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Concrete Mix Design Based on Spherical Shape Concept

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Abstract

The concepts of cement paste, mortar and concrete mix design have been important for products of concrete construction. Concrete mix designers almost always use the trial volume method which is based on absolute volume method or simple traditional mix design, to find the proportions of concrete components based on source of aggregates is different characteristics. The designer must use his experience to change the ratio of materials in concrete components and check concrete strength and workability of concrete to meet work requirements. The basic concepts of mix design, based on volume method, assume that the aggregate particle shape is spherical. The concept of mix design would be developed as an approximate method for civil engineers to modify the cement paste thickness or mortar thickness design to get the mix proportions of concrete to meet workability requirement while maintaining water cement ratio for any kind of characteristics of material, such as sizing and gradation. Using the spherical shape concept, civil engineers can apply these concrete mix design principles to durability-based or porous concrete mix designs.

Keywords: Cement Paste Mix Design, Mortar Mix Design, Concrete Mix Design.

1. NOMENCLATURE

Cement Paste (CP) is composed of cement (C) and water (W). Mortar (MT) is composed of cement paste and fine aggregate or sand (S). Concrete (CC) is composed of mortar and coarse aggregate or crush stone (CS) or gravel.

2. INTRODUCTION

Mortar and concrete mix design are important for concrete structure or reinforcement concrete structure. Concrete mix design can be calculated by absolute volume or ACI standard practice ACI211.1 (2022), which is worldwide and also used in academic units in Thailand. Almost, civil engineering designers always use the absolute volume method (Neville, 1995) and his experience in finding the trial mix design to meet project requirements due to characteristics of fine and coarse aggregate has different properties.

The selection of concrete mix proportions based on ACI211.1-22 can be used when the gradation of coarse aggregate and the fineness modulus of fine aggregate must be maintained in accordance with the criteria of standard practice (ASTM C33, 2023). Normally, each source of fine and coarse aggregate differs in sizing and gradation, which do not meet the same criteria as the standard specification. The standard practice provides only one solution for the water content in concrete mix components to meet the slump range requirement, based solely on the maximum size of coarse aggregate.

The absolute volume method (Neville, 1995) (Caltrans, 2013) (Goswami, 2018) is an easy way for designers to modify the parameters of the concrete mix components such as water cement ratio, cement per aggregate ratio or paste to aggregate ratio (Sun & Zhu, 2012) and fine aggregate per coarse aggregate ratio based on his experience to get the best proper mix for any sources of aggregate and can apply for high volume fly ash concrete (Yao et al., 2023), high performance or durability concrete.

Sirinaranun (2014) developed the mortar mix design based on the concept that fine aggregate has a spherical shape. This study used the basic material testing parameters in a concrete laboratory, such as specific gravity of materials, void of fine aggregate and fineness modulus of fine aggregate. This study proposed an important parameter: the average cement paste thickness, which affects the minimum cement content in each mortar mix proportion. This study also proposed fulfilling cement paste in void of fine aggregate.

This research would like to continue to use Sirinaranun (2014) concepts for developing the concrete mix design which uses basic characteristics of materials such as fineness modulus of fine and coarse aggregate (Neville, 1995), specific gravity of fine aggregate (ASTM C128, 2022), specific gravity of coarse aggregate (ASTM C127, 2024), void and unit weight of aggregate (ASTM C29, 2023). These characteristics of material are the basic parameters that almost testing in academic units in Thailand. This research would like civil engineering designers to get the idea from this designing concepts of maintaining the water cement ratio to maintain concrete strength and varying the cement paste thickness or mortar thickness design to meet its workability. The advantage of these concepts is that they allow us to determine the proper amount of cement paste to combine with fine aggregate to form mortar, ensuring good properties of mortar. Additionally, they help us determine the proper amount of mortar to combine with coarse aggregate to form concrete with good properties for normal concrete.

3. Theories and Conceptual Design

The conceptual mix design is based on the meaning of the terms cement paste, mortar and concrete, as shown in Figure 1. Cement paste (CP) is composed of cement (C) and water (W). Mortar (MT) is composed of cement paste (CP) and fine aggregate (S). Where, concrete (CC) is composed of mortar (MT) and coarse aggregate (CS).

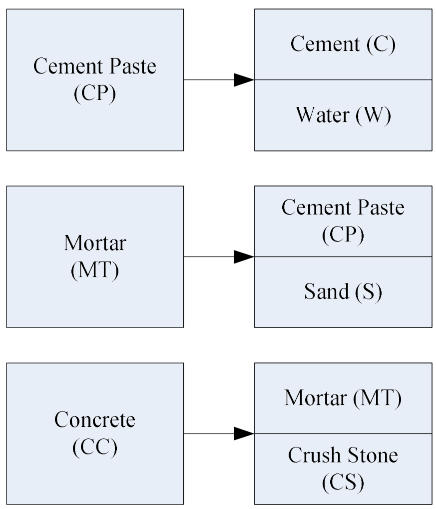

Figure 1 Conceptual Mix Design of Cement Paste, Mortar and Concrete.

3.1 Cement Paste Mix Design Concept

The conceptual design of the cement paste mix design is based on the water cement ratio parameter which is related to the concrete strength. In this concept has been used the relationship between the cylindrical compressive strength of concrete and water cement or water cementitious material ratio of non-air-entrained concrete without water reducing admixtures of ACI 211.1 (2022) as based on a parameter which is transformed to Thai unit style in terms of formula by regression method as shown in Equation (1).

$$W_C = 2.73 - 0.88 \log f_c' , \qquad (1)$$

where W_C is water cement ratio by weight, and f_c' is the cylindrical compressive strength of non-air-entrained concrete cured for 28 days in kilogram per square centimeter (ksc).

The conceptual design of the cement paste mix design uses the water cement ratio to transform the weight of cement and water to be its volume of cement and water by using specific gravity of cement and density of water. The total volume of cement and water is the volume of cement paste, which is not equal to one unit, then use the total volume of cement paste to normalize the volume of cement and water to be one unit of the cement paste volume. This concept will be shown in Figure 2.

3.2 Mortar Mix Design Concept

The conceptual design of mortar mix design (Sirinaranun, 2014) is based on the spherical shape of fine aggregate, which uses the voids of fine aggregate as the main parameter that is related to the one-unit volume concept and spherical concept. Other concepts are in terms of mortar particle and cement paste functions. Mortar is composed of cement paste and fine aggregate or cement paste and sand. When mixing cement paste and sand together, it is found that some parts of cement paste will seize around the sand surface and form mortar particles. The concept of mortar particles will be shown in 3. Where other functions of cement paste will fill in voids of fine aggregate. It can be said that cement paste has two functions when mixing with sand. One is covered around the sand surface. The other is fulfilled in voids of sand. Sand particles which mix with cement paste that grasp around the surface will transform into mortar particles. The cement paste that seizes around the sand surface will be called covering cement paste, while the cement paste that fills in voids in the sand will be called fulfilling cement paste, as shown in **Figure** 4.

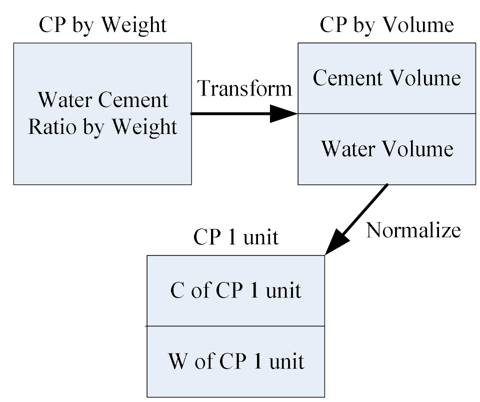

Figure 2 Conceptual Mix Design of Cement Paste

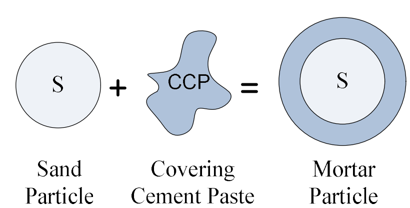

Figure 3 Mortar Particle Concept

The last concept of mortar mix design is the void of fine aggregate. Due to the idea of uniform aggregate, the bigger uniform aggregate or the smaller uniform aggregate also has the same volume of uniform aggregate and the same voids of uniform aggregate. When a sand particle which is a small size is mixed with covered cement paste and formed to be a mortar particle which is a bigger size, the voids in sand and the voids in mortar should be the same, while the sand particle volume will be replaced by the mortar particle volume as shown in Figure 5.

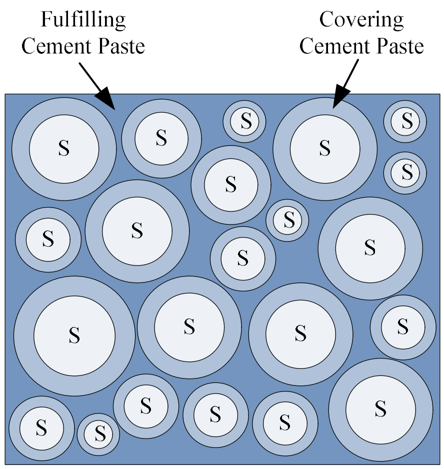

Figure 4 Functions of Cement Paste Concept

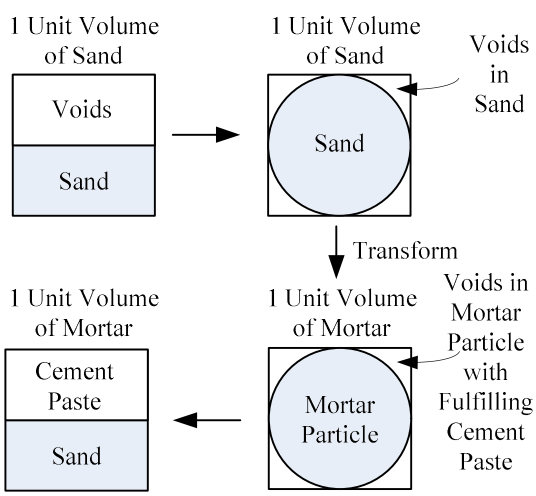

Figure 5 Concept of Voids in Mortar Particle

3.3 Concrete Mix Design Concept

The conceptual design of the concrete mix design, which looks like the conceptual design of a mortar mix design, is based on the void of coarse aggregate parameter which is related to the one-unit volume concept. The others are in terms of concrete particle and mortar functions. Concrete is composed of mortar and coarse aggregate or mortar and crush stone. When mixing mortar and crush stone together, it is found that some parts of mortar will seize around the crush stone surface and form to be concrete particles. The concept of concrete particles will be shown in Figure 6. Where other functions of mortar will be filled in voids of coarse aggregate. It can be said that mortar has two functions when mixing with crush stone. One is covered by the crush stone surface. The other is fulfilled in voids of crush stone. Crush stone particles which are mixed with covered mortar that grasp around the surface will form into concrete particles. The mortar that seizes around the crush stone surface will be called covering mortar, while the mortar that filling in voids in crush stone will be called fulfilling mortar, as shown in Figure 7.

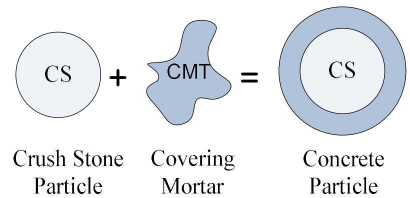

Figure 6 Concrete Particle Concept

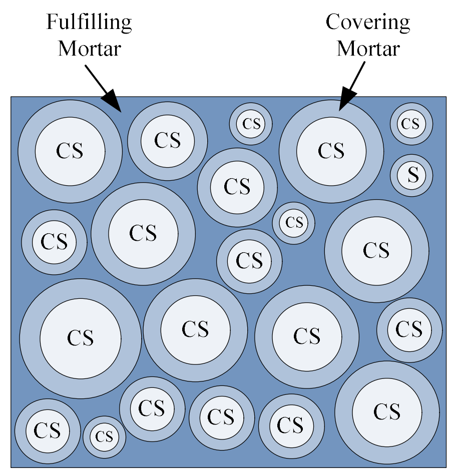

Figure 7 Functions of Mortar Concept

Void in coarse aggregate is the main concept of concrete mix design, which looks like a mortar mix design concept. Due to the idea of uniform aggregate, the bigger uniform aggregate or the smaller uniform aggregate also has the same volume of uniform aggregate and the same voids in uniform aggregate. When crush stone particles which are small mix with mortar and transform into concrete particles which are bigger. The voids in crush stone and the voids in concrete should be the same, while crush stone particle volume will be replaced by concrete particle volume as shown in Figure 8.

3.4 Aggregate Size

Grading of aggregate, which is the distribution of particles of granular materials of various sizes, in practice, will be represented in terms of fineness modulus, which is an index of the fineness of an aggregate and its voids. Fineness modulus (FM) is computed from sieve analysis data by the technique of normalizing the summation of cumulative percentages of aggregate retained on each sieve by 100 (Neville, 1995) and is represented the index of average aggregate size. The ASTM E11 (2024) standard test sieves and the size used for determining the fineness modulus will be shown in Table 1 and have an increasing ratio of 2 to 1. If some uniform aggregate is retained only on one sieve such as No. 30, it is found that the fineness modulus of that uniform aggregate is 3. Then, for another uniform aggregate that is retained on another sieve, the fineness modulus of each uniform aggregate can be computed as shown in Table 1. For any fineness modulus value, you can find the average aggregate size by using the larger sieve size and its size.

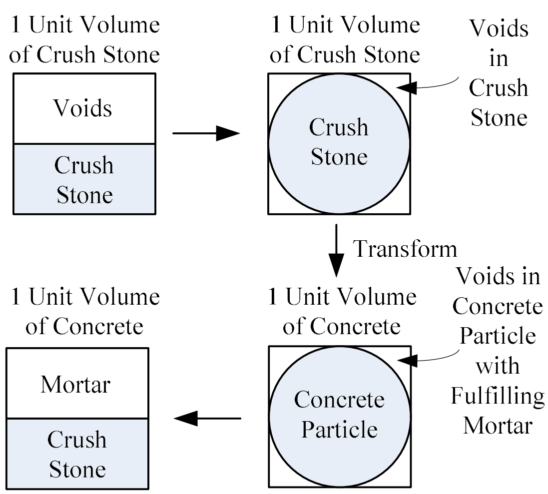

Figure 8 Concept of Voids in Concrete Particle

From the fineness modulus value and average aggregate size which are shown in Table 1, can be plotted this relative as graph shown in Figure 9 and this relationship can be found by the regression method as shown in Equation (2). In this paper, it prefer to use Table 1 and the linear interpolation method, which is most useful in engineering fields, to find the average aggregate size for any fineness modulus value by Equation (3).

Table 1 ASTM Standard Sieve, Sieve Size, Average Aggregate Size and Fineness Modulus (FM)

ASTM Standard Sieve	Sieve Size (mm)	Average Aggregate Size (mm)	FM
1 1/2 "	37.5	56.25	9
3/4 "	19.0	28.25	8
3/8 "	9.50	14.25	7
No. 4	4.75	7.125	6
No. 8	2.36	3.555	5
No. 16	1.18	1.770	4
No. 30	0.600	0.890	3
No. 50	0.300	0.450	2
No. 100	0.150	0.225	1

$$d_a = 10^{(0.3FM - 0.95)}, \qquad (2)$$

where d_a is average aggregate size in mm, and FM is the fineness modulus of aggregate.

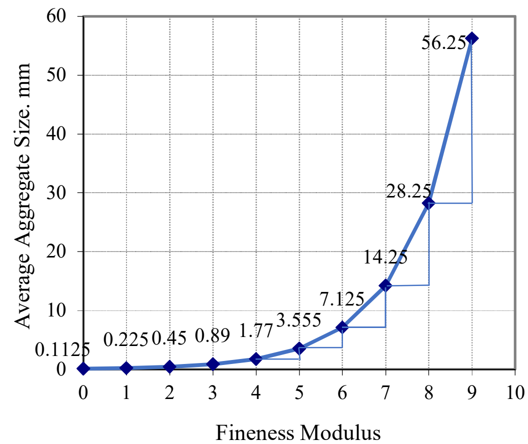

Figure 9 Average Aggregate Size and Fineness Modulus

$$d_a = d_L + \frac{(FM - FM_L)}{(FM_U - FM_L)}(d_U - d_L), \qquad (3)$$

Where d_a is average aggregate size in mm, FM is the fineness modulus of aggregate that would like to find average aggregate size, FM_u is a larger fineness modulus or upper fineness modulus in Table 1, FM_L is smaller fineness modulus or lower fineness modulus in Table 1, d_L is a lower average aggregate size following that lower fineness modulus in Table 1 and d_U is an upper average aggregate size follow that upper fineness modulus in Table 1

For example, if the fineness modulus value is 2.75, it can determine the average aggregate size by using linear interpolation technique or Equation (3) as 0.780 mm.

3.5 Mortar Particle Size

From the ideal of the mortar particle concept shown in Figure 3, the mortar particle size is the look like the diameter of the mortar particle, which comes from the average fine aggregate size and the covering cement paste thickness around the fine aggregate, as shown in Figure 10 and can be shown in Equation (4).

$$d_{mt} = 2t_{cp} + d_s, \qquad (4)$$

where d_{mt} is average mortar particle size in mm, d_s is the average fine aggregate size and t_{cp} is the cement paste thickness.

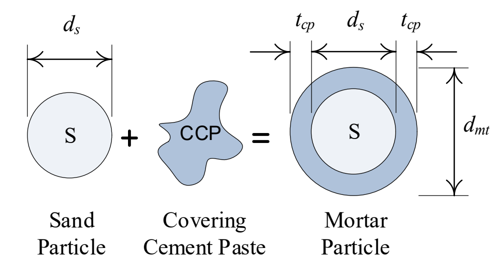

Figure 10 Mortar Particle Size

3.6 Cement Paste Thickness

Cement paste thickness is an important property of mortar and concrete mix design. How to know the proper cement paste thickness which makes workability mortar or performance concrete mix design. From knowledge of cement paste phenomena, cement paste thickness can be related to the cement particle size. From air permeability testing, the specific surface area which is almost reported by the manufactory plant is around 2,700 to 3,300 square centimeters per gram or 270 to 330 square meters per kilogram. If the specific gravity of cement is about 3.15 and the cement particles assume a spherical shape, the average size of the cement particle is about 6.3 microns, for 3,000 sq.cm. per gram of average specific surface area. It tells us that the minimum cement paste thickness should not be less than about 6.3 microns. The maximum cement paste thickness depends on the workability of mortar and concrete.

3.7 Concrete Particle Size

In the same concept related to mortar particle size, concrete particle size is the diameter of total coarse aggregate and covering mortar in terms of mortar thickness defined as d_{cc} as shown in Figure 11 and on Equation (5). Where, the diameter of a coarse aggregate can be obtained from its fineness modulus by using Equation (3).

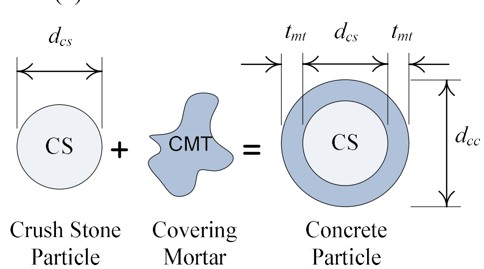

Figure 11 Concrete Particle Size

$$d_{cc} = 2t_{mt} + d_{cs}\,, \tag{5}$$

where d_{cc} is average concrete particle size in mm, d_{cs} is the average coarse aggregate size and t_{mt} is the mortar thickness.

3.8 Mortar Thickness

Mortar thickness is the second parameter for concrete mix design where the first is cement paste thickness. How to use the proper mortar thickness, which makes it workable, or performance concrete mix design depends on the mortar particle size. The mortar thickness can be the layer of mortar particle size as shown in Equation (6).

$$t_{mt} = nd_{mt}\,, \tag{6}$$

where t_{mt} is mortar thickness in mm, n is positive real number of layer of mortar particle size and d_{mt} is the average mortar particle size.

The number of layers of mortar particle size can be any positive real number up to the proposal of the designer. Mortar thickness is related to the sand particle size and depends on cement paste thickness.

3.9 Specific Gravity

The specific gravity of a material is the density ratio or specific weight ratio of that material to water and is the main property for conversion between its volume and its weight. In the civil engineering field, normally the specific gravity of cement is about 3.15 where the specific gravity of sand and crush stone is about 2.6 and 2.7, respectively. The normal unit weight of water or water density is about 1,000 kilograms per cubic meter.

3.10 Procedure of Mix Design

The main steps of concrete mix design following conceptual design from item 3.1 to 3.3 and including the rest of the items together, can be separated into 4 parts as follows.

Part I is a cement paste 1 unit mix design by finding the components of cement and water in 1 unit volume of cement paste based on parameters: strength of concrete or water cement ratio, specific gravity of cement and unit weight of water.

Part II is a mortar 1 unit mix design by finding the components of cement paste and sand in 1 unit volume of mortar based on parameters: covering cement paste thickness, fineness modulus of sand and sand void.

Part III is a concrete 1 unit mix design by finding the components of mortar and crush stone in 1 unit volume of concrete based on parameters, covering mortar thickness, fineness modulus of crush stone and crush stone void.

Part IV is the combination of part I part II and part III to get components of cement, water, sand and crush stone in 1 unit volume of concrete mix design. After getting 1 unit volume of concrete mix design can be applied to all unit volumes, such as cubic meter, cubic centimeter, cubic foot or cubic yard, by using specific gravity of cement sand and crush stone and the unit weight of water on those units to transform its volume into its weight.

4. Results and Case Study

The results of concrete mix design based on case study of material parameters, which are strength of concrete is 280 ksc at 28 days curing, specific gravity of cement is 3.15, fineness modulus of sand is 2.75, average sand void is 0.36 or 36%, cement paste thickness is 60 micron or 0.060 mm, specific gravity of sand is 2.60, fineness modulus of crush stone is 6.95, average crush stone void is 0.43 or 43%, mortar thickness design is 0.6 layer of normal mortar size and specific gravity of crush stone is 2.70 will be shown as following by procedure concepts in item 3.10.

Part I Cement Paste 1 Unit Mix Design

The concrete strength is 280 ksc. After substitution into Equation (1), we will get a water cement ratio equal to 0.577. After that, using the water cement ratio by weight, which means water is 0.577 grams and cement is 1 gram, to find the volume of water is 0.577 cubic centimeters (cc.) and cement is 0.317 cc. Normalizing the cement paste volume, which is 0.894 cc. to 1 unit, will make the volume of cement and water equal to 0.355 and 0.645 units, respectively, as shown in Figure 12.

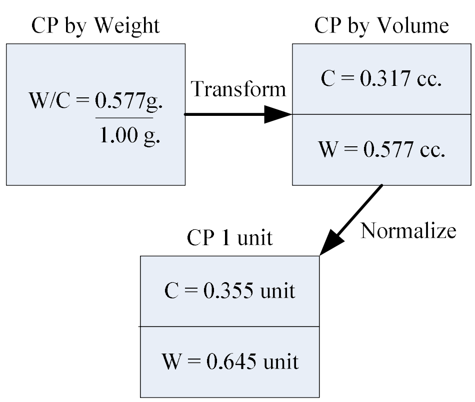

Figure 12 Component of 1 Unit Cement Paste

Part II Mortar 1 Unit Mix Design

Since the fineness modulus of sand is 2.75, the average sand size will be 0.78 mm using Equation (3). Then the average mortar particle size is about 0.90 mm using Equation (4). After this step, find the volume of the sand particle and mortar particle by the spherical shape concept to know the sand mortar ratio, which is 0.651. From the concept that the void of the mortar particle is equal to the void of the sand particle volume, which is 0.36 units in Figure5, then the mortar particle volume in 1 unit volume is equal to 0.64 units and the sand particle volume in 1 unit will be reduced by the sand mortar ratio which is 0.651 to get the sand particle volume equal to 0.417 unit. After that, the volume of covering cement paste volume in 1 unit is 0.223 units, which is the difference between mortar particle and sand particle volumes. For a good design of mortar, the cement paste that fulfills in voids must be 100 percent, then the fulfilling cement paste in the void is 0.36 units. The total cement paste volume in 1 unit mortar is 0.583 units by the sum of covering and fulfilling cement paste, where the sand volume is 0.417 units, as shown in Figure 13.

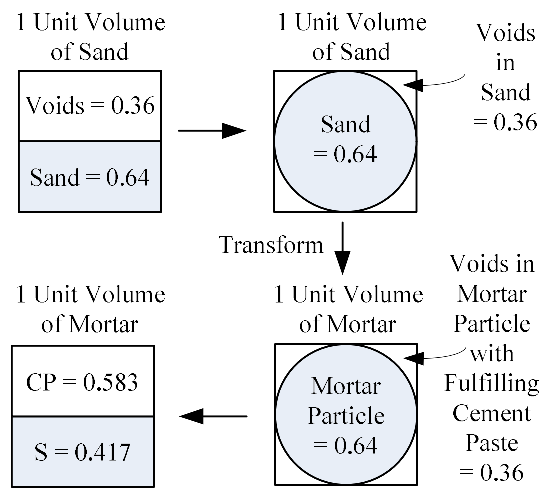

Figure 13 Component of 1 Unit Mortar

Part III Concrete 1 Unit Mix Design

From fineness modulus of crush stone is 6.95, the average crush stone size is 13.89 mm using Equation (3). Because the mortar thickness design is 0.6 of the mortar particle size, which is 0.90 mm, the mortar thickness will be 0.54 mm. Then the average concrete particle size is 14.97 mm using Equation (5). After this step, find the volume of crush stone particles and concrete particles using the spherical shape concept to know the crush stone concrete ratio, which is 0.799. From the concept that the void of concrete particles is equal to the void of crush stone particles, which is 0.43 units in Figure 8, then the concrete particle volume in 1 unit volume is equal to 0.57 units, where the crush stone particle volume in 1 unit will be reduced by 0.799 ratio of the crush stone concrete to get the crush stone volume equal to 0.455 unit. After that, the volume of covered mortar volume in 1 unit is 0.115 units because of the difference between concrete particle volume and crush stone particle volume. For a good design of concrete, the mortar that fulfills in the void should be 100 percent, then the fulfilling mortar in the void is 0.43 units. The total mortar volume in 1 unit of concrete is 0.545 units by the sum of covering and fulfilling mortar, where the crush stone volume is 0.455 units, as shown in Figure 14.

Part IV Final Concrete 1 Unit Mix Design

The last step is combining the mix design from part I part II and part III together with its meaning such as mortar is the component of cement paste and sand, where cement paste is the component of cement and water. When we would like to find the cement volume in 1 unit concrete volume, we use the ratio concept or multiplication tool to get each component. For example, cement volume is 0.1128 units by the multiplication result of 0.545 units of mortar in concrete and 0.583 units of cement paste in mortar and 0.355 units of cement in cement paste, as shown in Figure 15. After getting the volume of each component in 1 unit of concrete, the standard volume unit of concrete in Thailand, which is a cubic meter, will be applied to 1 unit of concrete to be 1 cubic meter of concrete. The last step is the transformation of its volume in terms of cubic meters to be its weight in terms of kilograms by its specific gravity and water unit weight, as shown in Figure 16.

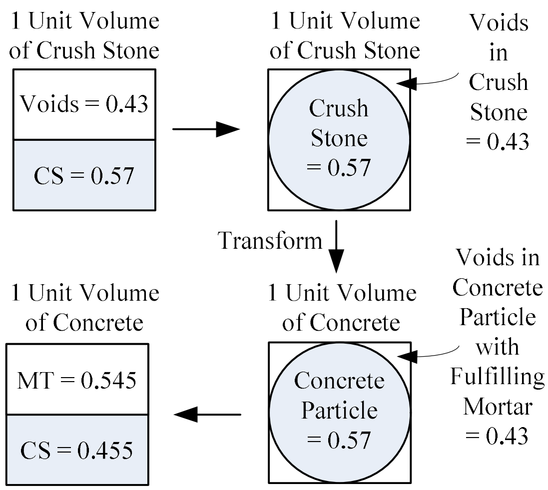

Figure 14 Component of 1 Unit Concrete

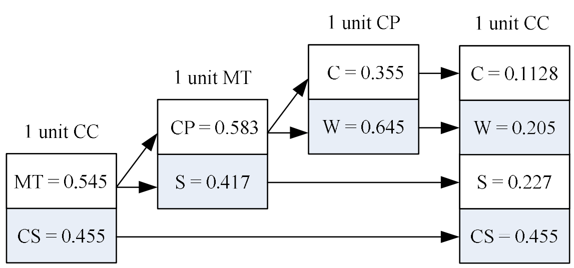

Figure 15 All Components of 1 Unit Concrete

5. CONCLUSIONS

The concrete mix design is an important tool for civil engineers used to find the mix proportions to meet proper work. The important keys or parameters that affect the mix design are many factors, such as fineness of cement powder, fineness modulus of fine aggregate and coarse aggregate, voids of fine aggregate and coarse aggregate, cement paste thickness, mortar thickness, the required concrete strength and workability of fresh concrete.

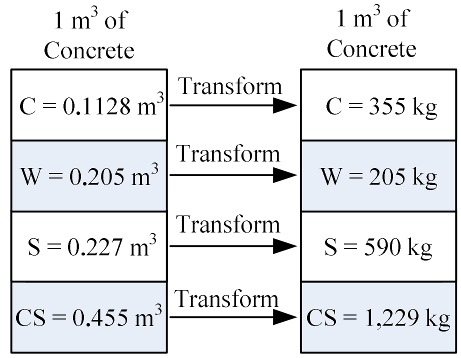

Figure 16 All Components of 1 cubic meter of Concrete

The results of the concrete mix design shown in Figure16 are only one solution to meet the concrete strength requirement based on water cement ratio and may not meet the workability requirement. From this research concept, the designer can have two ways to find the proper mix to meet workability requirements. The first way is to maintain the mortar thickness design and vary the cement thickness design. For example, if the workability of the first mix is above the requirement, the designer can reduce the cement paste thickness in the design lower than the first time, such as 15, 30 or 45 microns, to check its workability. Vice versa, if the first mix has poor workability, the designer can increase the cement paste thickness such as 75, 90 or 120 microns to check its workability again. After that, the designer will know the relationship between workability of fresh concrete and cement paste thickness and can find the cement paste thickness using regression method for workability requirement. The second way is to maintain the cement paste thickness and vary the mortar thickness design in terms of 0, 0.125, 0.25, 0.5, 1, 2, or 3 times the layer of mortar size. In the same way, designers can know the relationship between workability of fresh concrete and mortar thickness design and use regression method to find the mortar thickness for proposed workability. In future work on this concept, it has many points to study further. For example, designers can develop the relationship between cement paste thickness and water cement ratio and proper mortar thickness design as the first guidance for concrete mix design to quickly meet workability and strength requirements. The cement paste thickness for any type of cement is not the same, due to the compounds and fineness of Portland cement powder or hybrid cement powder. The other point is to study durability concrete mix design by changing the cement paste mix design concept to be a binder paste design concept which uses an absolute volume method based on water cement ratio, pozzolan to cement ratio and admixture to cement ratio while maintaining the mortar and concrete mix design concepts. The binder paste is not only the main part of the durability of concrete but also the durability of aggregate.

Normally, air voids can be in cement paste, mortar and concrete particles due to air voids in cement powder, fine aggregate and coarse aggregate. While mixing the concrete components, air voids in cement paste, mortar and concrete can be eliminated by vibration between mixing time and compaction time. Finally, it still has air voids in cement paste, mortar and concrete particles in real situations up to the water contents. Designers must first maintain or keep the fulfilling cement paste in the sand void and fulfilling mortar in crush stone void to perfectly 100 percent of its void in the concrete mix design concept to reduce air void in concrete due to void of aggregates first and can get minimum cement content from the design. Designers can use the standard method for air content of freshly mixed concrete by the pressure method (ASTM C231, 2009) to study the behavior of air in fresh concrete related to the mix design. The last point, designers must know that the water cement which is enough for chemical reactions, such as hydration reactions of calcium silicate hydrates, is about 0.21 to 0.24 (Neville, 1995), then the excess amount of water cement beyond reactions in mix design is used for workability. Hardened concrete can have air voids inside cement paste, mortar and concrete particles in later time, because the excess water can be evaporated by the environment, so the concrete may not have good permeability and durability.

The conceptual design of a concrete mix design based on a spherical shape looks like an approximate method or simple knowledge and is scientific that can be applied to use and to find satisfying mixes for various sizes and gradations of aggregates that meet workability and strength requirements based on important parameters, which are cement paste thickness or mortar thickness. The advantage of this mix design concept can also be used to find the minimum cement component by modification of cement paste thickness and mortar thickness. This concept mix design can be applied for durable concrete mix designs and also applied for designing porous mortar or porous concrete as well.

6. Acknowledgment

The author gratefully acknowledge the contributions of students in concrete technology class for their attention by using the concepts of mix design in this paper to change the cement paste thickness and mortar thickness to meet the concrete slump requirement for their workshop since 2016 where average aggregate size concept has been used since 2007.

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