Another slightly different method has been recently developed in Scandinavia [21]. This procedure, called the RA method, intends to measure the workability of the fresh concrete and can be used to continually control the production of RCC. As for the modified VEBE method, it consists in placing a certain mass of concrete into a cylindrical mold fixed on a vibrating table (see Figure 3). Then, a (13.3 kg) mass is lifted into place and the concrete is vibrated for 20 seconds. The difference between the initial position of the weight and the position obtained after the compaction serves to characterize the workability of the RCC mixture. Measurements can then be compared to previous laboratory results.

The ACI Mixture Proportioning Methods

In a survey of existing empirical methods specifically developed to proportion RCC mixtures, the ACI Committee 207 has divided the various procedures into three categories [22]:

- methods for proportioning RCC to meet specified limits of workability;
- methods for selecting mixture proportions to achieve the most economical aggregate-binder combination;
- methods for designing RCC using soil compaction concepts.

In the methods falling in the first category, where RCC mixtures are proportioned to meet a specified consistency, the mixture characteristics are generally determined according to the following three-step procedure. To determine the minimum paste volume, a first series of trial mortar mixtures of various water/binder and sand/cement ratios is prepared and cast. In each case, the density of the mixture is measured. As can be seen in Figure 4, for a fixed water/binder ratio, there is a certain sand/binder ratio that gives an optimum mixture density [23]. The water/binder ratio is selected to meet the required mechanical strength. Once water/binder and sand/cement ratios are determined, the coarse and fine aggregate proportions are adjusted to achieve a certain workability (VEBE time). This method is very similar to the one developed by TALBOT and RICHARDS in the early 1920s to design conventional concrete mixtures [23]. The main difference lies in the fact that the ACI method relies on the combined use of vibration and compaction to consolidate the concrete mixture. Although the ACI procedure was mainly developed for proportioning mixtures for dam construction, it can be used to design mixtures for pavements applications [24, 25].

RCC mixtures can also be proportioned on the basis of cost [22]. In this second approach, designers rely mainly on suggested gradation curves, such as that shown in Figure 5, to determine the fine to coarse aggregate proportion. Then several trial mixtures with various binder contents are prepared and cast. In each case, the water content is adjusted to meet the workability requirements. Compressive strength measurements are made, and the most economical combination of cementitious materials and aggregates that provide the specified strength is selected. This procedure, mostly established for the design of dams, is rarely used to proportion RCC pavements.

Finally, RCC mixtures are often proportioned using traditional soil compaction procedures. This method is believed to be more appropriate for RCC pavement mixtures where smaller aggregates and higher binder contents are used [22]. Usually, the fine to coarse aggregate proportions are fixed according to suggested gradation curves similar to that shown in Figure 5 [26]. Then, a series of concrete mixtures with various binder contents is prepared. The cementitious materials content may vary from 12 to 14% of the total mass of dry materials. For each series (i.e., for a fixed binder content), mixtures are prepared with different water contents. The optimum water content for each series is established by following the method described in ASTM D 1557 - Method D. It involves determining the moisture content corresponding to the maximum "dry density" of the mixture using a Modified Proctor compaction procedures. Each mixture is compacted in a cylindrical mold with a specified energy. The mass of the compacted volume is measured and the corresponding dry density is calculated. The peak of the density curve, as shown in Figure 6, indicates the maximum calculated dry density and the optimum moisture content. Usually, the wet density changes very little in the range of this peak even though the calculated dry density is more significantly affected [22]. Compressive strength measurements are made on mixtures at optimum water content. The mixture with the minimum binder content that meets the specified strength is selected.

The most popular of these three methods is the first one, which has proven to give good results in practice [22-24]. This method is generally believed to yield mixtures with optimum proportions (i.e., with the minimum binder content with respect to the given requirements). The mixture characteristics derived from the two other methods can be, in certain cases, far from the optimum proportions. The last two methods rely on tabulated grading curves to adjust the aggregate proportions of the mixture. These curves are averaged values derived from a large number of experiments made using various types of aggregates. Recent studies have clearly shown that fine/coarse aggregate ratios determined on the basis of these tabulated grading curves do not yield the optimum packing density [25, 27]. An inappropriate fine/coarse aggregate ratio can, in certain cases, contribute to artificially increase the binder content of the mixture. This is particularly the case for RCC mixtures designed for pavement applications for which the mechanical strength requirements often prompt the concrete producer to use larger binder contents to achieve the specified values.

The main drawback of these empirical methods is that they are time consuming. All three procedures solely rely on making laboratory trial batches to determine the optimum mixture. In some cases, as much as 25 trial batches are required to obtain one mixture design in the laboratory. In many cases, additional trial batches are required on site to adjust the workability of the mixture [18-21]. The mixing energy provided by a plant concrete mixer and pugmill mixer is generally much different from that of a laboratory pan-mixer, and that tends to affect the initial workability of the mixture. Furthermore, the entire mixture design process may have to be repeated if, for one reason or another, the source of aggregates (fine or coarse) or the type of binder is changed during the course of the project.

The US Army Corps of Engineers Proportioning Method

The US Army Corps of Engineers method can be used to proportion RCC for dams or other types of massive structures [28, 29]. The method is basically a step by step process that helps setting some mixture design parameters (water/cementitious material ratio (W/CM), binder content, aggregate grading, volumetric fractions of coarse and fine aggregates) in order to achieve any strength, workability or durability requirements. Suggested values for these design parameters come essentially from past experience and empirical relations.

The US Army Corps of Engineers method may be summarized as follows. The first step involves the selection of the aggregate proportions. Ideal grading curves for both coarse and fine aggregates are proposed. The fine to total aggregate ratio can be selected from tabulated values that are function of the nominal maximum size and type of coarse aggregate. The second step consists of selecting the water/binder ratio from durability and strength criteria. The selection of the water/binder ratio, to match the short and long term strength requirements, is based on empirical relationships. The next step consists in selecting the water content from suggested values that depend on the required modified VEBE time and on the maximum nominal size of the coarse aggregate. Finally, the total binder content is computed from the water content and the W/CM ratio.

According to the US Army Corps of Engineers guidelines, the mortar content must be within specified limits that depend on the nominal maximum size and type of the coarse aggregate. If necessary, the fine aggregate content can be adjusted to approach the recommended average value for mortar content. A minimum volumetric paste/mortar ratio of 0.42 is recommended for all types of RCC. If necessary, the volume of cementitious material, or the volume of filler material (less than 75 μm), or the volume of water, should be increased to achieve this minimum ratio.

Some trial batches are generally required to adjust the final mixture design to satisfy workability (VEBE time) and strength requirements. Adjustments of the paste volume are generally required to obtain the specified workability (VEBE time). Additional batches with lower and higher water/binder ratios may also be needed to select the final mixture proportions to satisfy the strength requirement.

The method can be considered as semi-empirical since it does not solely rely on the fabrication of trial batches to proportion the RCC mixture. The main drawback of the method is that it relies on tabulated grading curves to determine the fine/coarse aggregate ratio of the mixture. For the reasons mentioned above, the use of these empirical curves can contribute to yield inappropriate ratios.

Furthermore, the method can, in certain cases, be as time consuming as the fully empirical procedures since trial batches are always needed to adjust the workability. Workability is a key parameter controlling many important properties of RCC (compaction, strength, permeability, segregation, bonding between layers). Depending on the source of aggregates, the number of laboratory batches required to obtain the right workability can be quite important. Recent studies have clearly demonstrated that for a given paste volume the workability (VEBE time) is very sensitive to grading, shape and surface texture of the aggregates, particularly to the physical characteristics of the fine aggregate [30, 31]. According to the shape and surface texture of the sand, the VEBE time of a RCC mixture can be doubled.

The Optimal Paste Volume Method

The optimal paste volume method was developed to facilitate mixture design of RCC used for massive structures. Since workability of RCC is one of its key properties, this method puts emphasis on obtaining mixture proportions that closely match the specified workability.

The method is based on the assumption that an optimal RCC should have just enough paste to completely fill the inter-particle spaces remaining when the granular skeleton has reached its maximum density under compaction. If less paste is used, the voids remaining after compaction may reduce the mechanical properties and increase the permeability. On the other hand, excess paste increases the production costs and the heat generation, without any significant improvement in strength or impermeability.

The method includes three major steps. The first step is to select an aggregate grading that contains a minimal volume of voids under a given compaction energy. The volume of remaining voids per cubic meter of compacted aggregate is then used to determine the paste volume required to fill the voids and to obtain the specified workability. The next step consists of selecting the W/CM ratio and the proportions of cement and pozzolanic materials to produce a paste with enough binding capacity to satisfy the strength requirements.

Selection of an Ideal Grading

This step consists in selecting the proportions of the different size fractions of coarse and fine aggregates to produce a granular skeleton having a minimal amount of voids after compaction. The modified Fuller-Thompson formula can be used to obtain a grading curve that produces a compact skeleton [32]:

$$p = \left(\frac{d}{D}\right)^{0,45} \times 100 \qquad (1)$$

Where : d is the sieve opening (mm)
D is the maximum size of the aggregate (mm)
p is the proportion (%) of particles passing a sieve with an opening of d

Figure 7 shows typical modified Fuller-Thompson grading curves for different values of D. These curves generally give a compact granular skeleton when the particles are mostly made of natural sand and cubic shaped coarse aggregates [33, 34].

The Fuller-Thompson curves, gives only an approximation of the ideal grading, since the volume of voids after compaction is also dependent on shape, angularity, surface roughness and on the method used for compaction [30]. Natural rounded aggregates (smooth surface), or cubic shaped aggregates, gives a more compact skeleton, while highly angular aggregates containing large proportions of flat and/or elongated particles give a less compact skeleton. Changing the shape and surface roughness of the particles can produce relatively large compactness variations of the granular skeleton (more than 20%). The compactness of the granular skeleton is particularly sensitive to the shape and surface roughness of the fine aggregates (< 5 mm)[30, 31].

After selecting the proportions of the fine and coarse aggregates to approach the ideal grading, the next step consists of measuring the volume of voids in the compacted granular skeleton (*Vvc*). This volume (expressed as liters per m^3 of compacted aggregates) can be obtained by using a surcharge to compact a mix of aggregates in a cylindrical mold fixed on a vibrating table (the modified VEBE apparatus can be used). The volume of voids after compaction is computed from the final apparent volume of compacted aggregates and from the proportions and specific gravity of each type of aggregate.

Selection of the Paste Volume to Obtain the Required Workability

Numerous experimental results have shown that the workability of non-air-entrained RCC for massive structure (i.e., with low binder content) is essentially a function of the *Vp/Vvc* ratio where :

Vp is the paste volume in 1 m^3 of RCC (L/m^3)
Vvc is the volume of voids in 1 m^3 of the compacted granular skeleton (L/m^3)

For non-air-entrained RCC :

$$V_p = V_{water} + V_{cementitious\ materials} + V_{mineral\ filler} \qquad (2)$$

Figure 8 shows the experimental relationship between the workability of RCC (VEBE time) and the *Vp/Vvc* ratio for RCC with W/CM between 0.6 and 0.8. These results were obtained by three operators, with RCC made with different types of cementitious materials (cement, fly ash and slag), with or without mineral fillers (calcareous filler and mining by-product), with different types of grading curves (ideal and non-ideal grading) and different type of particles (rounded, cubic, flat and elongated). All these RCC mixtures have a water/cementitious materials ratio in the range of 0.6 to 0.8. [31, 34, 35].

Figure 8 can be used to determine the volumetric dosage of paste (L/m^3) required to obtain a specified workability. The general relationship indicates that a *Vp/Vvc* in the range of 0.95 to 1.05 is generally required to obtain a VEBE time of approximately 10 s to 25 s, whatever the water/cementitious materialratio, the type of cementitious materials, the type of filler, the grading curve or the shape and texture of particles used.

These results emphasize the importance of using a dense granular skeleton with a low *Vvc*. Lowering the *Vvc* of the granular skeleton significantly reduces the production costs by reducing the paste volume required to keep *Vp/Vvc* near 1.0.

The Effect of Air Entrainment on the Workability of RCC

As for conventional concrete, increasing the entrained air volume generally improve the workability of a RCC mixture (lower VEBE time) [34-37]. The mechanisms by which air entraining admixtures improve the workability of RCC are still not fully understood. Workability improvement may be caused by several factors such as:

- the fairly high number of small air voids increase the volume of the paste available to fill the inter-granular spaces of the granular skeleton and;
- the lower surface tension of the paste containing an air entraining admixture reduces the magnitude of the inter-granular forces and the amount of energy required for compaction.

With the optimal paste volume method, the effect of entrained air on workability is taken into account by assuming that air voids simply increase the paste volume in the RCC mixture. However, the method assumes that only a fraction of the measured air volume must be include in the effective paste volume (*Vp*). The entrained air volume is measured with the usual pressure air-meter placed on the VEBE vibrating table and compacted in two layers with a surcharge.

Figure 9 presents experimental results showing the effect of entrained air on the workability of RCC. The Figure shows that when all the measured air volume is included in the volume of paste (*Vp*), the experimental points corresponding to air-entrained RCC do not follow the general relationship obtained with non-air-entrained RCC. However, when *Vp* is computed by including all the entrained air volume less 2.6 % (or 26 L/m^3), all the experimental points approximately follow the usual relationship between the VEBE time and the *Vp/Vvc* ratio.

These results suggest that only the finer fraction of the total air entrained volume seems to effectively fill the voids of the granular skeleton. The larger entrained or entrapped voids are too big to fit between the particles of the granular skeleton. Their effect is probably to loosen the granular skeleton instead of filling the inter-granular spaces.

To illustrate how Figure 9 can be used to design an air-entrained RCC, consider the problem of determining the mixture to produce a 4% air-entrained RCC having a VEBE time of 15 s. The water/binder ratio (W/CM) must be 0,62 and the binder contains 50% cement and 50% fly ash by mass. The volume of voids in the compacted granular skeleton is 175 L/m^3.

From Figure 9, it is found that *Vp/Vvc* must be equal to 1.0 to obtain a VEBE time of approximately 15 seconds.

$$Vp = Vvc \times 1{,}0 = 175 \text{ L/m}^3$$

For air-entrained RCC :

$$Vp = V_{water} + V_{cement} + V_{flyash} + V_{air} - 26 \text{ L/m}^3 = 175 \text{ L/m}^3$$

From : $V_{air} = 40 \text{ L/m}^3$.

W/(cement+fly ash) = 0.62
Specific gravity of cement = 3.14
Specific gravity of fly ash = 2.64

We find :	$V_{cement} = 26.5\ L/m^3$,	Cement = 83.2 kg/m^3
	$V_{fly\ ash} = 31.5\ L/m^3$,	Fly ash = 83.2 kg/m^3
	$V_{water} = 103.0\ L/m^3$,	Water = 103 kg/m^3

The Effect of W/CM and Vp/Vvc on the Compressive Strength of RCC

After selecting the volumetric paste dosage to obtain the specified workability, the next step consists of selecting the water/cementitious material ratio (W/CM) and the type of cementitious materials to obtain the specified compressive strength. Roughly, lowering the W/CM ratio increases the compressive strength at all ages; increasing the proportion of fly ash decreases the short term strength but increases the long term strength. Trial batches should be used to determine the W/CM, the type and the amount of cementitious materials required to achieved the specified compressive strength. In some case, durability rather than strength governs the selection of W/CM.

The compressive strength of RCC for massive structure is also a function of *Vp/Vvc*. For a given W/CM, experimental results have shown that the compressive strength is generally maximized when *Vp/Vvc* is in the range of 0.95 to 1.0 (Figure 10). Outside this range, the compressive strength drops rapidly, particularly for values of *Vp/Vvc* lower than 0.90.

The results emphasize again the importance of carefully selecting the *Vp/Vvc* in RCC for massive structures. A *Vp/Vvc* higher than 1.0 increase the production costs, while slightly reducing the compressive strength. A *Vp/Vvc* lower than 0.95 may generate a significant drop of the compressive strength particularly for low W/CM.

The Solid Suspension Model

In recent years, the field of concrete mixture design has undergone rapid developments. One of the major breakthroughs in this field is the introduction of theoretical methods that permit the design of concrete with optimum packing densities [38]. One of the most promising methods is the one developed by de Larrard and his co-workers [39, 40]. This model is an improved version of a previous method which had been originally developed to design high-performance concrete mixtures [41]. The solid suspension model has recently been tested with success, in the laboratory, to design RCC mixtures for both dam and pavement applications [25, 27]. It has also been used to proportion high-performance mixtures that have served for the construction of full-scale RCC projects in Eastern Canada [20, 42].

Basically, the model can be used to predict the packing density of an arrangement of grains of various diameters d_i ($d_1 > d_2$ . ....> d_n) on the basis of:

- the intrinsic packing density (α_i) of each class of grains (i.e., the packing density of an arrangement of grains of similar diameter d_i);
- the mass proportion y_i of each class of grains (expressed as a ratio of the total solid volume).

The solid suspension model is derived from the work of Mooney on the viscosity of concentrated suspensions of solid particles [43]. The solid suspension model rests on the assumption that the reference relative viscosity (η_r*) of an arrangement of grains, consolidated by any type of technique, has a finite value. For an unimodal arrangement of grains of diameter d_i, the reference relative viscosity can be calculated using the following equation:

$$\eta_{r,i}^* = \exp\left(\frac{2,5}{\frac{1}{\alpha_i} - \frac{1}{\beta_i}}\right) \qquad (3)$$

where β_i stands for the intrinsic virtual packing density of the class of grains (i). It can be demonstrated theoritically that, if one was to place one by one a certain number of spherical grains, the packing density of this ideal arrangement would reach 0.74 (β_i = 0.74). However, such an arrangement is unachievable in practice. This is why β_i is termed the virtual packing density. It can also be showed that, in practice, the optimum packing density of spherical particles can hardly be higher than 0.64 (α_i = 0.64). If the values of β_i and α_i are placed in equation 3, it can be seen that the maximum relative viscosity (η_{ri}*) of a class of spherical particles is 136 000.

In practice, the actual values of α_i for each class of grains can be easily determined experimentally [39, 40]. For aggregate particles, this can simply be done by measuring the packing density of each size fraction using the VEBE apparatus. For powders such as cement, fly ash and mineral fillers, an experimental method has been devised to measure the value of α_i. This method consists in placing a certain amount of powder in a mortar mixer. While the powder is mixed, a certain amount of water is added to the mixture. The value of α_i is obtained when the amount of water is sufficient to pass from a dry cement to a plastic paste. Assuming that the maximum relative viscosity (η_{ri}*) is similar to that of an arrangement of spherical particles and is equal to 136 000, the value of β_i can be computed from equation 3 for each class of grains.

Once the values of β_i have been determined for each class of grains, the virtual packing density (γ) of the arrangement of grains can be obtained from the following relationship:

$$\gamma = \text{the lowest value of all } \gamma_i \quad y_i \neq 0 \qquad (4)$$

and the value of each γ_i can be computed using the following equation:

$$\gamma_i = \frac{\beta_i}{1-\sum_{j=1}^{i-1}\left(1-\beta_i+b_{ij}\beta_i\left(1-\frac{1}{\beta_j}\right)\right)y_i-\sum_{j=i+1}^{n}\left(1-a_{ij}\left(\frac{\beta_i}{\beta_j}\right)\right)y_j} \qquad (5)$$

As previously mentioned, y_i in equation (5) corresponds to the mass proportion of each class of grains. The value of y_i can be obtained on the basis of the grading curve of each material. For aggregates, these curves can be obtained by the usual methods. For powders, it requires the use of a laser apparatus.

Equation (5) takes into account the various interactions that can take place between grains of various sizes. For instance, small grains can contribute to decrease the packing density of larger grains. The parameter a_{ij} in equation (5) takes into account this effect. Similarly, large grains can also reduce the packing density of smaller grains. The latter is known as the wall effect and the variable b_{ij} takes into account this effect.

Once the virtual packing density (γ) of the mixture is known, one can calculate the "real" packing density of the mixture on the basis of equation (6):

$$\eta_r^* = \exp\left(\sum_{i=1}^{n}\frac{2{,}5y_i}{\frac{1}{C}-\frac{1}{\gamma_i}}\right) \qquad (6)$$

In order to use this equation, one has to assume a certain value for the reference relative viscosity (η_r*) for the mixture. For conventional concretes, the notion of viscosity can be more or less directly linked to that of the mixture workability. For no-slump concretes, such as RCC, the application of the notion of viscosity is more ambiguous. Experience has showed that the value η_r* can be quite variable from one RCC application to another. RCC mixtures for dam construction (that have to be designed with a VEBE time of approximately 15 seconds) should be proportioned with a value of η_r* that is much different than that of RCC mixture used for pavement applications. The value of η_r* has to be set on the basis of previous experience.

The optimum proportion of a given RCC mixture can be obtain by trial and errors or by using a numerical algorithm. All this procedure is arduous but with the use of a computer and a simple worksheet all the calculation is simple.

Systematic use of the solid suspension model has shown that it yields results very similar to that obtained with the ACI empirical method [25, 27]. The model can be used to design RCC mixtures for any type of application, and does not require making a large number of laboratory trial batches. The main advantage of the model is that it can be used to recalculate very quickly the optimum proportions of an RCC mixture. As previously mentioned, this can be of great help on the construction site where the source of aggregates or the type of binder may change on short notice.

Influence of Various Parameters

As seen in the previous sections, the mixture design of RCC has come a long way. However, a lot of useful information on the effect of various parameters has been gained, over the years, through laboratory experiments and field experience. The following paragraphs try to summarize, as briefly as possible, this information.

Only a few years ago, RCC mixture characteristics were still quite conventional, and it seemed that producers were more tempted to keep production costs as low as possible than to improve the performances of their products. Thus, to obtain a concrete with a given consistency, the required amount of water was simply added to a dry mixture of cement and aggregates. The quantity of water and the aggregate grading were empirically adjusted to reach a maximum density and the binder (cement) content was adjusted to meet the specified mechanical resistances. Most of the time, no chemical admixtures were used.

Gradually, producers have refined their mixture designs and materials selection. In order to allow greater transportation times and prevent any problems due to placement delays at the construction site, water-reducing agents and set retarders are often used. For economical reasons, mineral admixtures, such as fly ash and slag, are often considered as partial cement replacement. In order to obtain greater densities, gap-graded aggregates were recently introduced.

In North America, most RCC pavements are presently made of CSA Type 10 (or ASTM Type 1) cement and fly ash. In addition to the substantial economies made by reducing the cement content, the use of fly ash is believed to improve the consolidation of the concrete by increasing the percentage of fines in the mixture. It appears that the addition of fly ash also contributes to facilitate, during finishing operations, the formation of a wearing surface with a closed texture. The amount of fly ash is usually limited to a maximum of 20% (by mass) of the total binder content. Recent investigations have indicated that the addition of fly ash does not adversely affect the long-term compressive strength of RCC [27, 44, 45]. According to these studies, the "filler effect" of the fly ash particles can compensate for their lower hydraulic reactivity.

However, these conclusions should be considered with caution. The term fly ash covers a large range of different by-products with various chemical reactivities and particle size distributions. It is, therefore, possible that some fly ashes are more suitable than others for RCC production. Furthermore, recent studies tend to indicate that fly ash can considerably accelerate the loss in workability with time of some RCC mixtures [25] which can subsequently affect the consolidation operations and the subsequent mechanical strength. Such an effect is illustrated in Figure 11.

Although the addition of other mineral admixtures, such as slag and silica fume, is not very common in Canada and in the United-States, these products seem to be more widely used in Europe. For instance, producers in Scandinavian countries tend to use silica fume as partial cement replacement to obtain high mechanical strengths after only a short curing period [21]. The amount of silica fume is usually limited to 10% (by mass) of the total binder content. Silica fume has recently been used in Canada for the construction of high-performance RCC pavements [20, 41].