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The Optimum Replacement of Fine Recycled Concrete Aggregate on the Compressive and Splitting Tensile Strength of the Concrete

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Abstract: The increasing demand of new construction, the more amount of natural materials was used. This is because, quick populace development and urbanization dramatically affect the expanded interest for development of construction market. Due to this case, many countries were forced to rearrange, renovate and also demolished old building to design a new concept of building that covered more occupants in building than old building concept. There was a high mindfulness on the need to give elective utilization to reused materials, particularly in the development of construction field. This resulted in the idea of making use of fine recycled concrete aggregate (FRCA) in the concrete as fine aggregate replacement. It had been proved that with the right percentage of FRCA replacement can produce a concrete which performed better than the normal concrete. Most of the previous studies agreed that the replacement should took place within the range of 10% - 30% to make the concrete work optimally. However, within that range, the best optimal replacement shows on the 20% as there is no decreases in concrete strength. It was also found that the density of FRCA concrete was lower than the normal concrete due to the porosity properties of FRCA resulted to the high-water absorption rate. The physical properties of FRCA somehow tends to effecting the concrete performance positively and also negatively, that is why it is vital to get a better understanding about the recycled concrete aggregate (RCA) so that it could be used and provide a clear relevant fact for the industries to start review the existing regulation and consider the use of RCA in the concrete making.

Keywords: Concrete, fine recycled aggregate, replacement, mechanical properties

1. Introduction

Most of the building nowadays are being made mainly using concrete as it provides many favorable features such as satisfactory compressive strength, durability, availability, versatility and cost effectiveness. The current demand of the construction industry is to produce a new type of concrete which are incorporated by any waste material. Waste material may come from various source such as from the plantation industry, automotive and as well as the construction and demolition project itself.

The idea of recycling concrete aggregate material is due to the authorities sometimes overlooked about the construction and demolition (C&D) waste. Construction and demolition waste are becoming a vital issue especially to the environmental aspect in many large cities in the world [1]-[4]. There are several major reports about the generation of this C&D waste globally per annum. In United State, approximately 136 million tons of building-related C&D debris generated each year which is only 20 - 30% is recycled [5]. Other than that, United Kingdom produce 70 million tons of C&D waste and the wastage rate in UK construction industry as high as 10% - 15% [6]. Each year China produces 29% of the world's municipal solid waste (MSW) of which the construction industry contributes nearly 40%. Environmental

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Protection Department (EPD) of Hong Kong stated that every day, there is about 2900 tons of C&D waste had been dumped in the landfill in 2007 [7], [8].

For instance, concrete rumble is one of the major waste productions from C&D. Concrete rubble from the C&D waste that has been used as the aggregate replacement in the concrete production is called recycled concrete aggregate (RCA) [9]. From the crushed RCA, it will produce three type of materials. First material is the coarse RCA (CRCA) which size is more than 5mm in diameter. The second material is the fine RCA (FRCA) that have diameter size of 4mm and below and the last material is the cement mortar [10].

According to Senthamarai et al. [11], concrete which contain at least 20% a waste product whether it from the agriculture, daily waste or C&D waste is called green concrete that will create a sustainable development. The simple definition of sustainable development is the possibility to achieve the needs of present generation without preventing the future generation to meet their needs [12], [13]. To accomplish that needs, this review paper was conducted to gather an overview information on FRCA properties such as density and water absorption and the performance of concrete incorporating with FRCA in terms of compressive strength and splitting tensile strength regarding the percentage of FRCA replacement. It is important to acknowledge the properties of FRCA and the optimum replacement percentage of natural sand by FRCA to the concrete mix so that it can be widely useable not only just for the non-structural component, but also for the load bearing n structural component of a building.

2. FRCA Properties

2.1 Density

Process such as breaking, removing, crushing and sieving involved during the production of FRCA. Normally the density of FRCA is lower than the natural fine aggregate. For the density test, the RCA is 2520kg/m^3 which is lower compare to density reading of the natural aggregate that is 2680kg/m^3 and the possibility of RCA to be used in the production of concrete is strengthen by the result show in the sieve analysis test which lies within the range that had been stated by the British Standard. Research by Xiao et al. [14] also give the same reading of density of RCA that is 2520kg/m^3 while for the natural aggregate is 2820kg/m^3 which is around 10% higher. The same results go to other researcher, this value is due to the porosity of the RCA itself make by the attachment of old mortar. Table 1 shows the specific gravity result of the FNA and FRCA among the previous researcher.

Table 1- Specific gravity of fine recycled concrete aggregate and fine natural aggregate

Researcher	Fine Natural Aggregate	Fine Recycled Concrete Aggregate
Singh & Singh [15]	2.75	2.45
Pedro et al. [16]	2.70	2.30
Sai Samanth et al. [17]	2.64	2.41
Fan et al. [18]	2.65	2.35
Lotfy & Al-Fayez [19]	2.68	2.28
Carro-Lopez et al. [20]	2.72	2.30
Average value	2.69	2.35

This low in density properties was due to the shape of FRCA itself which is rounder then the natural aggregate [21]. The fine aggregate gathered from the recycling concrete was not consist of sand particle only, there is also consist of old mortar itself and sand covered in old mortar which give the rounder shape and the high porosity properties in FRCA. According to the study, 4/8 mm fraction contain 33% to 55% percentage of attached mortar while for 8/16 mm ranges from 23% to 44% for the attached mortar. This shows that the percentage of mortar attachment is higher as the fraction size is lower [10]. Other than that, the relationship of the mortar content and density shows that the higher amount of mortar attach to the RCA the lower the density of the RCA. The result of the bulk specific gravity and the saturated surface dry density of a natural aggregate is 2546 kg/m^3 and 2579 kg/m^3 respectively while for the for 100% of mortar is just 1665 kg/m^3 and 2000 kg/m^3 respectively for both type of density.

Even though the concrete fine aggregates had a lower bulk density than natural sand, the fresh mortar bulk density increases when the FRCA incorporated. This is because of the reduction of the water content in mortar linked to the filler effect [22]. The void in the fresh mortar incorporating with FRCA that is not occupied by sand are filled by the FRCA which are smaller. Thus, as the FRCA replacement ratio increases, the less void occupied by water and make the mortar become more compact [22]. The result from study found by Ishikawa [23] noted that the FRCA particle that pass through a 0.150mm sieve helps to decrease the air content in the concrete, pack the mix particle better and increase the bulk density had strengthen the result found by [22].

2.2 Water Absorption

High water absorption of the RCA is the main issue in the RCA concrete production. The calculation in the concrete mixing design should consider this matter in order to achieve the desire workability and strength. Result from the study by [9] shows the water absorption made by RCA is 4.2% compare to only 1.4% by natural aggregate and [14] also found the same result with higher water absorption made by RCA. Table 2 shows the others comparison of water absorption between FRCA and fine natural aggregate by several researchers.

Table 2 - Water absorption between fine recycled concrete aggregate and fine natural aggregate

Author	Normal fine aggregate (%)	FRCA (%)
Kumar et al. [24]	2.0	10.4
Fan et al. [18]	1.3	8.9
Evangelista et al. [25]	0.96	10.43
Gorjinia et al. [26]	4.16	14.05
Periera et al. [27]	0.11	10.9
Xiao et al. [14]	0.4	9.25
Khatib [28]	0.8	6.25

This high-water absorption characteristic is due to the high porosity of FRCA than fine natural aggregate which increase the specific surface area of the FRCA [29]. The present of old mortar in FRCA also brings a negative effect especially to the water absorption characteristic. This problem was studied by [10] on the influence of old mortar to the properties of RCA. The test result from water absorption test shows that increases of mortar will only lead to increasing of water absorption of RCA. Nishbayashi & Yamura [30] and Yagishita et al. [31] stated that to curb the high water absorption problem, the number of crushing process should be increases to diminish the content of old attached mortar but this method will only increasing the production cost [10]. Most of the researcher used 1% superplasticizer from the weight of cement [24], [25]. If there is no superplasticizer used in the study, researcher will use high water to cement ratio. According to Padmini et al. [32] and Ryu [33], the high water to cement ratio is not affecting the strength characteristic concrete, it was only affected by the quality of the RCA when the water to cement ratio is low. This study supported by Ryu [33], Khalid et al. [34] and Dhir et al. [35] stated that, the higher water to cement ratio, the less reduction of the compressive strength. This phenomenon is due to the presence of the unhydrated cement in the RCA that affected the properties of the concrete [36]. The high water to cement ratio is within the range of 0.55-0.7. Other researchers use the method that had been suggested by [37]. According to Leite [37], it was found that around 50% of the water absorption potential would be reached at the end of the mixing procedures. Therefore, extra water was added to the FRCA mixes. The extra amount was equal to the difference between the amount expected to be absorbed by the FRCA during mixing and the amount within them before they were used (since they were not oven-dried). Figure 1 shows the FRCA and natural sand water absorption over time. The author devised a test which led to the conclusion that the amount of water absorbed by the fine recycled aggregates grew during the initial 10 min of immersion, more or less stabilized until the 30 min mark at around 50% of the maximum absorption capacity of the aggregates and grew again thereafter until saturation was achieved.

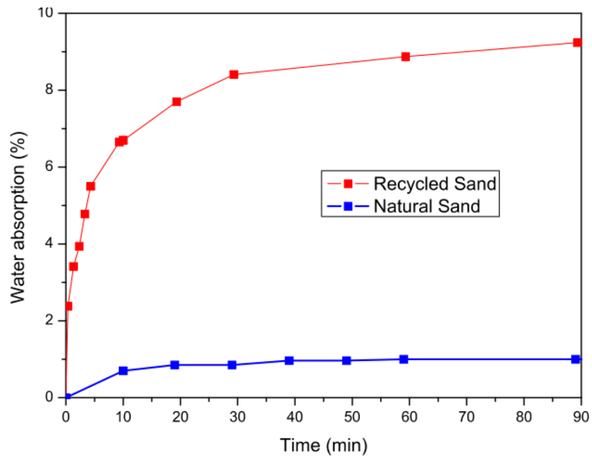

Fig. 1 - Potential water absorption of fine recycled concrete aggregate [38]

Another method is the pre-saturation process. Instead of adding extra water during the mixing process, this process is soaking the FRCA before the mixing process. This is to reduce the water exchange between the FRCA and the cement paste. According to Barra & Vásquez [39] and Poon et al. [40], the saturation point should not be reached because the risk of the later transfer of water from inside the FRCA to the cement paste that could alter the water to cement ratio in the interfacial transition zone (ITZ) between aggregate and cement and affecting the bonding strength. The best potential water content is within the range of 50% to 90%. Research conducted by Poon et al. [40] shows the best result made air dried FRCA with 50% of the potential water content.

3. Mechanical Properties

3.1 Compressive Strength

A research conducted by Kumar et al. [24] that was aimed to produce a high performance concrete shows that the replacement of 20% FRCA produce the highest compressive strength from days 3, 7 to days 28 that is 55.6MPa, 66MPa and 85.3MPa compare to normal concrete that is 39.6MPa, 59.8MPa and 72MPa respectively as shown in Figure 2. This result is attributed to the usage of FRCA in dry condition which lead to the low water to cement ratio which means that it requires high amount of superplasticizer in the mixture to acquire the targeted slump [24]. This situation happened due to the high-water absorption of FRCA. This result cannot be achieved when the total replacement of FRCA took place in the concrete production. According to Ajdukiewicz & Kliszczewicz [41], the compressive strength of the concrete produce by the total replacement of fine natural aggregate by FRCA only lead to decreasing of compressive strength and this research supported by Tu et al. [42].

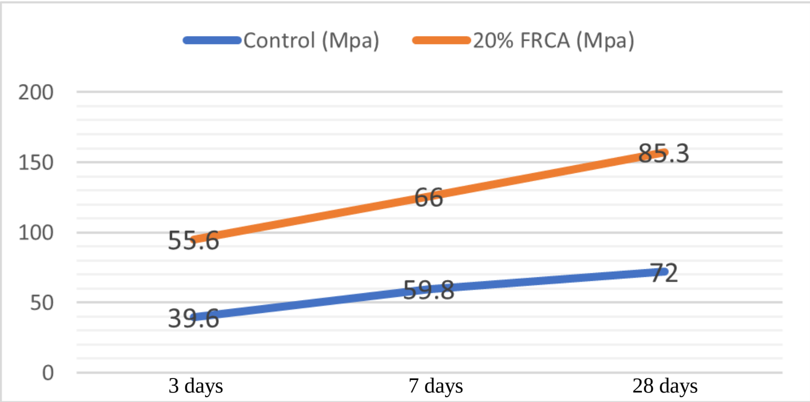

Fig. 2 - Control and 20% fine recycled concrete aggregate compressive strength

Furthermore, the result of compressive strength shown in the research conducted by Pereira et al. [27] is the replacement of the FRCA can be replace up to 30%. The compressive strength is better than the control concrete at 10% replacement and the result is slightly lower but comparable at 30% replacement that shown in Figure 3. This is also due to the reduction of the water to cement ratio during the mixing process and also a filler effect caused by the smaller size of FRCA compared with fine natural aggregate but only for the specific range of replacement ratios between 10% and 30%. This result also supported by the research conducted by Evangelista & de Brito [25] as they found that the uses of FRCA in the structural concrete is possible up to 30% replacement. This is due to the compressive strength performance of FRCA concrete is not affected as long as the replacement is within the range. The use FRCA in the structural concrete also bring positive outcome due to the un-hydrated cement of the original concrete and the specific surface of the FRCA tends to produce a better binder/recycled aggregate interface [37]. Katz [36] also mention that the FRCA contain high level of hydrated and un-hydrated cement that can increase the amount of cement in the mix.

According to Barra & Vásquez [39] and Poon et al. [40] concluded that the replacement of FRCA take place to the saturation state, the concrete strength will be affected due to the mechanical bonding between the cement paste and the recycled aggregates becomes weaker at higher saturation levels the mechanical bonding between the cement paste and the recycled aggregates becomes weaker. Therefore, lead to the weaker compressive strength. The high porosity of the FRCA also contribute to the loss in compressive strength. The high concentration of FRCA replacement will tent to reduce the compressive strength of the concrete [18]. Therefore, in study conducted by Poon et al [18], the replacement of FRCA is up to 25% only either with superplasticizer or without produce the comparable compressive strength to the normal concrete. The research made by Thomas et al. [43] has claimed that the more the RCA is replacing the Natural aggregates, the more reduction of workability of the concrete. Besides that, the density also will be reduced 13-17% when RCA is used alone.

3.2 Splitting Tensile Strength

The usage of FRCA to be accepted in the structural design, the FRCA concrete also have to pass the splitting tensile strength test. According to Carrasquillo [44], the splitting tensile-to-compressive strength ratio values ranged from 0.8 to

1.4 for normal concrete. The ratio of the splitting tensile-to-compressive strength gather form the research conducted by Sagoe-Crentsil et al. [45] was 0.89 to 1.21 for 100% replacement of the FRCA. Even though the result for splitting tensile for FRCA concrete is slightly lower than the normal aggregate, but the ratio to compression is comparable to the normal concrete at 100% replacement. There is a good bond between aggregate and the mortar matrix due to the absent of the damage in FRCA concrete prove the similarity in mechanism failure of the control concrete [45]. Result for 100% FRCA replacement also been showed decrease by Berndt [46] around 0.02MPa only lower than the equivalent normal concrete. The same result been found by Katz [36] that show the splitting tensile strength of the 100% FRCA replacement concrete decrease about 0.3MPa from the normal concrete.

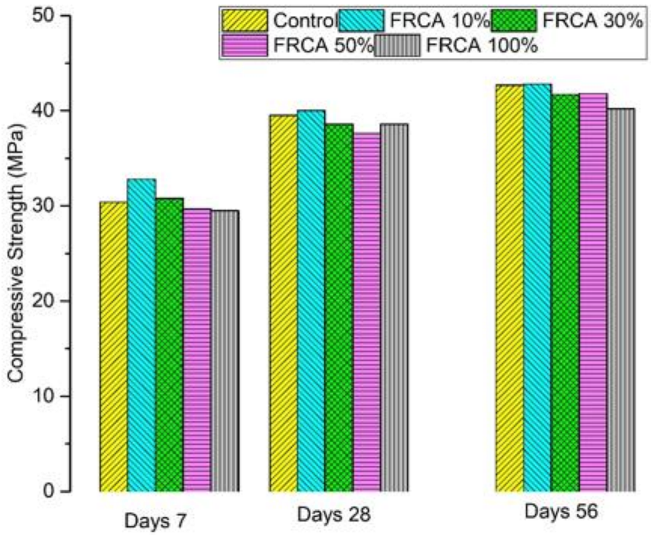

Fig. 3 - Compressive strength for normal against various percentage of FRCA concrete

Other than that, the result from Evangelista & de Brito [25] study found that there is a 5.2% and 30.5% decrease in splitting tensile strength for the 30% and 100% FRCA replacement respectively. Coutinho & Gonc Alves [47] stated that, the decrease in splitting tensile strength is due to the physical property of the FRCA itself that is more porous than the natural aggregate and its normal for it to be lower than the normal concrete and is also mention that the splitting tensile strength for the FRCA concrete is acceptable as long as it replacement percentage is below 30. According to Pereira et al. [27], the result for splitting tensile strength have no effect up to 10% replacement of FRCA. The value drops about 0.2MPa when the replacement increases to 30%. This decrease in splitting tensile value is due to the increase in the w/ c ratio to compensate for the additional water absorption of the FRA [25]. Evangelista & de Brito [25] stated that the splitting tensile strength can be decreases even though the compressive strength of the RCA concrete remains constant.

Another study conducted by Kumar et al. [24] found the highest splitting tensile strength of the FRCA concrete at the 20% replacement. The mix increase the strength up to 18% is due to the high-water absorption characteristic of FRCA which resulting in reduced water cement ratio and consequent increase in mortar strength. According to Gonzalez & Etxeberria [48] recycled concrete aggregate have little influence on the tensile strength and this result are supported by Kou & Poon [49] which found that the maximum tensile strength can be achieve from 25% up to 50% replacement. That is why most of the researcher including Ajdukiewicz & Kliszczewicz [41] that replace 100% of fine natural aggregate by FRCA only have slightly decrease in splitting tensile strength.

4. Optimum Range of FRCA Replacement

The percentage selection of fine natural aggregate replacement by FRCA should consider the most crucial aspect that is the water absorption rate of FRCA. According to Shayan & Xu [50], concrete which contain at least 20% a waste product whether it from the agriculture, daily waste or C&D waste is called green concrete. There are researchers that study on wide range of FRCA replacement percentage from 10% up to total replacement. Most of the researcher agree that the range of FRCA replacement is between 20% up to 30% and this percentage give the comparable and better performance or FRCA concrete in term of compression strength as shown in Table 2.

In respect to the splitting tensile strength, the replacement could be taking place up to 100% FRCA replacement and the strength of split tensile is still comparable to the normal concrete while maintaining in the allowable range. The compressive test result shows by the others researcher found the replacement of FRCA in between 20% to 30% will give the best performance in both compressive strength and also the splitting tensile strength. According to Limbachiya et al. [52], the RCA replacement brings no effect to the concrete up to 30% replacement. More than 30% replacement, the performance of concrete will decrease significantly. The same result shows by Zega & Maio [53] that the compression and splitting tensile strength decrease more notably when the replacement of the FRCA took place more than 30% in the concrete production.

Table 2 - Previous Study on the FRCA

Author	Replacement (%)	Compressive Strength	Tensile Strength	Recommended Replacement (%)	Conclusion
Cartuxo et al. [51]	12, 30, 50, 100	10% FRCA replacement show a better result, however the replacement can go up to 30% which is still comparable with the control.	-	<30	Increase due to the filler effect of the very fine broken particle of the FRCA which generated during mixing that offset the higher porosity of the recycled aggregate.
Lotfy & Al-Fayez [19]	10, 20	The range of strength produce by the FRCA is the same as the control which is lies under 40-45 MPa	Decreased as the percentage of FRCA increases	10, 20	The compressive strength of the concrete remains uninfected as the FRCA replacement take place up to 20. The tensile decreases is due to the angularity and the smoothness of the FRCA surface.
Carro-Lopez et al. [38]	20,50,100	20% FRCA and control behave similar even though the mix strength is slightly lower	-	20	the 20% replacement is considered feasible for the production of concrete.
Fan et al. [18]	25,50,100	Only 25% replacement produce the same grade of concrete. 50% and 100% replacement reduce 12% and 20% of compressive strength		25	FRCA can be use as the FNA replacement.
Kumar et al. [24]	20	FRCA concrete perform better than normal concrete.	FRCA concrete perform better than normal concrete.	20	Due to the high absorption of FRCA, the compressive strength and tensile strength increases. 20% replacement is the acceptable limit.
Singh & Singh [29]	50,100	5% and 9% decrease for 50% and 100% replacement respectively			Weak microstructure and the weak bonding between new and ole Interfacial Transition Zone (ITZ)

5. Conclusion

It can be seen that RCA has the potential to be used in the production of the concrete as the fine aggregate replacement. Concrete made from the present of RCA not only can be used for the non-structural component such as brick but also can be used to create a structural component of a building such as beam due to the performance of the RCA concrete is comparable and perform better than the normal concrete. However, to achieve that, there are several characteristics of RCA that need to be consider especially the water absorption of the RCA. The water absorption of RCA is higher than the natural fine aggregate is due to the present of the old mortar that still attach to the aggregate when the process of C&D took place. To overcome this problem, researchers either apply one of the methods that is the pre-saturation process, varying the water-cement ratio and used superplasticizer in their mixing design.

On the other hand, it had been agreed that to create a new green concrete, the concrete mix should contain at least 20% of any source of waste material. So, the least replacement will be set at 20% and most of the researcher found that the maximum replacement of fine natural aggregate by the FRCA will be at 30%. However, during the 30% FRCA replacement, noted that the compressive strength slightly decreases but still can be comparable to the control concrete and on the 20% FRCA replacement will be best replacement as most of the researcher found that there is not decreases in concrete strength.

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