

論文

**[2137] MODELING OF THE QUASI-STATIC BEHAVIOR OF FRESH CONCRETE****Somnuk TANGTERMSIRIKUL\* and Kohichi MAEKAWA\*\*****1. INTRODUCTION**

Various fresh concrete behavior can be considered as quasi-static, dewatering under pressure, bleeding and plastic shrinkage, for example. Deformability loss due to loss of water and porous surface due to water flow through the surface occur if the concrete dewaterers greatly. Bleeding, causing non-uniformity, affects strength and durability of the concrete. Plastic shrinkage causes severe cracking above the fixed objects in the fresh concrete if the concrete settlement is significant.

This paper introduces an analytical model to simulate the quasi-static behavior of fresh concrete. 3-D model was developed [1], however, only the simplified 1-D model is described. The model can be used as a tool to design good fresh concrete concerning quasi-static behavior.

**2. MULTI-PHASE MODEL AND THE RELATED GOVERNING EQUATIONS**

Fresh concrete consists of various particles with different sizes and properties. In this model, fresh concrete was treated as a 5-phase material namely gravel, sand, powder, water and air phases. By assuming that the relative displacements (segregations) among the solid particles (gravel, sand and powders) are negligible, the original 5-phase material model is reduced to a 3-phase material model in which fresh concrete is considered to be composed of solid (gravel, sand and powder), liquid (water) and air phase which exists in bubble form. Though the 3-D model had been derived, the 1-D model was described here. At first, explanation of each phase is given in the following section.

**2.1 Solid phase**

Solid phase consists of gravel, sand and powder materials. The water which always inhibits in the solid particles is considered as water as solid phase since it travels with the solid particle it inhibits. Derivation of water as solid phase will be given in the following section.

**2.2 Liquid phase**

Liquid phase is water which is regarded as being composed of 2 main

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components namely water as solid phase and water as liquid phase.

### 2.2.1 Water as solid phase (V<sub>ws</sub>).

Water as solid phase consists of water consumed in hydration process and water absorbed in the solid particles. These components of water are always contained in the solid phase and cannot be removed from the solid phase without applying evaporation process.

(1) **Water consumed by hydration (V<sub>whyd</sub>).** The amount of water consumed in hydration process is computed by assuming that it varies linearly with the accumulative hydration heat as ( Q is the accumulative heat of hydration at any moment and Q<sub>e</sub> is the total heat of hydration at the end of hydration process. The constant 0.25 • W<sub>c</sub> came from the fact that the amount of water needed to complete hydration process (when Q=Q<sub>e</sub>) is about 25% of the cement weight, where W<sub>c</sub> is weight of cement.)

$$V_{whyd} = 0.25 \cdot W_c \cdot Q/Q_e \quad (1)$$

(2) **Absorption.** Absorption is defined here as the amount of water which is retained inside the solid particles and can not be removed without being forced to evaporate. Absorption was only considered for sand and gravel and is neglected for powders since it is far less than the amount of water retained at the powder surface, trapped in the flocculated structure and retained by surface tension. The amount of water absorbed by sand and gravel can be calculated using coefficients β<sub>f</sub> and β<sub>g</sub> obtained from the centrifugal water retainability test [2]. The coefficients β<sub>f</sub> and β<sub>g</sub> are the water retainability of sand and gravel at very high centrifugal level where there is no considerable change (reduction) of the coefficients even the applied centrifugal force to expel the water is increased. The amount of absorbed water, V<sub>wab</sub>, can then be computed as (note that W<sub>f</sub> and W<sub>g</sub> are weight of sand and gravel, respectively)

$$V_{wab} = \beta_f \cdot W_f + \beta_g \cdot W_g \quad (2)$$

### 2.2.2 Water as liquid phase (V<sub>wl</sub>).

Water as liquid phase is the water component other than the water as solid phase and is composed of water of which the amount depends on liquid pressure gradient (water trapped by surface irregularity of solid, trapped in the flocculated structure and retained by surface tension) and free water.

The equation for obtaining amount of water which changes with liquid pressure gradient (V<sub>wlp</sub>) can be written as [1]

$$V_{wlp} = V_{wlpp} \left( \frac{\partial p}{\partial x}, t \right) + V_{wlpf} \left( \frac{\partial p}{\partial x} \right) \quad (3)$$

where V<sub>wlpp</sub> and V<sub>wlpf</sub> represent the amounts of water which change with liquid pressure gradient for powder materials and sand, respectively, ∂p/∂x is the liquid pressure gradient. V<sub>wlpp</sub> is function of time since the behavior of powder materials is time dependent.

The amount of free water (V<sub>wfr</sub>) which is movable and important for determining permeability of fresh concrete mixture can then be obtained, when the total amount of water in the mixture (V<sub>wt</sub>) is known, from

$$V_{wfr} = V_{wt} - V_{ws} - V_{wlp} \quad (4)$$

## 2.3 Air phase

Air in fresh concrete exists in bubble form, pressure in air bubbles is in balance with the pore liquid pressure. Air volume ( $V_a$ ) in the mixture varies with pore pressure ( $u$ ) and temperature ( $T$ ) following natural law of gas as (those with subscript  $i$  are the initial values)

$$\frac{u_i \cdot V_{ai}}{T_i} = \frac{u \cdot V_a}{T} \quad (5)$$

## 3. ANALYTICAL PROCESS

### 3.1 Equilibrium equations

From Fig.1, 1-D equilibrium equation of solid phase was derived as

$$\frac{d\sigma_s}{dx} - \frac{df_s}{dx} + F_{sl} + (1-e) \cdot \rho_s \cdot g = 0 \quad (6)$$

where  $\sigma_s$  is stress of solid phase,  $f_s$  is frictional force between solid and boundary,  $\rho_s$  is density of solid phase,  $F_{sl}$  is drag force acting on solid by liquid,  $e$  is void ratio of the solid phase and  $g$  is gravity.

Similarly, equilibrium equation of liquid phase can be derived as

$$\frac{d\sigma_l}{dx} - \frac{df_l}{dx} + F_{ls} + S \cdot e \cdot \rho_l \cdot g = 0 \quad (7)$$

where  $\sigma_l$  is stress of the liquid phase,  $f_l$  is frictional force between liquid and boundary,  $\rho_l$  is density of liquid phase and  $F_{ls}$  is drag force acting on liquid phase by solid phase. The definition of void ratio of solid phase,  $e$ , and saturation degree,  $S$ , are given as follows ( $V$  is mixture volume,  $V_a$  and  $V_l$  are volume of air and liquid in the mixture)

$$e = \frac{V_a + V_l}{V} \quad \text{and} \quad S = \frac{V_l}{V_l + V_a} \quad (8)$$

Considering that boundary friction of liquid phase is negligible since it is small when compared to that of solid phase, one can combine the equilibrium equations of both phases to give the following combined equation

$$\left( \frac{d\sigma_s}{dx} + \frac{d\sigma_l}{dx} \right) - \frac{df_s}{dx} + (1-e) \cdot \rho_s \cdot g + S \cdot e \cdot \rho_l \cdot g = 0 \quad (9)$$

### 3.2 Constitutive equation for solid phase and boundary friction

Since liquid phase is assumed incompressible and air phase is considered to behave according to the natural law of gas, only the constitutive equation of solid phase is to be determined. Stress of solid phase is a function of strain of the solid phase. However, the stress of solid phase can be treated as a function of void ratio of the solid phase in 1-D case since strain relates linearly with volume decrease and void ratio is function of volume decrease [3,4]. Then the 1-D constitutive equation of solid phase is

$$\sigma_s = \sigma_s(e) \quad (10)$$

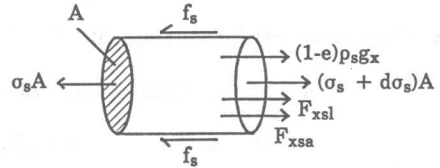


Fig.1 1-D equilibrium