perform multi-disciplinary research on a wide range of subjects. In 1989, fourteen such "Networks" were created, one of which was in the area of HPC. The HPC network is headed by researchers at the University of Sherbrook (Quebec, Canada), and includes six other universities and two industrial partners.

8.2.5 Japanese New Concrete Program

In 1988, the Japanese Ministry of Construction initiated the five-year project "Development of Advanced Concrete Buildings using HSC and Reinforcement" (termed "new RC"). The major objectives of the project are to survey and analyze existing R&D related to HSC to establish a technology system for "new RC" buildings; and to develop an understanding of the mechanical behavior of buildings using HSC and high strength reinforcing steel and to develop design systems for "new RC" buildings.

8.2.6 National Institute of Standards and Technology Workshop

Recognizing the potential of HPC, in 1989 the National Institute of Standards and Technology (NIST) proposed the initiation of a national research program on HPC. NIST (formerly the National Bureau of Standards) has had a long tradition of concrete materials research, development of standard test methods, and assisting the construction industry. Thus it was felt to be important that NIST should work with the cement and concrete community to develop the outline for a plan which would provide a framework for NIST and other organizations who wish to make resources available to advance the knowledge of HPC for the benefit of the U.S. construction industry and protection of future investments in the infrastructure.

8.2.7 French National Program

In France, a national project already cited earlier, called "New Ways for Concrete" has been undertaken to demonstrate the feasibility of producing HPC for major construction works. The demonstration project involved the construction of a 340 feet, three span, cast-in-place, post-tensioned bridge. The "experimental bridge" at Joigny was built with HPC having a 28-day design compressive strength of 8,700 psi.

The national project has three main objectives. Firstly, it intended to create close relationships between basic research, applied research, full scale trial, codes regulation and implementation of the innovation. It put the stress on the realization of real HSC structures to test research findings, in order to have basic research piloted by issues raised by implementation of previous works. Secondly, it combines concrete innovation with innovative design. Thirdly, it aims at developing the awareness that not only high strength is a major achievement of HSC, but also other improved concrete attributes, and among them, primarily, durability.

This program received a strong support from major French developers which enabled implementations of research results, illustrated by the Bridge of Joigny. Consequently, research could focus on technically and economically feasible solutions. Such a program cannot pretend to be successful without this kind of cooperation. Nevertheless, even if a diffusion of knowledge within the whole construction industry was the ultimate goal of the program, participants were concerned about cooperating and sharing their information, but confidentially.

The success of the project has convinced some French officials that HPC should be specified for all works where superior durability is desired, even if the high strength of HPC is not structurally necessary.

8.3 Conclusion

The recent tendancy of the construction industry in several countries to rely on a change agency to promote the use of HSC is linked with a need of a better coordination, improved communication, and awareness of some all important attributes of HSC (durability). A theoritical diffusion system including both centralized and decentralized elements has been proposed.

Chapter 9

High Strength Concrete Innovation : Consequences and Challenges for the Future

HSC represents an alternative to the construction industry which may prove to be very rewarding and profitable, and as change agencies claim, a challenge to be taken up. So far, this study has focused on factors explaining a slow diffusion of HSC, that is to say, what variables are related to innovativeness as regard HSC. However, a question of importance remains, what are expected to be the effects of adopting HSC. After all, invention and diffusion are but means to an ultimate end : the consequences from adoption of an innovation. It is of importance to assess challenges and consequences that a wider implementation of HSC could bring.

9.1 Integration

9.1.1 A Need for a Better Integration

The construction industry is very fragmented and suffer from a lack of coordination between the actors involved in the project from its beginning (owner, designer) to the end (contractor, subcontractor, concrete supplier). All successful HSC projects documented in the literature showed the importance of a deep involvement of all parties, as well as an intense communication. The Two Union Square project or the Bridge of Joigny illustrated this point earlier in the discussion. At the same time, this fragmentation entails high level of competition, the necessity of low bids with few resources remaining for R&D expenditures, and a risk premium to be paid to implement innovations.

Further more as P.C. Aitcin pointed out during a telephone interview, the construction industry suffers from a natural tendency to confine to well proven technologies. The industry is very conservative, researchers reproach designers for not reading technical journals and not being innovation oriented. An explanation for that is the risk and cost of a litigation if the implementation is not successful.

9.1.2 Performance Innovation and a Need for Communication

It has been pointed out in the section comparing plastics and HSC innovation (section 6.6) that a major difference between them lies in the fact that plastics innovation improves marketability whereas HSC improves performance. Fred Moavenzadeh [Moa91] explained how innovations that improve marketability are likely to be adopted more rapidly, since they reduced material costs, process costs, and in this case even use less skilled labor. He then showed that diffusion of performance based innovations required a structure in which the ultimate buyer had a chance to be involved in innovation decisions so that he be informed about its potential benefits (which is part of the uncertainty reduction process). Otherwise, the developer, and eventually the buyer, had to pay a risk premium since they assessed the willingness of potential buyers to pay for a new material improving performance. This additional risk retards the diffusion of innovations which improve performances.

Two conclusions follow from those remarks. First of all, more frequent and closer interactions between the different subsectors of the construction industry are necessary to reduce the uncertainty about the need for the innovation and consequently reduce the risk premium to be paid for it. Secondly, HSC is likely to be used first in projects where the developer is the final buyer and then implemented in speculative projects [Moa91]. This tendency can be seen in France where the national project "New Ways for Concrete" was successful in public contracts. This type of implementation is well on the way in Quebec where P.C. Aitcin is developing HSC projects in bridges erected for several cities. Other proposals intending to foster communication will be given in the next chapter.

9.2 New Skills in the Industry

9.2.1 Aggregate Industry

Careful consideration should be given to the shape, surface, texture, and mineralogy of the aggregates. Raymond C. Heun stated [Heu83] that "the compressive strength increases as the maximum aggregate size decreases". Nevertheless, each strength level will have its own optimum size of aggregate which will yield the greatest compressive strength. In all cases, trial batches are necessary to determine this parameter.

Albinger [Bee88] has results suggesting that gravel concrete produces lower compressive strength and modulus of elasticity than crushed stone concrete using the same size aggregate and cement content. This is probably a positive consequence of the angular surface texture of aggregates.

Those are the main requirements for HSC aggregates. But rarely will a producer find local coarse aggregates with an optimal combination of mineralogy, shape and gradation. Frequently, economic considerations or local availability will require him to accept a suboptimal material. And in practise, it appears that the consistency of the raw material is even more important. HSC is much more sensitive to variations than a regular concrete, and if consistency is not maintained throughout production, placement and testing, the required average strength may not be attainable.

9.2.2 Ready-Mixed Concrete Industry

Unfortunately it is so far not economical for the ready-mix supplier to invest in highly trained technicians and expensive equipment because the major market demand is for lower strength concrete (no more than 2% of the concrete delivered by ready-mix producers in the Chicago area, though a leader in the use of HSC, in the late 1980's was in excess of 7,500 psi). However, promotion of HSC requires professionals capable of answering questions on properties and design. Sale of this new material is yet another problem. Development and production costs must be evaluated, and a price that the market can bear must be established, so that the architect and structural engineer can determine the most economical method of construction, according to their needs and requirements.

These negative reasons for producing HSC are counterbalanced by some indirect benefits to the ready-mix supplier (synergistic effects). Through experience with HSC, the ready-mix producer is able to improve the quality of lower strength concretes. A better understanding of concrete allows the ready-mix supplier to develop special concretes. It is a product differentiation that facilitates the sale of lower strength concrete and improves the technical image of the company. These benefits have to be evaluated by the ready-mix company before the decision of moving from a comfortable and known low-strength market into an unknown and highly vulnerable market [Bee88].

An analysis of potential markets and risks associated with HSC in the ready mixed concrete industry was developed by Weston T. Hester of University of California at Berkeley [Hes89]. He also proposed strategies to mitigate risks.

He explained that there are few methods by which a buyer can judge the ability of a ready-mixed concrete producer to provide durable, high quality, HSC.

However, the key to successful marketing of HSC is to show the designer and contractor they will profit from its use. When the designer and contractor understand the economics of HSC, and believe it is readily available, they will use it.

The concrete producer must be able to demonstrate the ability to achieve the desired strength consistently, and at a reasonable cost. One approach to the concrete producer may take to publicizing its capability is to produce a "specification sheet" such as in table 9.1.

With these sheets, the concrete producer is able to summarize prior experience with this class of concretes without revealing the details of mix proportions, materials and costs. It also informs the designer of the other advantages, such as increased flexural strength, associated with HSC and may motivate still additional applications.

Moreover, HSC is an opportunity for ready mixed concrete producers to promote recognition of their work and to create new markets for concrete, innovative designs, and new types of structure using concrete. In Chicago, Weston Hester pointed out, producers promoted HSC for high rise buildings, and received national and international recognition for excellence of their operations. They succeeded in creating new markets for high and moderate HSC in buildings, bridges and parking structures.

Therefore, ready mixed concrete producers have a role to play in HSC diffusion by being more aggressive. Such an example has been documented in 1989, when during the preliminary design of a structure, an option was proposed using concrete with a design strength greater than 14,000 psi, and thereby decreasing the number of piles or caissons in the structure by more than 80%, with a substantial reduction in the foundation costs and time required for construction. On this project, use of HSC was estimated in savings of several hundred thousand dollars. Although the idea of using HSC was not suggested by the concrete producer, specific producers immediately returned very detailed proposals using their materials and technology.

9.2.3 Designers

It is known that HSC permits a designer to decrease the dimensions of the members, in both precast and prestressed, as well as in cast in place or, in other words, to design more slender units and longer spans and beams. The possibility to further expand in engineering design expressions, to use innovative design, could lead to more aesthetically attractive and more performant structural units. Moreover, new designs have to be found and used, that will fit more closely and use optimally HSC attributes.

It has been developed in section 3.3.3 that mostly two mineral admixtures are generally added to HSC : not only fly ash, which use is common today, but also silica fume which future is more promising. Unfortunately, this perspective depends on this by-product, available only in limited quantity. Here lies the challenge for the cement industry which now should develop this opportunity by either searching a substitute, or, if the demand is sufficient, producing silica fume.

It seems that contractors are really reluctant to change their habits on construction sites, and when HSC is specified, need either to be provided with cement enriched with silica fume, or to be supplied with high strength ready mix concrete. Consequently, the cement industry has first to evaluate the demand, and to find out if they would be better off incorporating silica fume in cementeries or in concrete mixers. Some silica fume cement mixes are now available in Canada, in France, and HSC with silica fume is on concrete suppliers catalogues.

9.2.4 Contractors

Contractors are the link in the chain which place HSC. It has a heavy responsibility since variations from specifications and established standards can have immediate and severe effects. Timing of concrete placing, as well as adequate quality control must be conducted carefully. When HSC arrives on the job, it should arrive at the proper slump so that the addition of water is not necessary. The contractor must understand the consequences of exceeding the specified slump and must be ready to place the concrete when it arrives. Concrete should be rejected, the literature says, after it is 90 minutes old unless it can be placed without the addition of retempering water. If the contractor wants to place the concrete with a pump and higher slumps are anticipated, some precautions should be taken. At times the amount of cement in a high strength mix is optimum and, therefore, an increase in slump cannot be compensated for with additional cement. If a a superplasticizers is not already being used, it should be considered at this point.

Job site control must be the responsibility of the party most familiar with the performance and use of HSC, whether that is the concrete supplier, a commercial testing laboratory, or a consultant. The survey showed that usually the concrete supplier is in charge of quality control on the construction site.

9.3 Conclusion

Each sector of the construction industry has a role to play in the diffusion of HSC and this chapter detailed specific changes adoption of this innovation should bring. However, it has also been pointed out that those changes and efforts have to be coordinated in the entire industry. In this perspective, the role of so called "diffusion champions" is crucial.

Table 9.1: Sample Sheet for High Strength Concretes.
This summarizes our prior experience with Mix 0152. We believe this information will be of interest to you as you design structures and consider alternate solutions to current construction needs. The following test data was provided by professional laboratories certified by the Cement and Concrete Reference Laboratory (CCRL). Please contact us for additional information about this and other concretes.

Compressive Strengths				
Age (days)	Average Strength (psi)	Standard deviation (psi)	Number tests	Modulus of elasticity (10^6psi)
3	5,070	700	23	4.5
7	9,020	750	120	
14	11,200	725	12	
28	12,090	760	160	6.5
56	13,300	735	34	
90	13,900	715	18	7.2
Flexural Strengths (28 days : 1,400 psi)				
Unit weight : 152 lb/ft^3)				
Water/cement ratio : 0.32				

Part IV

Proposals and Conclusion

Chapter 10

Proposals for a Better Diffusion of High Strength Concrete

10.1 Transfer of Information and Innovativeness

10.1.1 Importance of Information Transfer

A program promoting the use of HSC in the construction industry would yield big pay-offs if successful. Firstly, because short term savings could be made if construction costs themselves were reduced. Secondly, actions directed to improving durability, even if more expensive in the short term would prove less costly in the long term, due to the savings made on premature rehabilitation of deteriorating structures. The stake has been called "a multibillion dollar opportunity" by a report of the committee on concrete durability held by the National Material Advisory Board [oCDNO87].

At last, by adopting a new material, the construction industry would be able to use concrete in structures using currently other construction materials, and to implement new design of structures currently using concrete. This latter remark is at the same time a consequence of and a justification for HSC innovation. Therefore, its understanding by designers and developers is very important.

10.1.2 Description of the problem

Most of the knowledge about HSC is still possessed by researchers, but a successful diffusion will be achieved only when designers will gain it. One of the most important impediment to implementing HSC technology is the lack of information potential users suffer from. And there is little coordinated effort to gather, manage and provide the needed information. Without being knowledgeable or even aware of a new technology, a potential user cannot recognize its advantages or make the most efficient design for its application. So far, most of them perceive research as not having useful solutions to their practical problems, and there is a critical lack of an adequate diffusion system linking the research system with the practice system.

Therefore some actions should be taken to facilitate this transfer of information, and involve the most efficient type of communication, interpersonal relationships. However this type of communication is heterophilous [1], and consequently difficult to implement. Interdisciplinary symposium should be organized as well as continuing education lectures. In fact, they already exist to a certain extent : the "Ecole Nationale des Ponts et Chaussées" in Paris regularly holds such seminars, but they remain at a small scale. P.C. Aitcin during a telephone interview expressed the wish that contacts be more frequent; and only one respondent to the survey said he often tappes this kind of activities.

10.2 Already Existing Programs.

Some effective new ways of diffusing HSC innovation have been implemented. Among them, a successful approach was conducted by P.C. Aitcin who uses limited scale trials

[1] Individuals are heterophilous when they do not share certain attributes such as language, culture or objectives.

to develop the awareness of designers, prove the availability and safety of HSC. In some structures, he proposed to the owner and designer to replace in a member like a column in a building, a regular concrete by a HSC. Such program is likely to be accepted by the developers since it entails a very limited extra risk or cost, due to the very limited scale of the experimentation. By this way researchers can really bring the innovation to potential users and make a convincing demonstration of its relative advantage : designers realize that space saving is possible, and are then willing to implement further the new technology.

There is a urgent need for revision of codes concerning concrete strength. Designers need to work with established specifications that have proven themselves in the field over extended periods of time and environmental conditions. Unfortunately, this is an intrinsec obstacle to HSC diffusion. It can be partly solved by an extension of full scale testings, which will help building HSC science, improve predictability of HSC, and build professionals confidence. The French project "New Ways for Concrete", seems to be very efficient and promising, by enabling basic research to be piloted by potential users of HSC, and by implementing full scale trials. It has already won over some French officials to the extensive use of HSC in public works, who now not only seek immediate savings, but also expect durability to yield benefits in the case HSC use would prove to be more expensive at construction time.

Such new positive and open minded attitudes of researchers toward construction industry professionals are effective ways of diffusing HSC new technology. They constitute in themselves innovations, and therefore should also be diffused. A program similar to the French National Project "New Ways for Concrete" is now implemented in Quebec, headed by Yves Malier [2]. Several projects based on this framework are already well on the way, and other Canadian States are now looking forward to implement their own programs.

In fact, after having started from unorganized diffusion, more systematic methods

[2]Yves Malier already headed the "New Ways for Concrete" program.

are required, which begin to be implemented now in several countries. These "change agencies" have to harmonize and clarify as much as possible R&D programs, in order to base them on industry needs. An international cooperation in diffusing new ways of transfering HSC technology could be useful, an example of which is given by the French-Quebecois cooperation.

10.3 Proposals for a Better Diffusion

10.3.1 The Example of Consensus Conferences

A change agency could be an effective means to organize and promote such activities.

A good example is provided by the "Consensus Conference", started in 1978 in the medical field. Consensus conferences could be organized to address issues raised by the use of HSC. They would differ from usual state-of-the-art scientific meetings in that they would bring a broadly based panel composed of, among others, researchers, designers, concrete suppliers, developers. A series of research synthesis papers would be discussed by the various people involved in the diffusion process, generators of HSC innovation and potential users.

In particular, designers should be taught that the use of HSC implies in many cases new innovative design. F. de Larrard pointed out that a material change should bring also new concepts in design : at the time when concrete was a new material for concrete structures, designers kept on copying designs they were used to specifying for steel or masonry structures. Yet, the use of concrete implied an innovative approach of design. Similarly, designers and developers will realize the benefits of HSC when they use it in appropriate structures. The advantages of HSC should not be evaluated by comparing HSC and regular concrete or steel in the same structure, in which HSC might not prove to be successful, but rather by comparing for a given usage, a structure designed for HSC and one for another alternative construction material. It is likely to be a very beneficial contribution of HSC to give birth to innovative designs (this comment was made several times by survey respondents).

Such strategy would push professionals to better realize the savings they could realize by using HSC, and a stress could be put on crucial non-perceived attributes such as durability "the major stake of HSC", according to P.C. Aitcin. The participation of early adopters and opinion leaders [3], if identified would be of importance.

10.3.2 Improving Durability Assessment

We argued earlier that there is a dramatic underuse of HSC durability, though it is of crucial economic importance. There is a need for a different approach in durability evaluation of concrete structures.

To exploit the potential increased durability of HSC, research is needed on the mechanisms of concrete degradation., relationships among composition and microstructure and durability of concrete, and the effects on the environment on durability. This knowledge should be used to develop a Durability Design Code. This code could be used to give adequate consideration to concrete design, since the costs of maintenance or a curtailed life could often be large enough to justify initial expenditures in a more performant, more durable material.

As a matter of fact, maintenance costs should be assessed at construction time along with the costs of the original construction, being discounted to the present at the appropriate rate. Even if the evaluation of maintenance costs, overall durability, and especially discount rates is extremely difficult, the issue should not be ignored. And if the present value of increased costs of maintenance and repair or costs of premature replacement attributable to insufficient durability in the concrete exceeds the costs of increasing the durability, then it pays to invest more up front to enhance the durability of the concrete and avoid larger costs later. Methodologies for predicting

[3]Opinion leaders are members of the construction industry able to influence other members'attitudes [Rog83]

the service life of concrete are at a very low development stage, and they need to be developed and diffused largely so that they can be used to aid the design and financing of concrete structures.

10.3.3 Product Approval System

This idea was suggested by Nicholas J. Carino and James R Clifton [CC91]. Innovation, they thought, is hindered when standards do not exist for new products because potential users often view with skepticism data produced by manufacturers of materials for HSC. They proposed that a system to certify that new materials and products meet the relevant standards be established. Innovation, they thought, is hindered when standards do not exist for new products because potential users often view with skepticism data produced by manufacturers of materials for HSC.

10.4 Education

10.4.1 Education at Universities

Cooperation Research-Industry

The role of a leading university or research group must change, especially when today's overload of information on HSC is flooding the screening capability of most users. As a result, these groups must begin preparing strategies for the future. Many have long believed that writting technical papers was the only way of transferring technology. Recently, however, some have begun to understand that progress is much more rapid if a leading research group is working together with the industry : the research is carried out simultaneously on two fronts, at the frontiers of science and within the nexus of practical problems faced by the industry. Only such a coordinated group is capable of introducing technological change to a sector as conservative as the construction industry [CC90].

Academic Educational Programs

At present, civil engineering students entering the workplace have insufficient knowledge of concrete technology, whereas the use of HSC requires a higher level of knowledge of concrete technology than the use of conventional concrete. Change agencies should target educational programs to spread the knowledge on HSC, either by informing teaching staff or by providing lectures. The issue is to provide construction students with up to date knowledge on HSC, so that the new concepts are understood, possible practice known, and ready to be put to beneficial use.

10.4.2 In-Service Education

The industry is doing little to use the findings available in HSC field. It must be said that little formal in-service education exists. Knowledge has often to be gained through informal contacts, or by self study from books or other publications. Continuing education programs should be an effective way to overcome this problem. Many barriers would have to be surmounted to implement such programs. These obstacles were described by Clarkson H. Oglesby [Ogl90] and are the followings. Firstly, the industry is highly fragmented, interests are dispersed among many specific problem areas. It becomes difficult for the management, which is driven by many demands on its time and energy, to learn about, see the need for, or release personal to attend in-service programs that fit their needs. Secondly, there is a failure on the part of buyers and contractors alike to appreciate the demonstrated pay-offs that in service education can bring. In contrast, Japanese contractors, who recognize its value, have strong in-house training centers for their employees. Thirdly, management has a high level of confidence on its ability to do the job properly using known methods and techniques. Neither is it threatened by new approaches, since competitors seldom know of them either. and finally, as mentionned earlier, a short-term, profit oriented approach to expenditures, which looks for an early pay off than long range benefits does not play in favor of in service courses which, according to usual management opinion do not meet this criterion.

Chapter 11

Summary and Conclusion

This research has analyzed the current trends of HSC diffusion in the construction industry and proposed an evaluation of its different aspects related to its rate of adoption. Organizational, technological and economic factors were studied through seven steps to explain slow adoption.

The generation of the innovation itself was studied in chapter 3, and it was found that on the one hand its software component came from formal R&D program for its software aspect without enough concern about users needs, and therefore few applications were available for potential adopters, which is a typical drawback of technology push innovation processes, but on the other hand, users themselves had to carry out extensive applied research programs to have HSC fit their needs. There was a low level of compatibility with market needs, and more attention should be paid to users feed back.

Though all important in this technology push innovation process, the transfer of information is not effective between R&D and professionals in the construction industry who complain about the lack of relevant data they suffer from. Combined with some organizational barriers, such as the lack of gatekeepers in the industry and the fact that professionals usually do not seek information as much as they should, those factors explain that beside a good "awareness knowledge" of HSC, the industry needs more "how-to" and "principles" knowledge in order to be fully aware of what is achievable and what is not.

It is clear that the main expectation of professionals from the use of HSC is an increased profitability. It has been pointed out that they are not fully aware of the potential economic advantages of HSC. It has been showed through various examples, two of which are restated here.

Firstly, one of the most important attributes of HSC, improved durability, is underestimated because high quality construction, prevention and maintenance are not well integrated in the construction process, and because potential users seek above all immediate rewards. However, the increased durability of HSC is a "multibillion dollar opportunity" [oCDNO87].

Secondly, the full economic advantages provided by the use of HSC cannot be reached if designers keep on copying previously existing designs. At the birth of prestressed concrete the design of bridges evolved from masonry like bridges to modern girders; a new innovative type of design has to be found to use HSC attributes.

However, this development is not easy, since codes represent a serious deterent to innovation. Positive aspects of codes have been pointed out, such as the safe regulations they represent, and the extensive research programs on specific problems they lead to. But they also retard the introduction of new products and construction methods, and this entails added cost of construction and inefficiency. Two different "innovative" approaches have been proposed, through performance codes, that the European Community is attempting to work out, or through a close and early collaboration with code officials.

Therefore a need for more centralized and formal diffusion system was felt in many countries, and programs organized by what were called "change agencies" have been developed (chapter 8). Their objective is to improve vertical communication, in both ways (researchers forwarding their findings to the industry which provides

R&D institutions with an all important feed back), and to develop users' awareness of some crucial attributes of HSC (particularly durability).

It appeared through this study that a better diffusion of HSC is not only the responsibility of a specific group of individuals, but rather should result from a global effort of the different sectors involved in concrete constructions. In fact, a whole set of new attitudes and skills are required, including a will of integration by both researchers and construction professionals, leading to a better vertical communication, more agressive and innovative state of mind when problems are to be solved (and this could be achieved through better coordination, early contacts with code officials, or involvement of owners in the project, a will to propose and implement new ideas), and more research on innovation and product innovation in the construction industry.

Finally, several actions were proposed in the previous chapter to speed up HSC diffusion. The need for a centralized change agency appeared clearly, and its role should consist in organizing interdisciplinary symposium, foster continuing education lectures and perform full scale trials which would be considered and showed as effective trials, and experimentation to further revise codes. There is however a need to identify who are, if any, the opinion leaders in this field, so that change agencies could in a first step concentrate their efforts on this type of potential users, and then use them to diffuse HSC. These organizations should develop educational programs for students. At last, it has been proposed that the savings that durability can provide be extensively taken into account in construction finance.

Given its outstanding performances, it is likely that HSC will be used more widely in the near future, especially for compressive strength in the range from 8,000 to 10,000 psi which does not necessarily require mineral admixtures. The main factor leading to its wider use will probably be durability, of which professionals will little by little realize the importance. However, even if my conclusive statement is optimistic for HSC use, this research pointed out that the diffusion process is very slow, due to the structure of the construction industry and the mentality that prevails (risk adversity, conservatism), and that strategies to speed up diffusion could and should be implemented. This thesis proposed an analysis of factors playing a role in HSC diffusion, as well as proposals to attempt to overcome major hindrances.

Part V

Appendix and Bibliography

Appendix

Questionnaire mailed to 200 designers in the U.S..

In this questionnaire, high strength concrete means "a concrete with a compressive strength greater than or equal to 8,000 psi. When you are asked to grade, please use a scale from 1 (very low) to 10 (very high). Feel free to make any written comments.

QUESTION 1

Below are listed factors enabling a firm to implement the innovation of HSC. Please grade them by importance.

	Average grade	Standard deviation
- The company is large and therefore able to deal with risks.	3	2.4
- Organizational flexibility.	3.9	2.9
- The company is small and the decision making process is easy.	3.3	3.0
- Expertise and personality of key individuals.	7.1	3.0
- Innovative state of mind within the company.	6.4	3.3
- Intense communication within the company	4.4	2.9
- Communication with other sectors of the industry.	6.9	2.7
- Communication with colleagues in the same sector.	5.6	2.7
- Coordination among the participants in the project.	6.7	2.9
- An opportunity for an actual job.	6.9	3.5

Remarks

- A realistic need for HSC.
- Client acceptance.
- Economically justified.
- Flexibility of specifier.
- Local codes prevent use of HSC.
- Willing client who understands risks.
- Limited, not for high volume business.

QUESTION 2

Grade the risks involved in the use of HSC.

	Average grade	Standard deviation
- Difficult supply of materials	4.5	3
- Cost and duration of pretesting	4.5	3
- Constraints of quality control	5.4	3.4
- Uncertainty of long term behavior	4.9	2.5
- Lack of provisions in current codes	5.6	3.3
- Difficult placing	4.2	2.6

Remarks

- Premium cost of risk must be justified.
- Risks can be avoided if a good plan is prepared.

QUESTION 3

Have you heard of unsuccessful HSC projects.

- No 82%
- Yes 18%

Reasons for failures

- Finishing problems.
- Cost overruns.
- Concrete requirements not met.
- Creep in early construction phases.

QUESTION 4

In your opinion, what consequences (positive or negative) will greater use of high strength concrete likely have in the construction industry and in parallel industries.

	% of citation
- Improvements in the cement industry.	63%
- Specialization of concrete suppliers for HSC.	72%
- Specialization of designers for HSC.	51%
- Specialization of contractors for HSC.	54%

Remarks

- Better understanding of all kind of concretes.
- More durable structures.
- New uses for concretes.
- Improvement in performance of commercial testing organizations.
- More innovative design.

QUESTION 5

Where do you usually seek new ideas or advice.

	% of citation
- Internally (colleagues in your own company	82%
- Externally (colleagues in other companies)	79%
- Consultants	45%
- Publications	88%

Remarks

- Industry representatives.

- Seminar, conferences.
- Continuing education lectures.
- Product manufacturers.

QUESTION 6

Does your company have an R&D department

No 82%

Yes 18%

QUESTION 7

Is your company involved in any basic research program with a university or any organization.

No 82%

Yes 18%

QUESTION 8

Have you heard of organizations or programs promoting the use of HSC.

No 39%

Yes 61%

Name of the programs and organizations

- PCA, ACI,

QUESTION 9

Have you ever been involved in a project which made use of HSC.

No 68%

Yes 32%

Questions for companies with experience in a HSC project. The following questions focus on this particular experience.

QUESTION 10a

Type of construction

Building	73%
Bridge	9%
other	18%

QUESTION 11a

Concrete strength

- 8,000 - 13,000 psi	82%
- 13,000 18,000 psi	9%
- > 18,000 psi	9%

QUESTION 12a

Estimated cost of the HSC used

- < $ 80 per cu yd	11%
- $ 80 - 100	56%
- $ 100 - 120	33%
- $ 120 - 140	0%
- > 140	0%

QUESTION 13a

What was the profile of the owner

	% of citation
- Willing to invest more at the beginning of the project for applied research and testing.	0%
- Open to innovative methods.	70%
- Seeking short-term rewards (lower cost of construction).	90%
- Seeking long-term rewards (durability of the structure).	40%
- Technically expert.	10%

QUESTION 14a

What was the problem HSC had to solve.

	% of citation
- Porosity	18%
- Load	82%
- Durability	27%
- Space saving	72%

QUESTION 15a

Grade the following factors in the project

	Average grade	Standard deviation
- Owner's commitment to the project.	4.5	3
- Structural designer tendency toward innovation.	5.4	3.8
- Concrete supplier's progressive developmental efforts.	5.3	3.6
- Contractor's expertise.	4.0	3.2
- Interactions between those key players to overcome the inherent uncertainty of the innovation.	4.1	3.6

QUESTION 16a

Was the use of HSC successful in this project

No 0%

Yes 100%

QUESTION 17a

Your opinion toward HSC before the project was :

	% of citation
- Rather skeptical	0%
- Rather indifferent	30%
- Rather enthusiastic	70%

QUESTION 18a

Your opinion toward HSC after the project was :

	% of citation
- Rather skeptical	0%
- Rather indifferent	0%
- Rather enthusiastic	100%

QUESTION 19a

Do you feel your experience now represents a competitive advantage.

No	43%
Yes	57%

Questions for companies with no experience in HSC projects.

QUESTION 10b

What has prevented you from using HSC

	% of citation
- Lack of technical expertise.	20%
- Your company is willing to stay with traditional construction methods.	20%
- The size of your company does not allow it to take the risks of an innovative method.	20%
- You have not had an opportunity.	85%

Remarks

- No need, no opportunities.
- Must be economical.
- Confidence in adequate quality control in construction.
- Unaware and uncertain of availabilities and applications.
- When clients are public agencies, their specification have to be followed, which do not necessarily include HSC.

QUESTION 11b

What would push you to use HSC

	% of citation
- Up to date codes.	70%
- More technical information.	60%
- Expert partners in the project.	50%
- Expert individuals in your company.	70%
- Support by industry and professional organization.	70%

Remarks

- Project need, opportunity.
- Cost advantage.
- Client interest.

QUESTION 12b

What kind of rewards would you expect from the use of HSC.

- Innovative design
- Publicity, opportunity for other projects and profit.
- Gains in experience.
- Reduced cost of construction.
- Client satisfaction.
- More efficient structures.
- Durability.

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