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The Properties of Mortar Mixtures Blended with Natural, Crushed, and Recycled Fine Aggregates for Building Construction Materials

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Abstract

In this research, the possible applicability of mixture blended with natural, crushed, and recycled fine aggregate are discussed. The fresh and hardened properties of mortar using blended fine aggregates are monitored depending on various blending ratio of fine aggregates. Newly developed ternary diagram was also utilized for better interpretation of the data. It was found that air content increased and unit weight decreased as recycled fine aggregate content increased. With moisture type processing of recycled fine aggregate, the mortar flow was not negatively affected by increase in the recycled fine aggregate content. The ternary diagram is found to be an effective graphical presentation tool that can be used for the quality evaluation of mortar using blended fine aggregate.

Keywords : recycled fine aggregates, blend, cement mortar, ternary diagram, fine aggregate, building construction materials

1. Introduction

The river has been a good source of high quality fine aggregates for several decades. However, the recent rapid economic growth increased the number of construction projects for buildings and civil engineering infrastructures. As a result, the large amount of natural aggregate has been consumed and its supply has been shortened. Some attempts were made to solve the shortage of natural aggregates by using crushed aggregates. However, the supply of crushed aggregate also started to decrease due to the shortage of such resources, mainly because the environmental regulations (e.g., to protect mountain rocks, etc.) prevented people from abusing these sources. For these reasons, the research focus has been moved to use recycled aggregates to replace natural aggregate for concrete production. Since the cost for disposal of the waste concrete has been increasing significantly due to the limited availability in the landfill site, the processing cost required for aggregate recycling becomes more economical and beneficial[1]. It is also environmentally sustainable.

Various research works have been performed in order to investigate the possible use of recycled aggregate for civil and architectural engineering applications[2,3,4]. Most of the research on recycled aggregate has been focused on the use as a coarse aggregate[2,3,5,6], but not so many literatures has been focused on the use as a fine aggregate[4]. The use of recycled fine aggregate is not as much

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recommended because it significantly increases water demand due to its large surface area which affects the workability of the mixture. Water absorption capacity is mainly dependent on the surface quality of recycled aggregate, which are very difficult to control. Therefore, localized difference in w/c ratio near the recycled aggregate may exist, which may lead to the unpredictable strength results. To control such drawbacks, Korean Standard Test Specification (KSTS) recommends blending of recycled fine aggregate with natural fine aggregate for the use in construction site. The replacement ratio of recycled fine aggregate to natural fine aggregate should not exceed more than 30%, especially in case that the quality of recycled aggregate is unknown.

Although blending of recycled fine aggregate is recommended by KSTS, it does not suggest any criteria for blending more than 2 different fine aggregates (natural + recycled, natural + crushed, or crushed + recycled). In addition, research works using more than 3 different fine aggregates, including recycled fine aggregate, is hardly available in the literature. This research is performed to evaluate the properties of mortar using blending of natural, crushed, and recycled fine aggregate. The objective of this research is to evaluate the effect of blended fine aggregate (natural, crushed, and recycled) on various properties of mortar. Mortar specimens were used since it is easier to find the correlation between the physical and mechanical performance of the blended fine aggregate while the effect of coarse aggregate is removed. To facilitate the analysis of the results, a ternary diagram was utilized.

2. Experimental Procedure

2.1. Materials

The natural, crushed, and recycled fine aggregates were used in this research. The natural fine aggregate is from Oksan-gun, Choongchungbuk-do, South Korea. The crushed fine aggregate is from Jinchun-gun, Choongchungbook-do, S-Korea. The recycled fine aggregate was wet-processed at Daegil Environmental Industry Co. at Hongseong-gun Choongchungnam-do, South Korea.

The photographic images of fine aggregates used in this research are presented in Figure 1. The properties of the fine aggregates are presented in Table 1. The shape of the fine aggregates is generally round, but some flaky or elongated shapes also exist. There is no clear difference in the shapes among natural, crushed, and recycled fine aggregates, so aggregate angularity is not expected to affect the properties of mortar specimen.

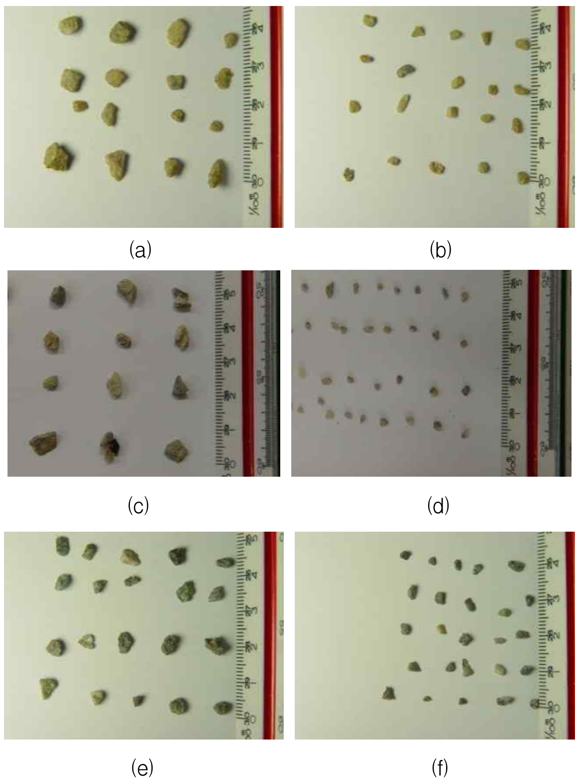


Figure 1. The shape of natural, recycled, and crushed fine aggregates : (a) and (b) is natural fine aggregate (2.5-5mm) and (1.2-2.5mm), (c) and (d) is recycled fine aggregate (2.5-5mm) and (1.2-2.5mm), and (e) and (f) is crushed fine aggregate (2.5-5mm) and (1.2-2.5mm), respectively.

Table 1. The physical properties of natural, recycled, and crushed fine aggregates

	Bulk density (g/㎤)		F.M.*	AC* (%)	UW* (kg/㎥)
	SSD*	OD*			
Natural	2.55	2.51	3.33	1.54	1654
Natural	2.56	2.52	2.74	1.61	1723
Recycled	2.42	2.29	2.74	5.75	1592
Crushed	2.69	2.66	2.15	1.06	1741
Crushed	2.68	2.66	2.74	0.96	1770

* SSD, OD, F.M., AC, and UW indicate Surface Saturate Dry, Oven Dry, Fineness Modulus, Absorption Capacity, and Unit Weight, respectively.

It should be noted that the wet process was used for the production of recycled fine aggregate. The purpose is to remove fines and dusts from the recycled fine aggregate. After this process, the surface condition of recycled fine aggregate was aimed to be close to that of other two fine aggregates. It will reduce the water demand associated with recycled fine aggregate. Since the workability is a key issue for using recycled fine aggregate in the mix, the most attention was given to achieve the similar workability (e.g., keep all the fine aggregate in water and make SSD condition prior to the mixing).

The production process affects the gradation of recycled and crushed fine aggregate, thus affecting the F.M. of blended aggregate. Therefore, this research made on two different approaches on specimen preparation: 1) the F.M. of all fine aggregates was set to 2.74, which was considered to be at intermediate level, to investigate the properties of mortar by eliminating the effect of gradation, and 2) the F.M. of fine aggregates varied following the common production procedure of each aggregate company (as shown in Table 1, F.M of natural, recycled, and crushed fine aggregates were 3.33, 2.74, and 2.15, respectively) and therefore different proportions of fine aggregates produced different value of F.M.. This indicates that F.M. of blended fine aggregates increases with the increase in the natural fine aggregate content (since F.M of natural fine aggregate is the highest), and decreases with the increase in the crushed fine aggregate content (since F.M. of crushed fine aggregate is the smallest). In this research, the first set of specimens is referred to as MMM (middle middle middle) series mortar and the second set of specimens is referred to as LMH (low middle high; crushed: 2.15, recycled: 2.74, and natural: 3.33) series mortar.

For blending of three fine aggregates, the fine aggregate content of one kind was fixed (e.g., 0, 10, 20 … 100%) and the proportions of the other two fine aggregate varied to make 100% total. For example, when natural fine aggregate content was fixed to 10%, the sum of the other two fine aggregates were 90%, so recycled fine aggregate content can vary from 0 to 90% whereas crushed fine aggregate varies from 90% to 0%. The amount incremental was set to 10%.

According to ASTM C 305 "Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency", mortar was mixed with 493.5 kg/㎥ type I ordinary Portland cement and 246.8 kg/㎥ tap water, making water to cement ratio of 0.5. The properties of the cement are presented at Table 2. The mixing ratio between cement and blended fine aggregate was set at 1:3. As mentioned, all the fine aggregates were maintained in SSD condition prior to mixing.

Table 2. The physical properties of cement

Density (g/㎤)	Fineness (㎠/g)	Set time (min)		Compressive Strength (MPa)		
		Initial	Final	3 days	7 days	28 days
3.15	3,265	210	300	22.0	28.9	38.9

2.2. Experiments

The mortar flow measurement was performed following ASTM C 1437 "Standard Test Method for Flow of Hydraulic Cement Mortar" using flow table specified at ASTM C 230 "Specification for Flow Table for Use in Tests of Hydraulic Cement." Prior to the measurement, the flow table was cleaned, and centered. The mortar mixed with various blended fine aggregates was placed at 25mm height mold and 20 times tampering was applied. The mortar was kept unagitated in flow mold for a minute. As soon as flow mold was removed, the specimen was exposed to 12.7 mm height drop for 25 times, which occurred for 15 seconds. The flow value was recorded as the average of the largest and the smallest diameter.

The air content was measured according to the ASTM C 185 "Standard Test Method for Air Content of Hydraulic Cement Mortar." Prior to the air content measurement, the unit weight of the mortar was measured.

ASTM C 109 "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)" was used for molding and testing 28 day compressive strength of cube specimens. Mortar was poured into the cube mold in two layers. A 32 rodding was applied for each layer to ensure proper compaction. Specimens were cured for a day. Specimens were demolded and placed in the lime saturated solution with 23 ± 2 ° C temperature for 28 days. During compressive strength measurement, the loading rate was maintained between 900 and 1800 N/sec.

3. Results

3.1. Mortar Flow

According to Figure 2, the mortar flow data of MMM series mortars using 100% natural, 100% crushed, and 100% recycled fine aggregate were 141.9, 154.2, and 160.9 mm, respectively. The mortar flow data of LMH series mortars 100% natural, 100% crushed, and 100% recycled fine aggregate were 176.6, 129.65, and 160.9 mm, respectively. When the F.M of the fine aggregates are set to 2.75 (MMM series), the mortar flow was the highest with 100% recycled fine aggregate. When F.M. of the fine aggregates varies (LMH series - natural fine aggregate: 3.33, crushed fine aggregate: 2.15, recycled fine aggregate: 2.74), the mortar flow followed the trend of fineness modulus. This result indicates that there is no adverse effect on the mortar flow from recycled fine aggregate. The wet recycling process seems to effectively remove the dust or fines from recycled fine aggregate, and thus positively affected on the flowability of the mortar. The result indicates the significance of preprocessing of recycled fine aggregate. It was recognized that the preparation of fine aggregate in SSD condition also reduced the adverse effects on workability of mortar with recycled fine aggregate.

The mortar flow is known to decrease with the presence of fines or dirt[7] when F.M. is set to fixed value. Therefore, the lower value of mortar flow (MMM series) with natural fine aggregate indicates the presence of fine dirt on its surface. This result also means that the attention should be given to the production process of recycled fine aggregate that washed out all the fine dusts from the surface of recycled fine aggregate.

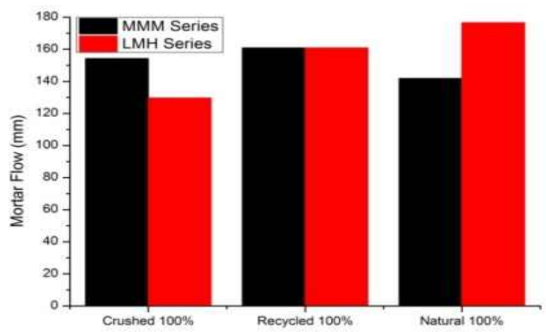
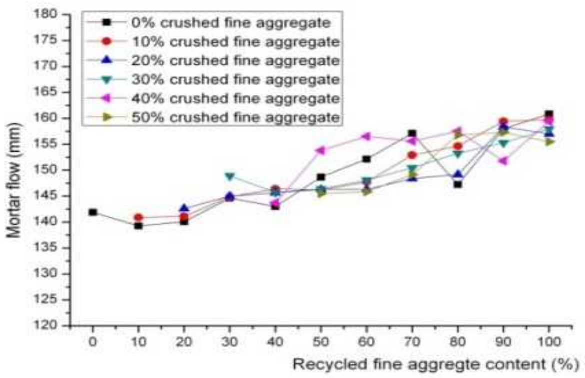


Figure 2. Mortar flow of MMM and LMH series mortar using 100% natural, recycled, and crushed fine aggregate.



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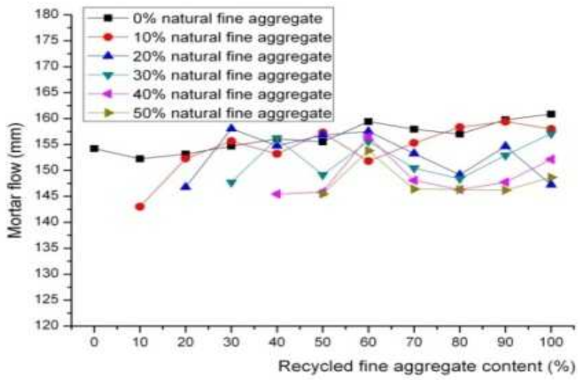
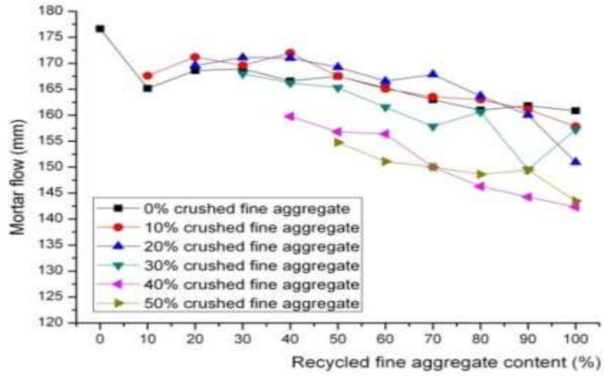


(b)

Figure 3. Mortar flow changes in MMM series mortar: (a) crushed vs. recycled fine aggregate and (b) natural vs. recycled fine aggregate.

Figure 3 shows mortar flow data of MMM series mortars. As shown in Figure 3 (a), when recycled fine aggregate content increased (natural fine aggregate content decreased), the mortar flow increased. From Figure 3 (b), when the recycled fine aggregate content increased (crushed fine aggregate content decreased), the mortar flow seemed to show very slight increasing trend. It was found at least that the use of recycled fine aggregate did not show large decrease in mortar flow as generally understood[8]. It is also reported that the mortar flow of recycled fine aggregate is better than natural fine aggregate when natural fine aggregate has bad shape with lots of fines[9]. Since the shapes of the fine aggregates used in this research (shown in Figure 1) were found to be similar, the results clearly presented that recycled fine aggregate used in this research contains less fines than natural fine aggregate.



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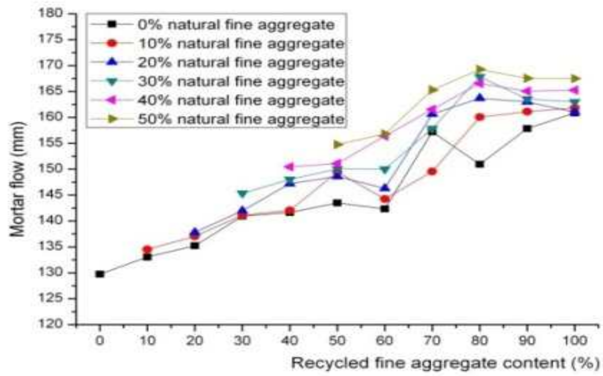


(b)

Figure 4. Mortar flow changes in LMH series mortar: (a) crushed vs. recycled fine aggregate and (b) natural vs. recycled fine aggregate.

The crushed or recycled fine aggregates have been mostly used to replace some amount of natural fine aggregate. Therefore, it is difficult to find an example that uses the recycled fine aggregate to replace crushed fine aggregate. The main reason is associated with the difficulty in controlling the quality of both aggregates. However, the results from Figure 3 (b) presented that the quality of crushed and recycled fine aggregate in terms of mortar flow were similar to each other at least the ones used in this research, and therefore can be used to replace each other without using any natural fine aggregate.

Figure 4 shows mortar flow of LMH series mortars. When recycled fine aggregate content increased (natural fine aggregate content decreased, Fig. 4 (a)), the mortar flow decreased. The higher natural aggregate content to recycled fine aggregate indicates higher F.M., so mortar flow increased as F.M. of blended fine aggregate increased. From Figure 4 (b), when recycled fine aggregate content increased (crushed fine aggregate content decreased), the mortar flow increased. Similarly, the higher recycled aggregate content to crushed aggregate content indicates higher F.M., and as a result, the mortar flow increased as F.M. of blended fine aggregate increased.

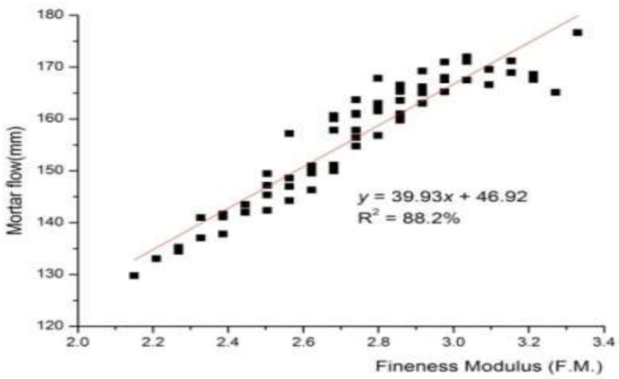


Figure 5. Mortar flow in LMH series mortar depending on the F.M. of blended fine aggregate

In order to verify this finding, the authors have performed calculation of F.M. of blended fine aggregate using proportion of each fine aggregate. The calculated F.M. was correlated with mortar flow of LMH series mortar, and the results are presented in Figure 5. As shown in Figure 5, the mortar flow was clearly affected by the changes in F.M.. The correlation can be presented as linear relationship with correlation factor R^2 to be 88%. The correlation factor goes up to 94% when 4th degree of polynomial curve fit was used, but it is not showing so much of significance. Anyhow, from the results presented in Figures 2, 4 and 5, it is clearly shown that the higher mortar flow was obtained by aggregates with higher F.M., regardless of the aggregate type.

3.2. Air Content

It is known that the air content using good quality of river sand usually contains about 0.5-2% entrapped air [7]. It is also known that the amount of entrapped air actually depends on the quality of river sand. As presented in Figure 6, the air content of MMM series of mortar using 100% natural fine aggregate was shown to be 3.6%. The result indicates improper gradation of the natural fine aggregate although the fineness modulus was set at 2.74. The air content with 100% crushed fine aggregate was 3.7% for MMM series of mortar. This is quite high in air content compared to the reported value (2.77% with 0% dust)[7]. The difference between natural fine aggregate and crushed fine aggregate was minimal, and does not shown to present any trend.

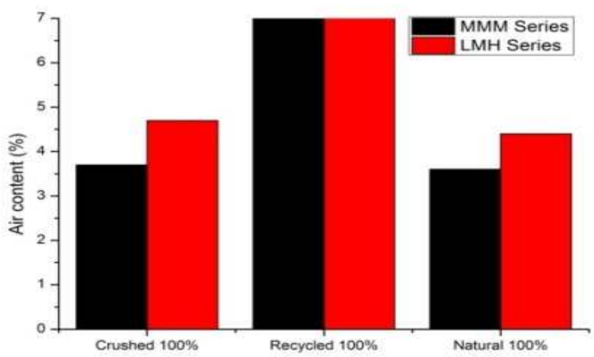
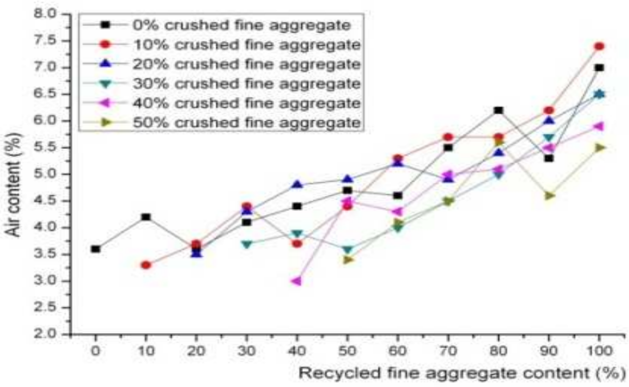


Figure 6. Air content of MMM and LMH series mortar using 100% natural, recycled, and crushed fine aggregate.

It is known that the air content of mortar using recycled fine aggregate is generally 2.5% higher than that with natural fine aggregate[9]. The air content of MMM series mortar using 100% recycled fine aggregate was 7.0%, which is 3.4% higher than that using 100% natural fine aggregate. It is also 0.9% higher than the reported value[9]. However, this value is considered quite reasonable because such difference with recycled fine aggregate may exist depending on the condition of recycled fine aggregate. It is possible to consider that the removal of dust by wet processing actually increased the air-filled volume of the recycled fine aggregate.

As presented from Figure 7 (a) and (b), the air content of mortars increased as the amount of recycled fine aggregate increased. When recycled fine aggregate content increased for 10%, there is an increase in the air content about 0.33% (Figure 6 (a)). This amount is approximately 10% of the difference in air content between mortars using 100% recycled and 100% natural fine aggregate (7.0 - 3.6 = 3.4%). The rate of increasing in air content was proportional to the increase in the recycled fine aggregate content. The same effect was observed between recycled and crushed fine aggregate (Fig. 6 (b)). Therefore, in MMM series mortars, the air content of mortar using natural, crushed, and recycled fine aggregate is mainly governed by the recycled fine aggregate content in the mortar.



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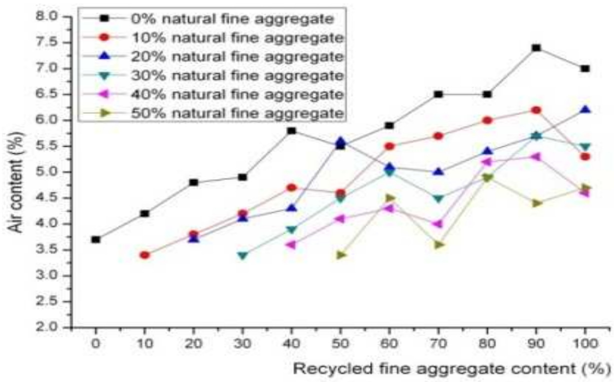
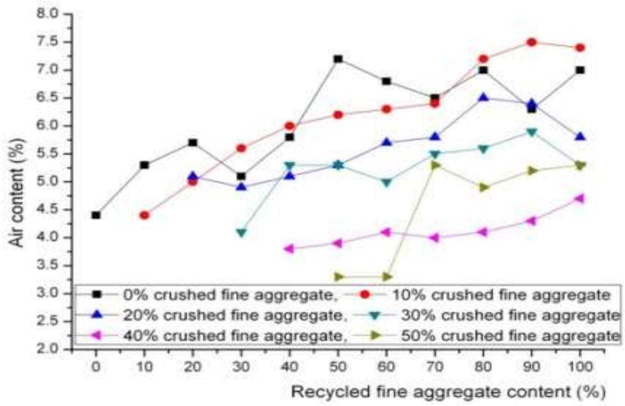


(b)

Figure 7. Air content changes in MMM series mortar: (a) crushed vs. recycled fine aggregate and (b) natural vs. recycled fine aggregate.

Figure 8 shows the air content of LMH series mortars. From Figure 8 (a), the air content generally increased as recycled fine aggregate content increased. However, the air content showed "V" shape curve in Figure 8 (b) showing the minimum air content at 50% of the aggregate was recycled fine aggregate. In fact, the minimum air content in Figure 8 (a) was also observed when 50% of the blended aggregate is recycled fine aggregate. In LMH series, the air content seems to be affected by both recycled fine aggregate content (porosity) and gradation of aggregate particles (F.M.) which make the analysis more complicated.



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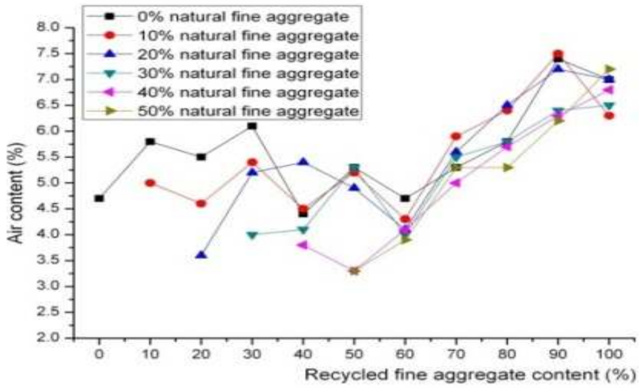


(b)

Figure 8. Air content changes in LMH series mortar: (a) crushed vs. recycled fine aggregate and (b) natural vs. recycled fine aggregate.

Considering the data from LMH series mortar with 100% natural, recycled, and crushed fine aggregate in Figure 6, the air content of mortar using 100% crushed fine aggregate (F.M. 2.15) increased to 4.7% (from 3.7% of MMM series mortar), and the air content of mortar using 100% natural fine aggregate (F.M. 3.33) also increased to 4.4% (from 3.6% of MMM series mortar). It was found that the air content increased when F.M was moving away from 2.74 as it was blended. The result may be associated with improper size gradation of fine aggregate since proper size distribution is required for the maximum packing of the particles that reduces entrapped air content.

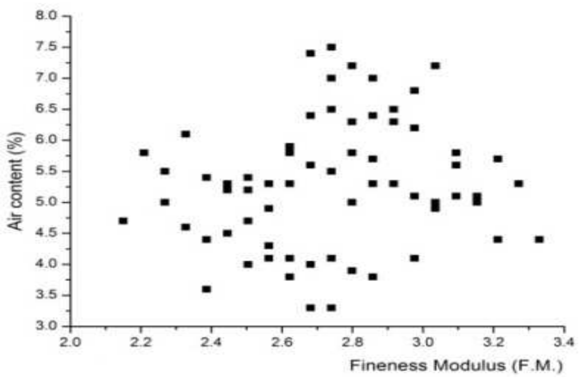
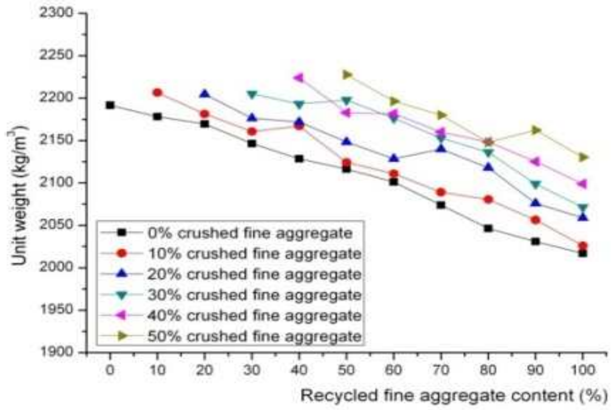


Figure 9. Air content in LMH series mortar depending on the F.M. of blended fine aggregate.



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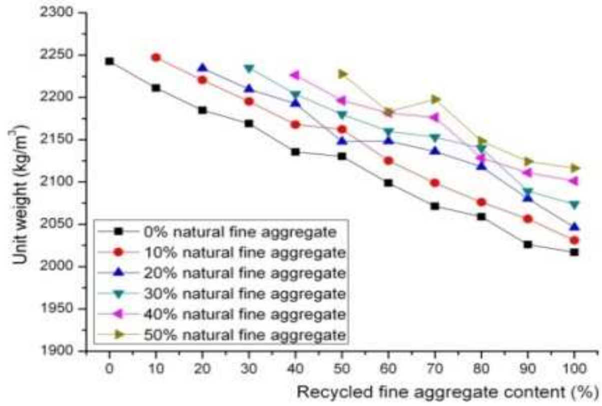


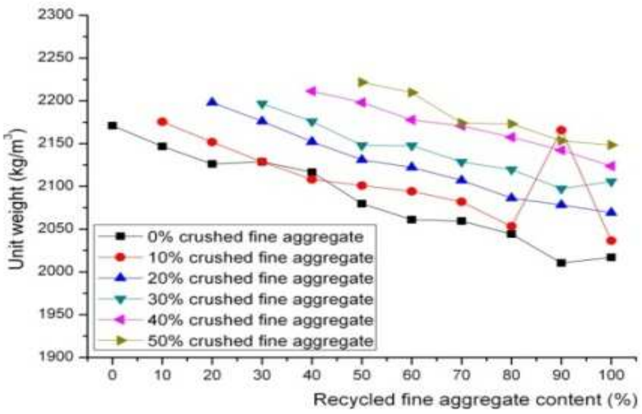
(b)

Figure 10. Unit weight changes in MMM series mortar: (a) crushed vs. recycled fine aggregate and (b) natural vs. recycled fine aggregate.

The same approach done for mortar flow (calculating F.M. of blended fine aggregate using proportion of each aggregate and correlating that to air content) was applied to verify this hypothesis whether F.M. is affecting the air content or not. As shown in Figure 9, no clear changes were observed from the changes in F.M., verifying the air content of the mortar is affected by the porous characteristic of recycled fine aggregate.

3.3. Unit Weight

As shown from Figure 10 (a) and (b), when the recycled fine aggregate content increased, the unit weight of MMM series mortar decreased. The same phenomenon was observed with LMH series mortar (Figure 11 (a) and (b)). Although three data points in LMH series mortar were completely out of the trend (anomaly), general trend was clearly observed and is because of the differences in the oven dry bulk densities of natural, recycled, and crushed fine aggregates that were 2.51-2.52, 2.29, and 2.66 g/㎤, respectively (Table 1).



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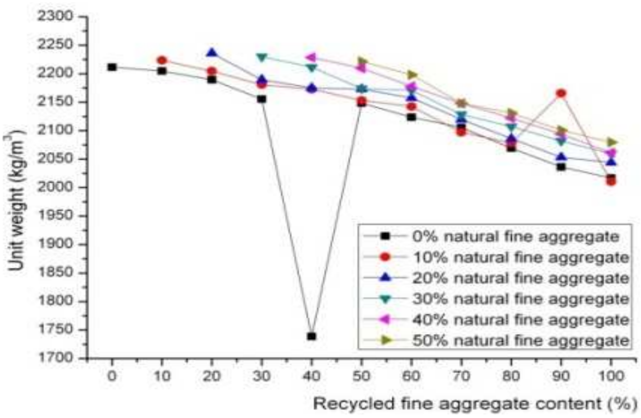


(b)

Figure 11. Unit weight changes in LMH series mortar: (a) crushed vs. recycled fine aggregate and (b) natural vs. recycled fine aggregate.

3.4. Compressive Strength

The compressive strength of mortar using recycled fine aggregate depends on the quality and the amount of recycled aggregate. In case that recycled fine aggregate is used (fine aggregate that is smaller than 2 mm), the compressive strength can decrease up to 40%[10]. Some research[11] reported that the compressive strength increased when 10~20% of the natural fine aggregate was replaced with recycled fine aggregate. They attributed the increase in compressive strength with recycled fine aggregate to the advanced techniques used in recycled aggregate processing facility.

As shown from Figure 12, both MMM and LMH series mortars using 100% recycled fine aggregate showed significant drop in compressive strength. The drop of compressive strength seems to be associated with weaker bond between recycled fine aggregate and cement paste. Such trend with varying recycled fine aggregate content can be observed from Figure 13.

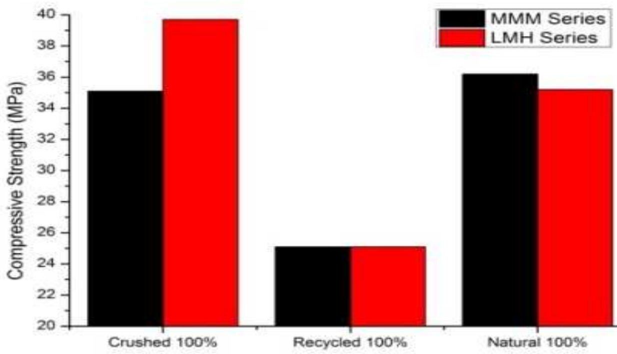
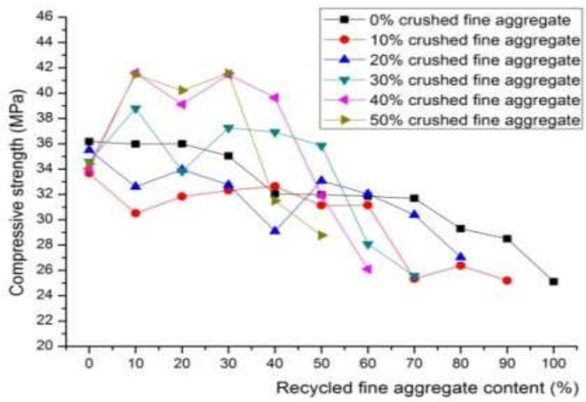


Figure 12. Compressive strength of MMM and LMH series mortar using 100% natural, recycled, and crushed fine aggregate.



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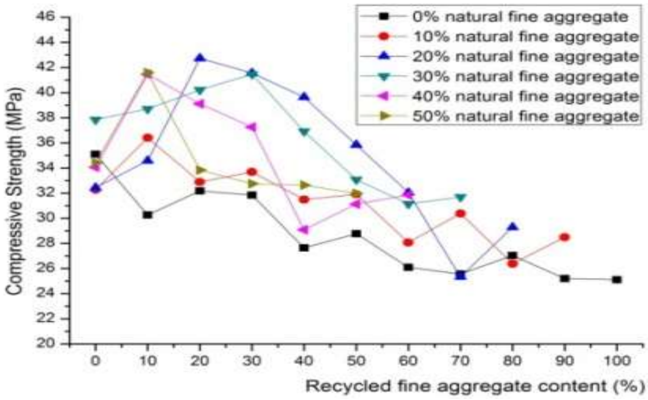
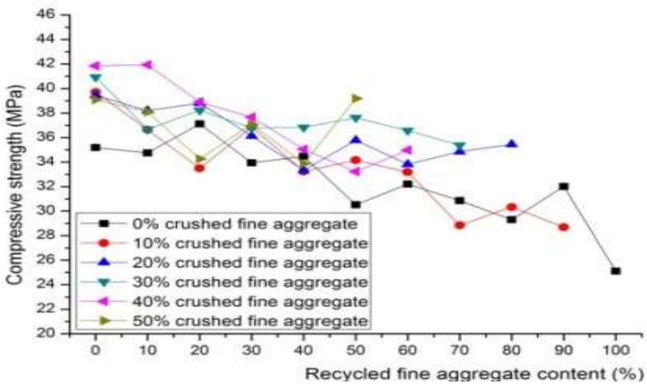


(b)

Figure 13. Compressive strength changes in MMM series mortar: (a) crushed vs. recycled fine aggregate and (b) natural vs. recycled fine aggregate.

As shown from Figure 13 (a) and (b), the compressive strength of MMM series mortar generally decreased as recycled fine aggregate increased. However, as presented from Figure 13 (a), the compressive strength of MMM series mortar showed some notable increase with the recycled fine aggregate content ranges from 10 to 50%. Such increase in compressive strength was observed when crushed fine aggregate contents ranges from 30 to 50% (Figure 13 (a)), but not observed when crushed fine aggregate contents are lower (0 to 20%) (Figure 13 (a)). Various effects seem to be associated with the increase in compressive strength depending on proportion of each fine aggregate. Similar trend is also observed in Figure 13 (b) that the compressive strength tends to be maximized at the recycled fine aggregate content is set at 10 to 40%. This occurred when the natural fine aggregate content is smaller (20%, 30%, and 40%) (Figure 13 (b)). However, the LMH series mortar did not show such synergetic effect as MMM series mortar (Figure 14 (a) and (b)). The compressive strength of LMH series mortar decreased as recycled fine aggregate increased.

The minimum compressive strength that was observed from all the mixtures in this research was 25.1 MPa (with 100% recycled fine aggregate). According to KS F 2573 (2006, Recycled aggregate for concrete), it only specifies concrete with recycled fine aggregate to be used for concrete block, the basement of the pavement, which does not exceed the strength requirement of 27 MPa. However, according to Kim[10], the improved production system in recycling concrete allowed to use recycled fine aggregate up to 50-60% replacement with increase in compressive strength. The result presented in this research, showing the maximum compressive strength of 42 MPa for mortar, suggests that the use of recycled fine aggregate for concrete production is possible for other applications.



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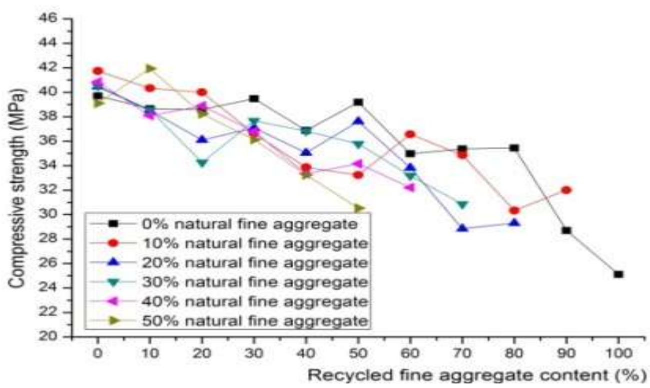

(b)

Figure 14. Compressive strength changes in LMH series mortar: (a) crushed vs. recycled fine aggregate and (b) natural vs. recycled fine aggregate.

4. Ternary Diagram

Both fresh and hardened properties of mortar using natural, recycled, and crushed fine aggregate were presented through Figures 2 to 14. It was difficult to include all the information in a single plot, so the figures had to be divided into two separate ones for better presentation of test results (e.g., Figure 3 (a) and (b) instead of Figure 3). However, such an effort seems not to be sufficient for easy interpretation of the results in some cases. It was still difficult to analyze the effect of blending recycled fine aggregate at one glance because each figure already contains so much information. Various types of graphic methods have been considered for effective presentation of the results to resolve this problem, and the most efficient plot was found to be a ternary diagram, the idea of which was originated from the ternary cement phase diagram. Such ternary presentation method is not available in common spreadsheet programs, so a computer program was developed using C^{++}.

The ternary diagrams presenting various properties of MMM series mortar are shown in Figure 15 (a), (b), (c), and (d). As presented from Figure 15 (a), the differences in mortar flow of MMM series mortars were clearly identified at one glance. The upper part of the region (green) color shows the ranges of mortar flow from 135 mm to 150 mm, and the lower part of the region (yellow) shows the ranges of mortar flow from 150 mm to 165 mm. The mortar flow was lower with higher natural fine aggregate content, and mortar flow was higher with higher recycled fine aggregate content.

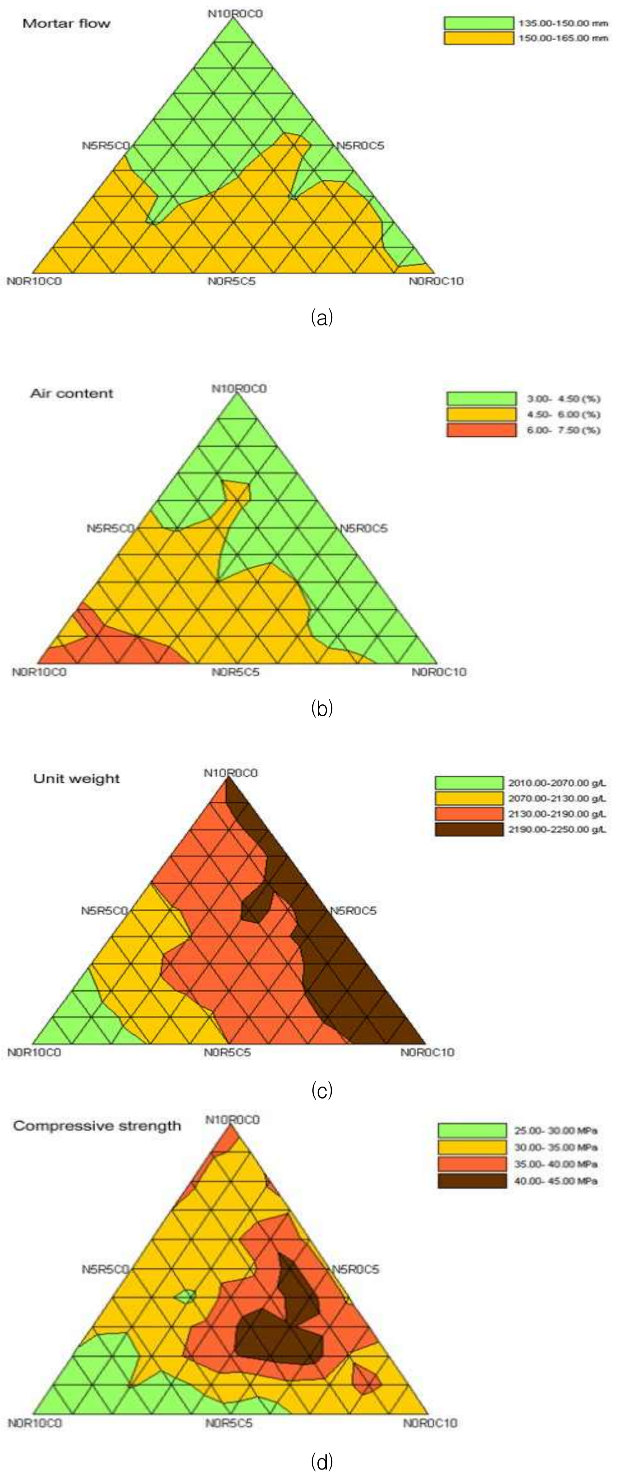

Figure 15. Various properties of MMM series mortar presented using ternary diagram: (a) mortar flow, (b) air content, (c) unit weight, and (d) compressive strength. Note that the symbols N, R, and C indicate natural (N), recycled (R), and crushed (C) fine aggregate, and the numbers after symbols indicate the proportion of the specific fine aggregate (N0R5C5: 0% natural, 50% recycled, and 50% crushed fine aggregate).

As shown from Figure 15 (b), the air content increases with increase in recycled fine aggregate content. The anomaly was observed with N1R9C0 (lower left corner: 10% natural and 90% recycled fine aggregate), and it was quite distinguishable from ternary diagram. The unit weight shown in Figure 15 (c) tends to show decrease as recycled fine aggregate content increased.

The ternary diagram presenting compressive strength of MMM series mortar is shown in Figure 15 (d). As shown from Figure 15 (d), the maximum compressive strength (dark brown region) was observed at lower right part of the ternary diagram. The maximum compressive strength region is located at about 20~30% recycled fine aggregate, 40~60% crushed fine aggregate, and 20% to 50% of natural fine aggregate. The evaluation of compressive strength is much simpler compare to the results shown in Figure 13. The Figure 15 (d) shows the maximum strength at the lower right portion of the plot, and the compressive strength decreases as it moves away from this region. It is clearly noticeable that there is an optimum blending ratio to obtain higher compressive strength. It is also noted that significant loss in the compressive strength is observed when recycled fine aggregate content increased higher than 60%.

The ternary diagrams presenting various properties of LMH series mortar are shown in Figure 16 (a), (b), (c), and (d). The results are also well presented and easily identified. According to Figure 14 (a), the mortar flow was the highest (dark brown region) with upper left region of the ternary diagram which represents the proportion of natural aggregate 70% to 100%, recycled fine aggregate 0 to 50%, and crushed fine aggregate 0 to 30%. The mortar flow decreases as the proportion of fine aggregates moves to lower right corner (higher proportion of crushed fine aggregate). This trend follows the effect of F.M. on the mortar flow that is presented in Figure 9.

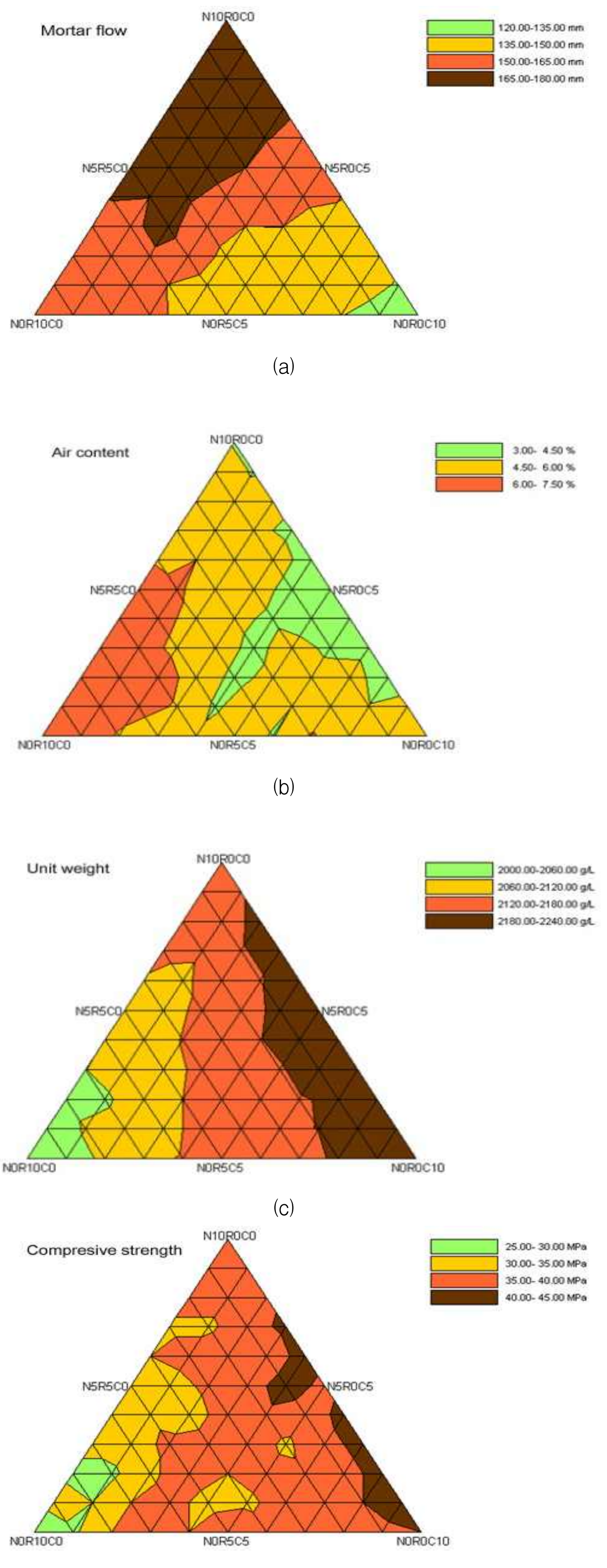

Figure 16. Various properties of LMH series mortar presented using ternary diagram: (a) mortar flow, (b) air content, (c) unit weight, and (d) compressive strength.

The air content of LMH series mortar seems to follow with the amount of recycled fine aggregate. However, green region (air content from 3 to 4.5%) was observed when recycled fine aggregate were used about 30 to 50%. The unit weight strictly affected by the recycled fine aggregate content (Figure 16 (c)). The compressive strength did not show as much synergetic effect as MMM series mortar (Figure 14 (d)). In fact, the compressive strength of LMH series mortar was more affected by the crushed fine aggregate content. When crushed fine aggregate content increased, the compressive strength generally increased.

The main advantage of using this program is to visually present the results at one glance. The results can be effectively presented for the people who need such data for applying to the construction field. The graphical presentation can be a direct indication whether the mixture can be used in the field or not. It means that the program proposed in this research can be used to guarantee the quality and properties of concrete using blended fine aggregates. For example, if the compressive strength requirement is 35 MPa for construction field, the specimens which pass or fail the requirement can be easily determined by simply looking at the ternary diagram (color difference associated by the selection of proper index value).

5. Conclusions

This research used various blended mixtures of natural, crushed, and recycled fine aggregates for production of cement mortar. Considering the environmental regulation on natural aggregate resources, the authors hope that the data presented in this research can be further utilized for production of concrete using recycled fine aggregates. From the results provided in this work, following conclusions can be drawn.

1) The moisture type processing successfully removed the fines and dusts from the recycled fine aggregate. As a result, the mortar flow was not affected by the recycled fine aggregate content, but affected by Fineness Modulus (F.M.) of the blended fine aggregate.
2) Air content increased and unit weight decreased as recycled fine aggregate content increased. It is mainly because of higher surface area and lower oven dry density of recycled file aggregate.
3) Maximum compressive strength was observed with certain blending proportions in MMM series mortar. The ternary diagram effectively shows the results at one glance.
4) The ternary diagram can be effectively used for the quality evaluation of mortar using blended fine aggregate.

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