TRENDS AND CHALLENGES IN CONCRETE TECHNOLOGY

by Odd E. Gjørv, The Norwegian Institute of Technology, NTH, Norway

SUMMARY

Over recent years a rapid development in the field of concrete technology has taken place. Increasing construction challenges in combination with new innovations in materials and production techniques have provided a new basis for producing high-performance concrete structures and concrete products. Thus, based on natural mineral aggregate it is now possible to produce concrete with compressive strengths of up to 230 MPa. If the natural mineral aggregate is replaced by high-quality ceramic aggregate, compressive strengths of up to 500 MPa can be achieved. Even with lightweight aggregate, compressive strengths of more than 110 MPa with densities of less than 1800 kg/m^3 can be produced. In combination with high molding pressure and hot curing, special concrete materials with compressive strengths of up to 800 MPa have been obtained. Also over recent years, however, many relatively new concrete structures and industrial products have shown a poor performance. It is a great challenge, therefore, both to utilize and apply and also further develop existing technology on high-performance concrete to the benefit of both the concrete industry and the society.

INTRODUCTION

The new and rapid development in the field of concrete technology has strengthened the stature of concrete as a major construction material. Having been an empirical technology in a typical craft type of industry, concrete technology has already entered into a high-technology profession, with a potential for utilization far beyond the traditional construction industry.

In Norway the development over the last 20 years has been characterized by two special features:

(1) The rapid development in oil and gas explorations on the Norwegian continental shelf.

(2) The introduction of strict environmental requirements to the Norwegian ferrosilicon alloying industry which has resulted in large amou nts of condensed silica fume.

The first feature has obviously given the most dominating results with m ore than 20 large offshore concrete platforms operating in the North Sea, most of which have been produced in Norway. The term "Condeep" has almost been an international notation for gravity-based offshore concrete platforms. The biggest one which is currently under construction in Stavanger in Southern Norway, will be located in a water depth of more than 300 m and will be taller than Empire State Building when completed in 1995 (Fig. 1).

Since Norway was one of the first countries which introduced strict environmental control to its extensive ferrosilicon alloying industry (Fig. 2), Norway also became one of the first countries which got the challenge of finding proper ways for handling and utilization of large amounts of condensed silica fume. At an early stage of research it soon became clear that this industrial by-product was a highly valuable resource which provided a basis for the development of a completely new generation of cementitious materials. Today condensed silica fume has become so valuable that one of the Norwegian ferrosilicon alloying plants at the time being is primarily operated in order to produce silica fume rather than alloying materials.

As a result of the above two features a rapid development and utilization of high-strength concrete, e.g. more than 65 MPa, has taken place in Norway[1]. According to the current Norwegian Concrete Code[2] an upper grade limit of 105 MPa for a structural utilization of concrete is permitted.

HIGH-STRENGTH CONCRETE

General

The traditional approach to the production of high-strength concrete has been to reduce the porosity of the cement paste (Fig. 3). During recent years, however, more attention to the concrete as a three-phase composite has been given, where the important role of the cement paste - aggregate transition phase is emphasized. At the same time it has become more clear that it is the aggregate which is the limiting factor for obtaining high compressive strength.

Thus, for high-quality natural mineral aggregate, compressive strengths of up to 230 MPa have been obtained[4]. If the natural mineral aggregate is replaced by high-quality ceramic aggregate, compressive strengths of up to approximately 500 MPa can be achieved[5]. Even with lightweight aggregate, compressive strengths of more than 110 MPa with densities of less than 1800 kg/m^3 have been produced[4].

Normal weight concrete

In Norway the structural utilization of high-strength concrete has mostly been limited to the production of offshore concrete platforms. Thus, from the first platform produced for the North Sea operations in 1973 ("The Ekofisk Tank") to the Troll Platform currently under construction (1994), the specified concrete grade has steadily increased from 45 to 75 MPa. In North America high-strength concrete is primarily being used in tall-rise buildings, where up to 130 MPa has been used in the columns[6].

Since high-strength concrete is characterized by a low porosity and a more uniform microstructure compared to that of normal-strength concrete, "high-strength concrete" is very much equivalent to "high-durability concrete" or "high-performance concrete". Therefore, it is not necessarily the improved compressive strength which represents the

greatest potential for utilization but rather the improved overall performance. In particular, it appears to be a great potential for utilization of high-strength concrete in aggressive environments or where high abrasion resistance is needed.

In the Scandinavian countries a severe mechanical abrasion on highway pavements and bridge decks is due to the use of studded tires. This type of abrasion has been studied under controlled laboratory conditions, where an accelerated load facility for full-scale testing of abrasion resistance of highway concrete pavements exposed to heavy traffic by studded tires was built in 1985 (Fig. 4). Fig. 5 presents some data from that test facility. By increasing the concrete strength from 50 up to 100 MPa the abrasion of the concrete was reduced by roughly 50%. At 150 MPa the abrasion of the concrete was reduced to the same low level as that of high-quality massive granite. Compared to an Ab 16t type of asphalt for a typical Norwegian highway traffic, this represents an increased service life of the highway pavement by a factor of approximately 10.

In the Scandinavian countries where studded tires are extensively used, even high quality asphalt pavements may have a service life of only two to three years or less. Encouraged by the above test results several high-strength concrete pavements have been completed over recent years.

Also non-pavement surfaces such as concrete floors, sidewalks, stairs, etc. may be exposed to the wear by vehicular traffic and the skidding, scraping or sliding of objects on the surface. In some types of industrial operations, the use of steel wheel vehicles, forks, buckets or lift trucks and loaders may also inflict severe damage to the concrete surface.

Lightweight concrete

In the Norwegian Concrete Code[2] structural utilization of high-strength lightweight concrete is permitted up to a grade limit of 85 MPa. So far, lightweight concrete with compressive strengths in the range of 55 to 65 MPa has recently been used i four Norwegian bridges, two of which are floating bridges, and one floating offshore concrete platform. For some of the platforms currently under construction the high-strength normal weight concrete has also partly been modified by incorporating smaller amounts of high-strength lightweight aggregate. It should be a great potential also for utilization of high-strength lightweight concrete in the precast concrete element industry.

Special concrete materials

By optimalization of constituent materials, mix design and mixing procedure it is possible to produce a whole range of special concrete materials for more advanced applications. Such materials may have compressive strengths of 140-460 MPa, flexural strengths of 20-70 MPa, and a modules of elasticity of 50-100 GPa. At the same time it may be resistant to temperatures of up to 1000^0C[5,8]. By incorporating small steel fibers into the mixture, a very high fracture toughness and fracture energy may also be obtained.

While the above materials can easily be mixed, cast and vibrated more or less in the same way as conventional concretes, more sophisticated production techniques can further improve the final properties. Thus, by combinations of high molding pressure and hot

curing, compressive strengths of up to 800 MPa have been obtained[9].

CONCRETE PRODUCTION

Constituent materials

In the selection of cements for high-strength concrete both the chemical and mineral composition as well as the particle size distribution of the cement are important factors to be considered.

In addition to the strength development, the type of cement is also important for the water requirement and workability of the mix, for which it is primarily the C_3A content and the particle size distribution which are the main controlling factors[10]. The gypsum/hemihydrate ratio and the compatability with chemical admixtures are also important for the fresh concrete workability[11].

Although fly ash also contributes both to strength and improved workability, silica fume is a much more efficient pozzolanic material[12]. In addition, silica fume represents a valuable range of very fine particles which fill out the voids inbetween the larger cement particles. Thus, for most binder combinations, the use of silica fume is reported to provide the only way of producing concrete with compressive strengths of more than 80 MPa[13].

In order to sufficiently disperse all finer particles and reduce the water content of the concrete mixture while still maintaining an acceptable workability, high-range water-reducing admixtures (superplasticizers) have to be used. In addition, set-retarding and air-entraining admixtures may also be needed.

A special problem for many superplasticizers is the rapid loss of concrete workability taking place; in particular for the combination of high C_3A containing cements and high sulfate containing superplasticizers. New superplasticizers are now becoming available, however, which are less sensitive to loss of workability[14].

Since the aggregate makes up the biggest part of the concrete volume, it is not surprising that the aggregate quality generally is of considerable importance to the concrete properties. For high-strength concrete, however, experience has shown that the quality of the aggregate is one of the main limiting factors both for obtaining good workability and high strength. In particular the homogeneity of the aggregate is important for an optimalization of the concrete mixture.

Workability and placing

For high-strength concrete, the very low w/c ratios, silica fume and superplasticizers all affect the fresh concrete properties in such a way that neither the "static" nor the "dynamic" behavior can be compared to that of normal-strength concrete. Therefore, the conventional test methods such as slump or flow table do not predict the response to

compaction in the usual way. These conventional test methods are still valid for giving an indication of whether the workability is plastic, heavy plastic or fluid, but they do not provide any information about the flow properties of the concrete. Thus, concrete with varying contents of silica fume and superplasticizers may have the same slump but very different flow properties. Therefore, a more basic approach to the testing and characterization of the workability for high-strength concrete is needed.

In the testing of the fresh concrete workability by use of a viscometer[15], the concrete normally behaves like a Bingham liquid[16] as shown in Fig. 6, where:

$$\text{Torque} = \tau_0 + \mu \cdot \text{Rotation speed} \qquad (1)$$

By measuring the torque and the rotation speed at various speed levels, the values of τ_0 and μ can be determined. These parameters define the workability of the fresh concrete, where:

τ_0 which is the "yield strength" or "flow resistance", is a measure of the force necessary to start a movement of the concrete.

μ which is the "plastic viscosity", is a measure of the resistance of the concrete against an increased speed of movement.

By using these two workability parameters it is possible to provide a more general and basic characterization of the fresh concrete behavior. If the reference point in a τ_0 - μ diagram is moved in various directions as shown in Fig. 7, it indicates that the mixture either becomes more wet, stiff or viscous. Various combinations of yield strength and viscosity can be obtained through proper mix design adapted to particular construction procedures or production techniques.

While the above workability parameters only can be used for characterization of flowable concrete, a different approach is necessary for characterizing the compactability of non-flowable concrete. Also for the testing of non-flowable concrete proper test methods exist, the principle for one of which is shown in Fig. 9.

Quality assurance and quality control

In most codes and job specifications, the requirements to the concrete quality are almost exclusively based on concrete composition, properties and composition of concrete constituents, casting and compaction procedures as well as curing conditions, and still the compressive strength is the most commonly used quality parameter. For several reasons, this approach has frequently shown to yield insufficient and unsatisfactory results.

In order to ensure proper performance more relevant quality parameters have to be applied, which can provide a better basis both for job specification and control of final quality. For this purpose a number of different test methods are available[19]. Also, it is important that the testing are carried out on the real concrete structures and the concrete products or on test specimens which are as identical as possible to the final

product in question.

CONCLUDING REMARKS

Since the early 1970-ties a rapid development in the field of concrete technology has taken place. Increasing construction challenges in combination with new innovations in materials and production techniques have provided a new basis for producing high-performance concrete[20]. After more than 20 years in service, a number of offshore concrete platforms exposed to the most harsh and aggressive environment in the North Sea are still demonstrating an excellent performance[21]. It is very frustrating, therefore, that so many conventional concrete structures on shore show such a poor performance. In Norway, a number of relatively new major concrete bridges and concrete buildings have shown severe distress after a period of only 15 to 20 years and some already after 10 to 12 years of service[21]. Also, a recent field survey of concrete pipes in the Norwegian public sewer system revealed that more than 10% of the 22000 km total concrete sewer network was in such a poor condition that it needs replacement, a long time before expected service life[22].

Over recent years much professional improvement has taken place in the concrete industry. The above problem indicates, however, that more efforts on education and training as well as more spending on industrial research and development still represent a great challenge to the concrete industry.

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Division of Building Materials, The Norwegian Institute of Technology, NTH, N-7034 Trondheim, Norway, Fax. no. 47-73594551.

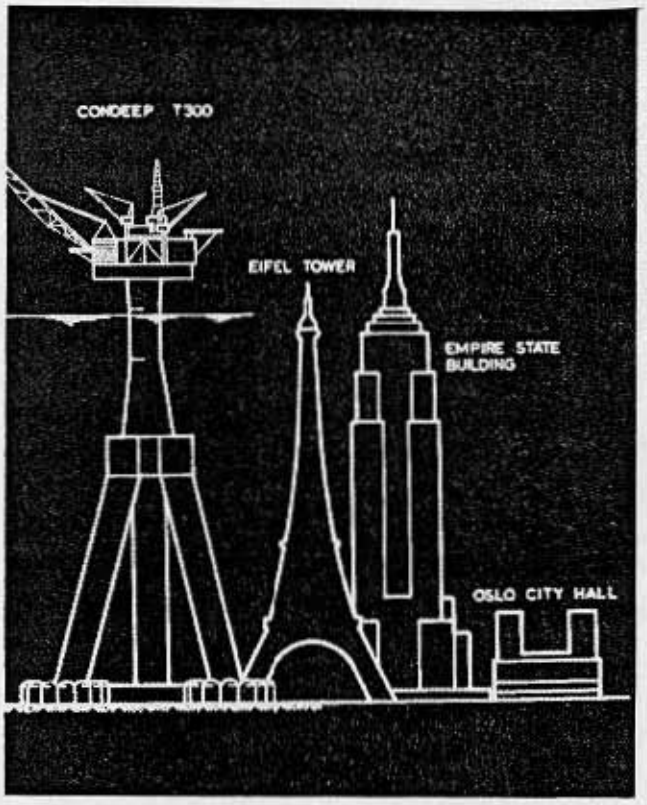


Fig. 1. The offshore concrete platform currently under construction for the Troll field in the North Sea.

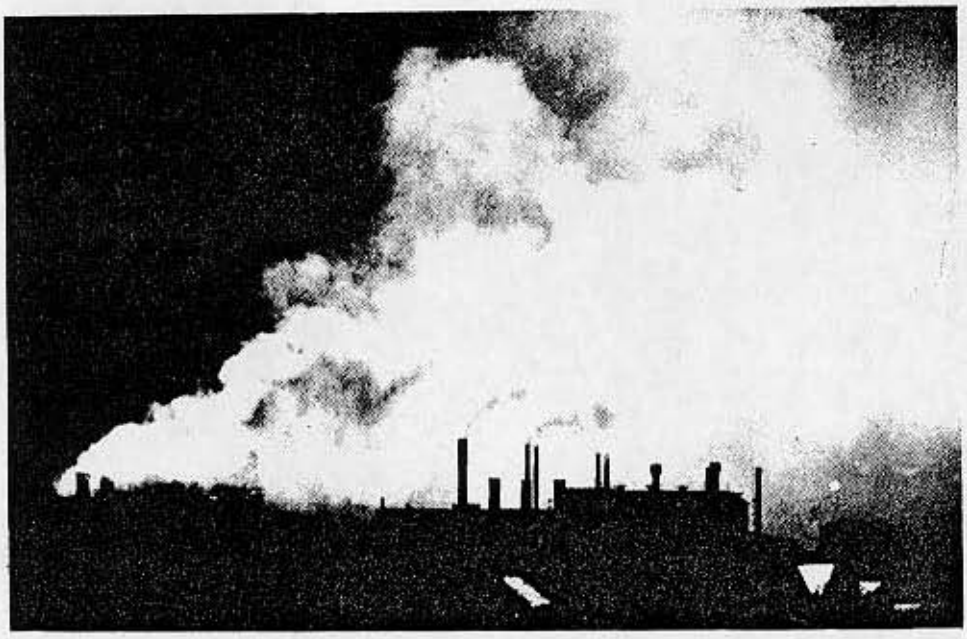


Fig. 2. Until the mid 1970-ties large amounts of smoke was a seve re pollution from Norwegian forrosilicon alloying plants.

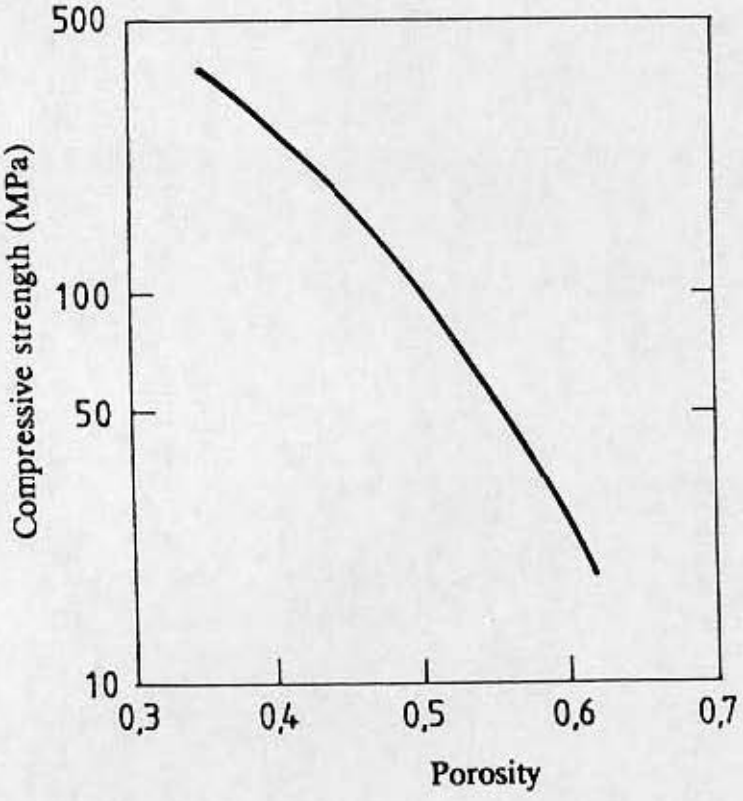


Fig. 3. Effect of porosity on compressive strength of cement paste[3].

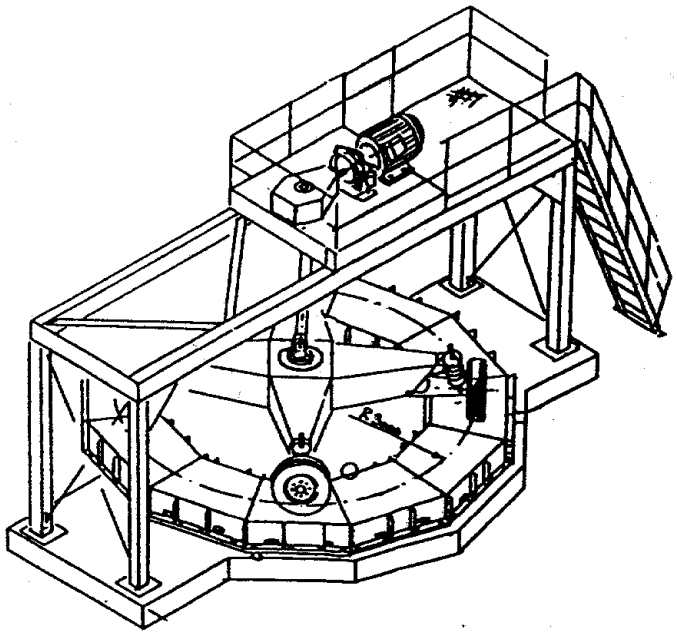


Fig. 4. Accelerated load facility for testing the abrasion resistance of highway pavements exposed to studded tires[7].

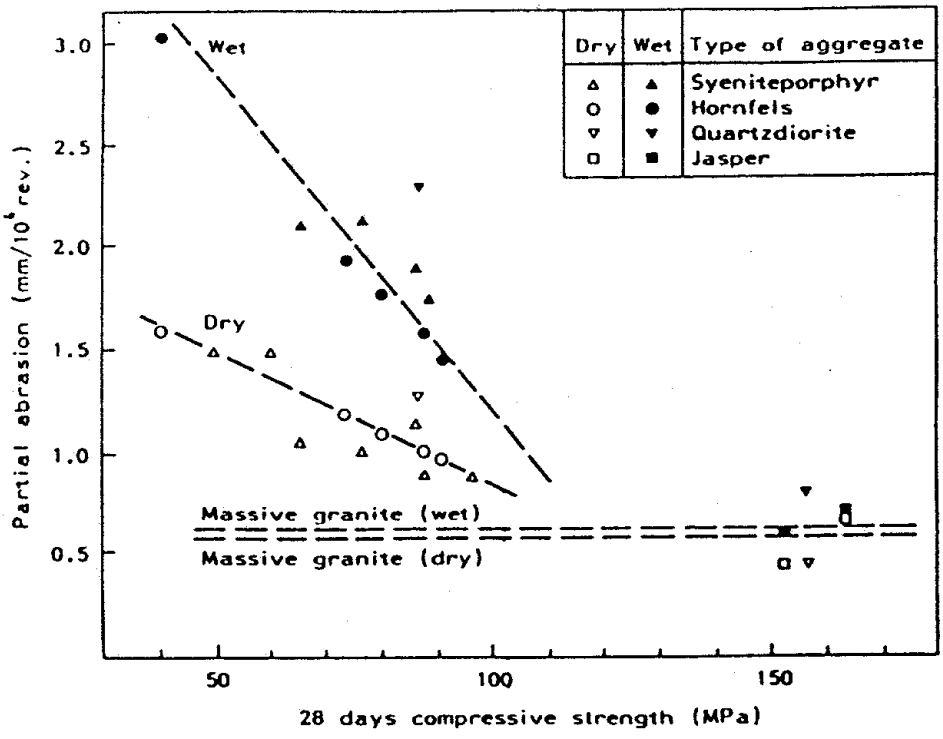


Fig. 5. Relationship between abrasion resistance and compressive strength[7].

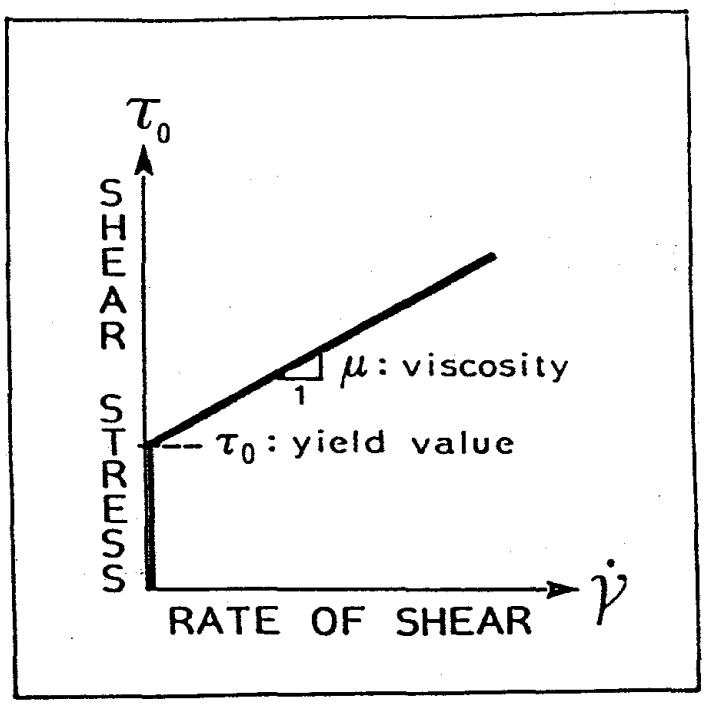


Fig. 6. Bingham behavior.

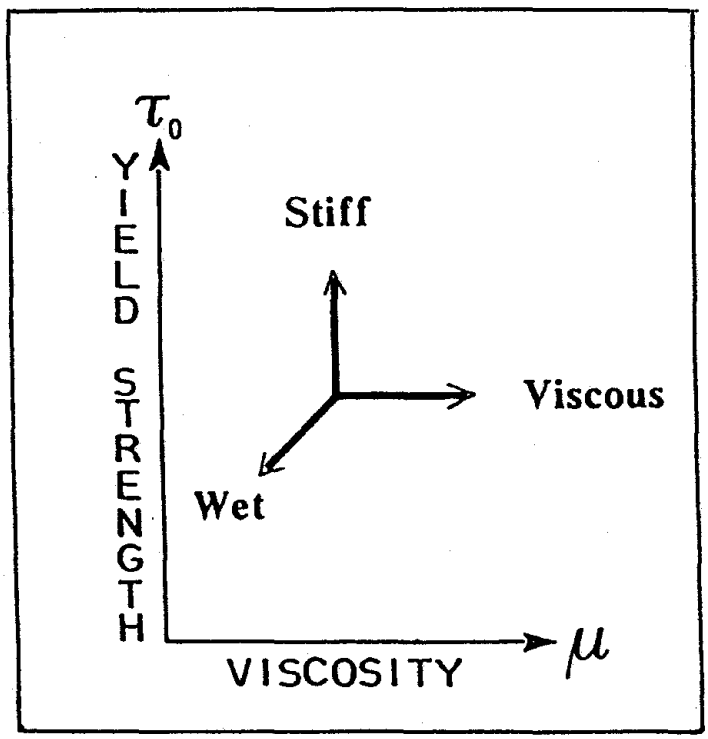
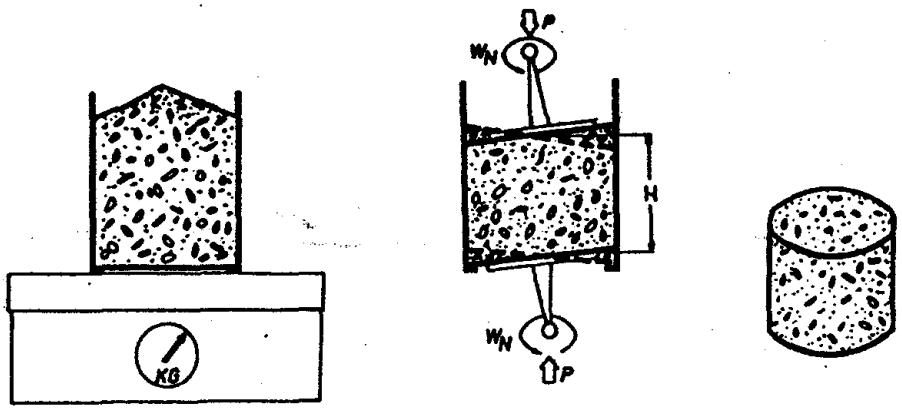


Fig. 7. Qualitative significance of yield strength and viscosity[17].



a) Weighing of the concrete sample in the work cylinder.

b) Compaction of the concrete sample between the cylinder plates.

c) Compacted sample

Fig. 8. Prinsicple for intensive compaction testing[18].