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Effect of Cement–Water Ratio on the Mechanical Properties of Reactive Powder Concrete with Marble Powder as Constituent Materials Widodo Kushartomo, Henny Wiyanto, and Daniel Christianto Abstract The main principle of developing reactive powder concrete is to improve the microstructure by compacting density and increasing toughness. To achieve this principle very high-grade cement is used together with pozzolanic materials. The research was conducted to study the effect of the water-cement ratio on the mechanical properties of reactive powder concrete with marble powder as con- stituent materials. Trial mixes were prepared using cement, sand, silica fume, marble powder, and super-plasticizer. A mix ratio of 1.0:1.1:0.2:0.1:0.03 was adopted with water-cement ratio of 0.18, 0.20, and 0.22. Concrete cylinder of size ø10 cm 20 cm and the concrete beam of size 10 cm 10 cm 35 cm were cast and cured in steam curing at 95 °C for 4 h and tested to study the compressive strength, modulus elasticity, splitting strength, and flexural strength in relation to the water-cement ratio. The results indicate that reduced water-cement ratio from 0.22 to 0.18 increases the compressive strength, modulus elasticity, splitting strength, and flexural strength. Using a lower water-cement ratio for the mixing process is difficult to handle, so this research recommended a 0.20 water-cement ratio to produce reactive powder concrete with optimum mechanical properties. Keywords Concrete Water-cement ratio Mechanical properties Strength Marble powder 1 Introduction The low water-cement ratio (w/c ratio) impacts concrete's high strength and durability, as shown in Fig. 1 [1], but a lower water-cement ratio resulted in dif- ficulties in mixing and placing. Workability can be resolve by using admixture such as super-plasticizer. W. Kushartomo (&) H. Wiyanto D. Christianto Department of Civil Engineering, Faculty of Engineering, Universitas Tarumanagara, Jakarta 11440, Indonesia e-mail: widodo@untar.ac.id © The Author(s), under exclusive license to Springer Nature Singapore Pte Ltd. 2022 177 H. A. Lie et al. (eds.), Proceedings of the Second International Conference of Construction, Infrastructure, and Materials, Lecture Notes in Civil Engineering 216, https://doi.org/10.1007/978-981-16-7949-0_16 Fig. 1 Correlation water-cement ratio with compressive strength for normal concrete [1] However, a mixture with a water-cement ratio between 0.18 and 0.22 will not mix well and is not plastic enough to be poured into the formwork. The presence of water is technically required for the hydration reaction to occur in cement. Water-cement ratios between 0.45 and 0.60 are more often used in regular concrete. For high-strength concrete, use a low water-cement ratio plus a plasticizer to increase workability. Excess water in a mixture causes segregation of the coarse aggregate to the cement paste. Water that is not used in the hydration reaction, when the concrete hardens, will leave a trail in the form of pores, whether the pores are open or closed. The pores that are formed will reduce the strength of concrete. A concrete mix with too much water can also cause shrinkage as the concrete dries and cracks concrete corners. The shrinkage in the end also reduces the strength of the concrete [1]. Reactive powder concrete (RPC) is categorized as ultra-high-performance con- crete (UHPC). The term reactive powder means that all powder components in RPC can react chemically. However, the word concrete is preferred over mortar to describe UHPC by including steel fiber as one of its compositions. The use of steel fiber aims to increase its ductility. However, the RPC development does not include steel fiber as one of the development objects. The microstructural modification method is chosen as an effort to develop RPC with very high compressive strength, very high durability, and very high toughness. The principles of RPC development are as follows: • Develop microstructure and eliminate coarse aggregate • Enhance particle packing • Increase toughness. RPC's performance is associated with a low water-cement ratio, admixture, fineness of quartz sand, super-plasticizer, and small-sized steel fiber. Due to its excellent mechanical properties, RPC is exhibited in various applications in the construction field, such as bridge structures, high rise buildings, nuclear waste structures, marine structures, precast applications, and as an effective repair material [2]. To achieve the perfect density and homogeneity of the matrix to form pores as minimal as possible, the RPC must be related to the aggregate gradation between 150 and 600 μm. It is not recommended to use fine aggregate with a grain size below 150 μm to produce an optimum granular packing [2]. The function of marble powder is as a paste-aggregate interface filler, which significantly reduces the void of RPC, which will cause the pores to break and result in very low permeability, no cracks, and thus increase the strength. An Improvement of the RPC microstructure can be made by increasing the curing temperature, which causes the C-S-H (Calcium Silicate Hydrate) chain to be longer due to the high hydration of the cement. The high curing temperature also causes an increasing pozzolanic activity from marble powder to reactive silica, thus encour- aging the pozzolanic reaction and producing more CSH gel [1, 2]. The addition of marble powder to the RPC can increase the compressive strength by up to 20%. The amount of marble powder used in the manufacture of RPC should be 10–30% of the amount of cement. RPC quality can be achieved if the ratio of the amount of water-cement ranges from 0.18 to 0.22. The low water-cement ratio will reduce porosity on RPC and increase the compact density. Increasing compact density has a positive impact on decreasing porosity in the mortar. The primary purpose of the RPC mix design development process is to get the best mechanical properties. There are two basic parameters in achieving the best mechanical properties: • Appropriate selection of RPC constituent materials • Water-cement ratio. Packing density for RPC can be achieved by adjusting all grain sizes used, such as fine aggregate, silica fume, and quartz powder. Temperature and maintenance pressure also significantly affect the mechanical properties of RPC. Steam main- tenance at high temperature and pressure can accelerate the hydration reaction and force a chemical reaction to occur in all RPC ingredients. This study aims to develop the mechanical properties of RPC with the water-cement ratio as an influencing component. 2 Methodology The materials used in this investigation are cement, sand, silica fume, marble powder, and super-plasticizer, and water. Experimental Test Procedures Mix pro- portions of 1.0:1.1:0.25:0.1:0.03 were adopted with a water-cement ratio of 0.22, 0.20, and 0.18 was determined using cement, fine aggregates, silica fume, marble powder, and super-plasticizer, respectively as shown in Table 1. The cylinder ø10 cm 20 cm and the beam of size 10 cm 10 cm 35 cm molds of con- crete were oiled to ease the de-molding process late. After 24 h of sitting time, the samples were de-molded and placed in a curing water tank for 7. After that, the samples were cast and cured in steam curing at 95 °C for 4 h. All samples were tested to study the compressive strength, splitting strength, and flexural strength in relation to the water-cement ratio at 28 age. 3 Result and Discussion The mechanical properties of reactive powder concrete (RPC) as w/c ratio functions results are presented in Fig. 2. The strength value of mechanical properties RPC will be increased if the w/c ratio reduces. The highest value of mechanical prop- erties reached the lowest w/c ratio, which corresponds to an improvement of microstructure, particle packing, and cementitious constituents. 3.1 Improvement of Microstructure RPC's mechanical properties and durability are influenced by the bond between the cement paste and aggregate, known as the Interfacial Transition Zone (ITZ). Observing the microstructure in the ITZ area shows the pattern of micro cracks and Table 1 Materials composition Materials m3) q (kg/ w/c = 0 .22 w/c = 0.20 w/c = 0.18 Ratio Wight (kg) Ratio Wight (kg) Ratio Wight (kg) Cement 3150.0 1.00 880.00 1.00 896.00 1.00 912.00 Water 1000.0 0.22 193.60 0.20 179.20 0.18 164.16 Micro silica 2200.0 0.25 220.00 0.25 224.00 0.25 228.00 Sand 2617.8 1.10 968.00 1.10 985.60 1.10 1003.20 Marble powder 2563.0 0.10 88.00 0.10 89.60 0.10 91.20 Superplasticizer 1150.0 0.03 26.40 0.03 26.88 0.03 27.36 Fig. 2 Mechanical properties of RPC as w/c ratio functions the occurrence of crack propagation. The stress–strain graph for aggregate, con- crete, and cement paste is shown in Fig. 3 [2]. Figure 3 shows the elastic and brittle behavior of cement paste and aggregate, while concrete shows ductile behavior. This is related to the development of the rift in the ITZ area. RPC is designed by developing microstructures, such as compact density using pozzolanic materials and admixtures that increase its homogeneity. The addition of fine particles such as marble powder can increase the packing density, increasing the density in the ITZ region without noticeable pores, as shown in Fig. 4. The low water-cement ratio significantly impacts the decrease in porosity, as shown in Fig. 4. As shown in Fig. 4, ettringite is formed between the material that is not entirely hydrated and the C-S-H gel. The main hydration products (C-

S-H gel) were homogeneous, $Ca(OH)_2$ was not found, and ettringite was formed [1, 2]. The microstructure of RPC depends on the conditions of heat treatment behavior. This is because the treatment temperature can change the microstructure of ITZ and the activity of pozzolanic materials. The real improvement in improving the microstructure of RPC as well as dis- tinguishing RPC from other classic high-performance concrete HPC is the removal of coarse aggregate and replacing it with quartz sand to increase bond strength within the matrix, increase homogeneity, reduce the effect of heterogeneity of microstructure which minimizes internal defects of the material such as voids and microcrack [2]. Fig. 3 Comparative stress–strain curves for aggregate, paste, and concrete [2] 3.2 Particle Packing The primary purpose of applying the packing density model is to obtain high mechanical strength. This can be achieved by combining the appropriate size and proportion of small particles to reduce the voids formed. In this case, the perfor- mance of RPC is influenced by the size and percentage of pores formed, which affects the type and a density level of the constituent components. The finer par- ticles fill the voids found between the cement and the aggregate particles. This causes efficient compaction of the voids between cement grains so that the overall performance of the concrete mix increases significantly [2–4]. The performance of RPC is enhanced by incorporating powder into the mix, which is the opposite of ordinary concrete which is highly affected by these fine materials. This powder creates a large surface area which requires high amounts of C-S-H gel. The high cement content in the RPC anticipates the formation of large C-S-H gels and increases the powder's surface area, thereby increasing the packing density [1, 2]. Fig. 4 Scanning electron microscope (SEM) of RPC, compacting interfacial transition zone with low w/c ratio Ideally, the gradation curve and filling properties of powder materials such as cement, silica fume, quartz sand, and marble powder are the main concepts of the packing density approach, as shown in Fig. 5. Some of the cement grains remain hydrated in the RPC mixture due to the low moisture content. Cement granules play a crucial role in the packing density of RPC because the grain size is between the sizes of silica fume and marble powder, thus helping in the process of filling pores [2, 4, 5]. The distance between the particles is filled with finer grains so that the density becomes better, as shown in Fig. 4. Using the principle of granular packing of cementations materials in RPC, capillary porosity in RPC is significantly reduced. Fig. 5 Scanning electron microscope (SEM) of RPC, particle packing 3.3 Cementitious Constituents The binder in RPC is divided into two materials, namely cement and pozzolan. The most used pozzolanic material is silica fume. The cement and pozzolan used in the manufacture of RPC can be anything because there are no special requirements for the type of cement and pozzolan. The cement that is often used is cement with a low heat of hydration, considering that the quantity used is very high, namely type II cement. In the selection of cement, the cement grain size is also a consideration. Using cement with a high level of fineness will consume large amounts of water. The low water-cement ratio and the fine grain size of cement in RPC impact the mortar's performance factor, so caution is needed to use cement dosage. The dosage of cement commonly used in RPC ranges from about 700–1000 kg/m3 to achieve ultra-high strength with very low moisture content. High cement content is vital to increase the formation of C-S–H gel to cause the compaction of particles in fine grains. Incomplete hydration of cement in RPC causes a lot of free cement granules. These grains play an essential role in the granular packing in RPC [1, 2, 6]. The use of enormous amounts of cement in RPC has many disadvantages to the environment, cost, and concrete behavior when it hardens. A high temperature of hydration, shrinkage, and dimensional stability are problems that often arise in using a lot of cement. Mineral admixtures such as silica fume can be an excellent alternative to reduce the adverse effects of using high cement content in RPC. Improvement of concrete performance through the packing density effect acti- vates a pozzolanic reaction. It accelerates the cement hydration process, which increases the formation of calcium silicate hydrate (C-S–H) and its derivatives. In terms of mechanics and durability, the advantages obtained from combining steel fiber and pozzolanic materials in RPC are high tensile strength, high flexural strength, high compressive strength, low permeability, high resistance to chemical attack (acid, nitric, chloride, and sulfate), high abrasion resistance, toughness, excellent durability [1, 2, 4]. 4 Conclusions 1. The mechanical properties of RPC are determined mainly by the water-cement ratio and the components used. The smaller the value of the water-cement ratio, the greater the value of the mechanical strength of the RPC. Likewise, the finer the grain of the components used, the higher the value of the RPC mechanical strength. 2. Improvement of microstructure, removing coarse aggregate, adjusting grain size are the basic principles in the manufacture of RPC to improve its mechanical properties. 3. RPC requires high cement content, and pozzolanic materials must be used to obtain the required reactivity. 4. The enhancement in compressive strength can reaches when using marble powder. References 1. Mindess S, Young JF (2002) Concrete. Prentice Hall, New Jersey 2. Mayhoub OA, Nasr ESAR, Ali YA, Kohail M (2021) The influence of ingredients on the properties of reactive powder concrete: a review. Ain Shams Eng J 12(1):145–158. https://doi. org/10.1016/J.ASEJ.2020.07.016 3. Kim YY, Lee KM, Bang JW, Kwon SJ (2014) Effect of W/C ratio on durability and porosity in cement mortar with constant cement amount. Adv Mater Sci Eng 2014. https://doi.org/10.1155/ 2014/273460 4. Apebo NS, Shiwua AJ (2013) Effect of water-cement ratio on the compressive strength of gravel—crushed over burnt bricks concrete. Civ Environ Res 3:74–81 5. Hiremath PN, Yaragal SC (2017) Effect of different curing regimes and durations on early strength development of reactive powder concrete. Constr Build Mater 154:72–87. https://doi. org/10.1016/J.CONBUILDMAT.2017.07.181 6. 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