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EFFECT OF CEMENT ON STRENGTH PROPERTIES OF RECYCLED CONSTRUCTION AND DEMOLITION MATERIALS

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ABSTRACT

Evaluation of innovative ways is necessary to use a huge amount of recycled construction and demolition materials generated in Bangladesh and require satisfaction considering environmental, economic and engineering perspectives. In that sense, this study evaluates the outcomes when stabilized with locally available ordinary Portland cement. Furthermore, this study evaluates the research laboratory characterization of physical, geotechnical, and strength properties of unbound construction and demolition materials, for example, reclaimed asphalt from the pavement (RAP), recycled crushed concrete (RCA) and crushed brick (CB). The results advocated that cement can be a feasible alternative for the stabilization of unbound construction and demolition materials. Based on the test outcomes, RAP, CB, and RCA were found to require 2% of cement to meet the requirements for stabilization with a curing duration of 7 days.

Keywords: *Bangladesh; Ordinary portland cement; recycled materials; strength.*

1. INTRODUCTION

Stabilization is referred to a number of differentprocesses which has been adopted to improve the pertinent properties of the unstabilized materials to permit their use in engineering purposes (Ali, 1992). Better gradation of the particles, decreased plasticity index or swelling potential and improved stability and strength are the most common changes obtained by stabilization (Ali *et al.*, 1992; Jongpradist *et al.,* 2010; Kilic *et al.,* 2015; Mohammadinia *et al.,* 2014). The generated solid waste in the universe expected to be about 3.4 billion tonnes in the year 2050 and it is an emerging threat that the generated waste will be reached in the range of more than three times by 2050 at lower-income countries, as general pupils of that regions are not well-concerned about the severity and potentiality of the wastes (Kaza *et al.,* 2018). Due to tremendous development activity in the world, construction and demolition (C&D) waste materials gained considerable attention among all generated waste in the globe. A large proportion of C&D waste materials have been generated as unwanted materials incidentally or directly from the construction and demolition of new, renovated as well as old structures. The proportion of C&D waste materials is critical in most of the nations that challenged the performance of the development trade as well as its sustainable aims (Kulatunga *et al.,* 2005). Recently, C&D materials are widely used in several civil engineering operations, for example, backfilling, filter media, embankments of roads, footpath applications, retaining walls, the support structure of pipelines, abutment of the bridge and roads (Rahman *et al.,* 2014; 2016). Typically, these C&D waste materials include asphalt concrete, metal, wood, asphalt shingles, cardboard, soil, plastic, Portland cement concrete, and drywall (Ganiron Jr, 2015). According to Arulrajah *et al.* (2013), reclaimed asphalt from the pavement (RAP), recycled crushed concrete (RCA) and crushed brick (CB) are common litters generated among C&D litters in the sphere. The C&D waste materials are about in the range of 25% and sometimes over half of the total municipal solid litters generated in the globe (Yeheyis *et al.,* 2013). Developed countries produced about 35% of construction wastes, whereas, developing countries like Bangladesh, produced about 50% construction wastes of total municipal solid waste generated (Bansal and Singh, 2014; Najafpoor *et al.,* 2014). A study stated that about 2.24 million tons of C&D waste materials such as concrete, plastic, tiles, bricks, steel, aluminum, glass, and timber produced every year in Bangladesh. Environmental Protection Agency projected that around 230-530 million tons of C&D waste materials are generated nationwide in the USA in a single year (EPA, 2017). The generated wastes mostly dumped into landfills, which create an enormous burden on landfill loading. Evidence presents that C&D waste materials contribute approximately 13-60% of all deposited solid waste in landfills in the world (Luangcharoenrat et al., 2019). For example, in the UK it is approximately 59% (Sharman, 2018), in Europe approximately 36% (Eurostat, 2019), and 85-90% in Bangladesh (Islam, 2016; Abedin and Jahiruddin, 2015), of the total, generated C&D waste.For this, the management of C&D waste materials has gained considerable attention in both economically developed and developing countries.

In developing countries, like Bangladesh, a significant amount of improvement in waste management is required, including C&D waste management. Although these countries are recently experiencing significant development in multiple sectors during the last decades, they are suffering from mismanagement systems of wastes installed in their urban environments. Nowadays, the use of the volume of materials increasing for the

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construction of infrastructures of a nation with the pace of the increase of population and industrialization, for example, roads, culverts, bridges, buildings, footpaths, public residents, parking lots in both rural and urban areas. The development in the construction sector is emerging in developing countries, like Bangladesh. Some mega-developments work, such as Padma Multipurpose Bridge, Second Meghna-Gumti-Kanchpur Bridge is continuing across the country are enormous as well as many are waiting to start in forthcoming days. From all the available technical resources and research associated with construction and demolition litter management situation in Bangladesh, authors have acknowledged that the scenario is very frustrating (Chowdhury *et al.,* 2016a). Lack of public knowledge, lack of law enforcement, lack of public knowledge and the use of ancient technologies are the key causes of increased C&D waste generation in Bangladesh compared to many developed and developing nations in the world (Chowdhury *et al*., 2016b). Some literature is available regarding municipal solid litters' generation and its management, but, in the case of C&D litters, enough statistics are not available to forecast the future scenario. In Bangladesh, a large volume of C&D litters is generated in the process of "water line improvement work" in the road and demolition of buildings, especially building the infrastructures of a nation, such as roads, culverts, bridges. The replacement of conventional construction materials with high-quality alternative recycled materials, for example, C&D materials are actively being performed by researchers internationally considering environmental (noteworthy savings of carbon), and construction cost perspective (Disfani *et al.,* 2014; Mohammadinia *et al.,* 2016a; 2016b). Furthermore, as discussed earlier, most of these litters are generally disposed to landfills. And so, landfill cost is another considerable concern aside from environmental effects and construction costs to 3R's (reduce, reuse, and recycling) of C&D materials.

For that reason, industries adopted low-carbon material replacement technology to lessen the exhaustion of virgin resources as well as reuse the generated debris from C&D operations (Du *et al.,* 2013a; Tam and Tam, 2006). Furthermore, improvement of soil properties for the application in roadway embankments and pavements is one of the emerging issues. Chemical stabilization is now extensively adopted for this purpose. Different types of additives, such as an emulsion of asphalt, cement, kiln dust of cement, lime, and fly ash for the chemical stabilization of recycled materials has been comprehensively investigated by numerous researchers to improve the efficiency of recycled roadway C&D materials (Hoyos *et al.,* 2011; Puppala *et al.,* 2011; Mohammadinia *et al.,* 2014; Latifi *et al.,* 2018).

Roads and Highways Department (RHD) of Bangladesh summarized that the overall maintenance cost needed for RHD paved road is approximately BDT 26 thousand million in five year period (2018-19 to 2022-23) and insufficient budgetary provision makes it impossible to undertake the maintenance program (RHD, 2018). It is a common belief of Engineers of Bangladesh, the initial construction cost of rigid pavement is high enough without involving any comparative economic analysis (Bhuyan, 2009). Although the initial construction cost of rigid pavement is very high, the consideration of some operational and functional benefits as well as the perspective of life cycle cost, the investigation of cement for the stabilization of weak pavement constituents is one of the desired alternatives in modern ages for the construction and refurbishment of roads of urban areas of the major municipalities in the globe (Du *et al.,* 1999; 2013b; World Highways, 2004). For example, the engineering and geotechnical characterization of Australian RAP, RCA and CB stabilized with general-purpose Portland cement has been researched by Mohammadinia *et al.* (2014). Based on a personal meeting with RHD personnel in July 2018, RHD estimates that approximately BDT 23 thousand crores can be reserved from 25 years periodical maintenance if the country's road networks built with cement-treated aggregates. It is an estimation only of RHD roads. If the country's entire road network is taking into consideration, it will be multiple of the mentioned figure. Besides, the material cost of cement stabilized roads is almost half of the cost of bituminous roads (Bhuyan, 2009). As per the authors' knowledge, generally superior class crushed bricks and stone aggregates treated with cement widely used for cement stabilized roadway bases and sub-bases in Bangladesh, and so it is necessary to assess the efficiency of cement stabilized C&D materials as a substitute roadway aggregate material. There is no research work done to determine the properties of C&D waste materials generated in Bangladesh using cement as a stabilizer, according to the information available to the authors. However, the diversity of sources of C&D materials, as well as the process of production, may create a detrimental effect on the properties of stiffness, strength, and plastic deformation characteristics of recycled substances (Kim *et al.,* 2007; Kootstra *et al.,* 2010; Al-Bared *et al.,* 2018; Yaowarat*et al.,* 2018). Therefore, laboratory investigation of the locally available C&D waste materials stabilized with cement is focused on this research.

2. METHODOLOGY

In this research, C&D resources encompass of reclaimed asphalt pavement (RAP), crushed brick (CB), and recycled concrete aggregate (RCA), with a nominal size of the particle of 6.3 mm, are culled from the road under construction of the third-largest city of Bangladesh (Figure 1). RAP is the term given to reused pavement materials containing basalt aggregates and aged asphalt binder. Such materials are created when pavements with asphalt are removed for renovation, resurfacing, or for access to buried utilities, conducted regularly. Such products would end up in landfills without reuse of it by a sustainable process (Arulrajah *et al.,* 2013). CB is a by-product of the buildings and other infrastructure construction and demolition operations. CB usually consists of 70 percent brick and 30 percent other non-removed materials, for example, rock, concrete, and asphalt (Arulrajah *et al.,* 2011; 2013).

RCA is created by crushing reclaimed concrete from demolished highways, buildings, bridges, and other structures. The difference between natural aggregate physical properties and RCA is highly influenced by the cement paste, which surrounds the aggregate in crushed concrete (Langer, 2001). Based on the area of application, these concrete chunks are broken into aggregates of varying sizes (Arulrajah *et al*., 2013). Impurities include organic materials, gypsum, clay materials, dry mortar paste, and other construction materials that give reduced quality material as compared with the natural aggregate (Lemanska, 2019; Arulrajah *et al.,* 2013).

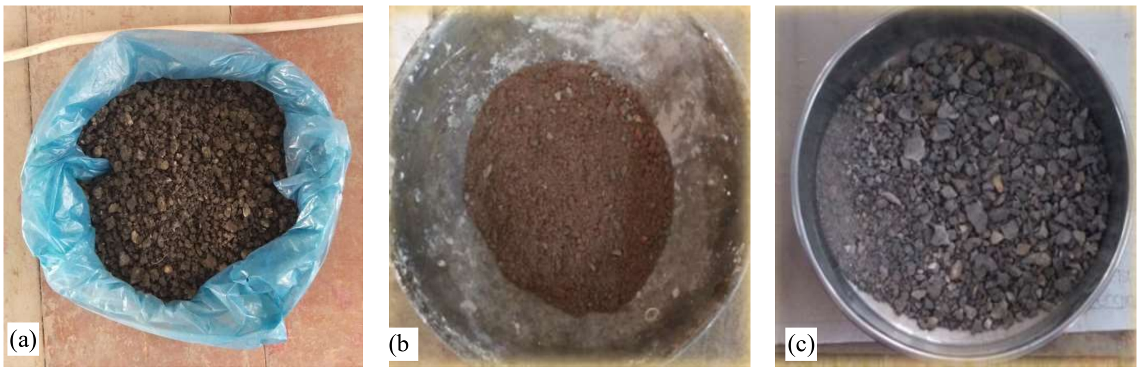

Figure 1: C&D resources used in this study a) RAP, b) CB and c) RCA

Laboratory testing program on untreated C&D materials are comprised of grain size analysis with sieve and hydrometer, Atterberg limit test, determination of particle density (specific gravity), Los angles abrasion, aggregate impact value, flakiness index, water absorption, pH value, Atterberg limits, organic content, modified compaction, and unconfined compression strength (UCS) test. The relevant testing standards are followed to perform all the tests as presented in Table 1. A minimum amount of 5 kg sample of each category of C&D materials has been sieved using the ASTM standard sieve [ASTM D 6913 (ASTM, 2017a)]. Hydrometer analysis has been directed to ascertain the distribution of the size of the particle for the particle sizes smaller than 75-micrometer sieve [ASTM D 422 (ASTM, 2007)]. Hydrometer analysis has not been performed on RAP aggregates as it contained about less than 5% fines content, as suggested by Mohammadinia *et al.* (2014).

The static compaction method is selected for the preparation of the samples as it prevented the cracking along with the interfaces of the aggregates layer (Mundy, 1991). A split compaction mold having a height to diameter ratio (h/d) of 2, with a collar is used for this purpose. Specimens were compacted at a persistent pressure in 8 layers (layers of 1 inch) with the OMC obtained from the laboratory compaction curve under modified proctor energy to acquire the target density. UCS tests were conducted using this split mold of the unprocessed and stabilized C&D substances following ASTM D 5102 (ASTM, 2009). Samples are compacted at static loads to ensure the homogeneity of the mixture, to prevent the damage during the removal, and to maintain the parallel end faces. Initially, the water is mixed with aggregates and has been left for about 1-2 hours (based on the type of material) so that the aggregates absorb the water at room temperature just before the compaction. The dry aggregate materials are blended with the relevant moisture content earlier than the addition of additives to keep away from the free water absorption in the mixture in the course of the curing duration. The materials are thoroughly mixed for 2 to 3 minutes to obtain a homogeneous mixture. Furthermore, the mixing of the additives and the relevant C&D aggregate are performed before compaction to ensure the adequate hydration process with the available free water.

Also, a comprehensive laboratory research program is carried out to evaluate the geotechnical and engineering characterization of RAP, CB, and RCA, when stabilized with ordinary Portland cement (OPC) Type I. The specific gravity (G_s) of cement is about 3.15 and loss on ignition (LOI) is about 3%. The chemical composition of OPC is determined by the X-ray Fluorescence method. In this study, 2 and 4% OPC are selected for the stabilization of the untreated C&D materials. Due to economic considerations, the cement dosage was restricted to a maximum of 4% by dry weight in this research.Moreover, the moisture content of the sample was ascertained after UCS tests and instantaneously after compaction of the mixture to check the moisture content of the sample. The stabilized materials were cured in a moist chamber, maintaining the room temperature from 30^0C to 33^0C and humidity of 97 to 99%. For cement-treated materials, curing periods of 1, 7, and 28 days were adopted to assess the consequence of curing duration on the development of strength.

3. RESULTS AND DISCUSSION

The engineering properties of the untreated C&D substances are highlighted in Table 1. The pH values of the untreated samples point out that the C&D aggregates are alkaline by nature.The observed organic content is highest for RAP compared to other C&D materials; this may be due to the presence of carbon-rich bitumen in RAP. Figure 2 illustrates the grain size analysis plots of the unprocessed C&D substances (before compaction). This figure indicates that the gradation of the CB finest followed by RCA and RAP.RAP, CB, and RCA are classified as well-graded sand as per the Unified Soil Classification System (USCS). RCA exhibits the highest uniformity coefficient (C_u), meaning it is the most well-graded of C&D substances, and CB is more uniform than other C&D materials as it has low C_u value.Besides, Atterberg limit analysis is carried out and the obtained test results indicate that the C&D substances are non-plastic by nature as fine contents are relatively low.

Particle density (specific gravity) and water absorption measurements were conducted on both coarse (4.75 mm sieve retained) and fine (4.75 mm sieve passed) percentages of C&D substances. From Table 1, it is observed that for all the materials tested the particle densities of coarse aggregates are significantly higher than those of the fine aggregates. Of the three C&D materials tested, the RCA showed the maximum particle density for coarse and fine materials. Water absorption of coarse aggregates is smaller than that of fine aggregates for all recycled materials because small particles absorb more water than coarse ones with a larger specific surface. RAP reported the lowest water absorption values between the three recycled C&D materials. It is observed that the water absorption values of untreated C&D materials vary from 2.3% to 12.6%, although the value does not exceed 3% for natural aggregate (Poon and Chan, 2006).

Table 1: Engineering Characterization of Untreated C&D Resources

Engineering properties	Testing standards	RCA	CB	RAP
Water absorption-coarse (%)	ASTM C 127 (ASTM, 2015a)	5.2	5.6	2.3
Water absorption-fine (%)	ASTM C 128 (ASTM, 2015b)	12.6	11.3	6.1
Specific gravity–coarse	ASTM C 127 (ASTM, 2015a)	2.56	2.48	2.43
Specific gravity–fine	ASTM C 128 (ASTM, 2015b)	2.54	2.46	2.42
Fine content (%)	ASTM D 422-63 (ASTM, 2007)	4.2	2.9	1.3
Sand content (%)	ASTM D 422-63 (ASTM, 2007)	58.6	65.4	60.2
Gravel content (%)	ASTM D 422-63 (ASTM, 2007)	37.1	31.8	38.5
Coefficient of uniformity (C_u)	ASTM D 422-63 (ASTM, 2007)	11.0	10.6	6.0
Coefficient of curvature (C_c)	ASTM D 422-63 (ASTM, 2007)	1.3	1.2	1.8
USCS	ASTM D 2487 (ASTM 2017c)	SW	SW	SW
Atterberg limit	ASTM D 4318 (ASTM, 2017b)	Non-plastic		
Flakiness index	BS 812-105.1 (British Standards Institution, 2000)	14	23	11
Aggregate impact value (AIV)	BS 812-112 (British Standards Institution, 1990)	21	17	11
Los Angeles abrasion loss (%)	ASTM C 131 / C 131M – 14 (ASTM, 2006)	35	40	25
pH	ASTM D 4972 (ASTM, 2019)	9.9	10.2	7.7
Organic content (%)	ASTM D 2974 (ASTM, 2014)	1.8	1.0	2.9
Maximum dry density (Mg/m^3)	ASTM D 1557 (ASTM, 2012)	1.92	1.95	2.02
Optimum moisture content (%)	ASTM D 1557 (ASTM, 2012)	11.52	10.50	5.82
UCS (kPa)	ASTM D 5102 (ASTM, 2009)	170	160	340

Note: SW = well graded sand; UCS = unconfined compressive strength; USCS = unified soil classification system

The characteristics of an impact-resistant material are known as toughness. The aggregates are exposed to damage due to the passage of traffic on the road resulting in breaking down into smaller pieces. Therefore the aggregates should have enough toughness to withstand their impact-related disintegration. The measure of resistance to sudden shock or impact is aggregate impact value (AIV), which may vary from its resistance to compressive load when applied gradually. Of the three C&D materials tested, the RCA showed maximum AIV compared to other materials. C&D materials are suitable for construction purposes, as all values are less than 30 (BS 812-112-1990).

The presence of flaky particles is considered undesirable for base course and construction of bituminous and cement concrete forms, as these create inherent vulnerability with the possibility of breaking down under heavy loads. Of the three C&D materials tested, the CB showed maximum flakiness index value compared to other materials. C&D materials are suitable for construction purposes, as all values are less than 30 (RHD, 2011). The aggregate used in the highway pavements surface course is prone to wear due to traffic movement (Hatt, 1939). The Los Angeles abrasion test (LA) is a popular test tool used to demonstrate the aggregate toughness and abrasion properties. The findings of the LA abrasion test show that RAP detects the lowest abrasion and is preceded by RCA. Except for CB, all C&D materials meet the standard stated value range of 30–35 for traditional quarry substances (RHD, 2011).

The compressibility properties of the untreated and treated C&D aggregates are evaluated by the compaction test using a modified effort. The recycled C&D materials are treated with cement. The chemical constituents of this cement are presented in Table 2. Figure 3 illustrates the grain size analysis plots of the treated C&D substances. Figure 4 presented the variation of dry density of materials with moisture content. This figure illustrates that the maximum dry density (MDD) and optimum moisture content (OMC) for untreated C&D aggregates and aggregates stabilized with 2 and 4% OPC. RAP exhibits the highest MDD among the three inspected C&D aggregates, followed by CB and RCA. Furthermore, with the increase in cement content, the MDD values are increased considerably. The MDD value of untreated CB is slightly higher than the 4% cement-treated sample, which may be due to the variations of the application of modified compaction effort. However, RCA presented the highest OMC among the three investigated C&D aggregates, followed by CB and RAP. The fluctuations of the OMC values are negligible with the increase of cement content. The otherness in OMC can be due to the variations of water absorption values of the aggregates.

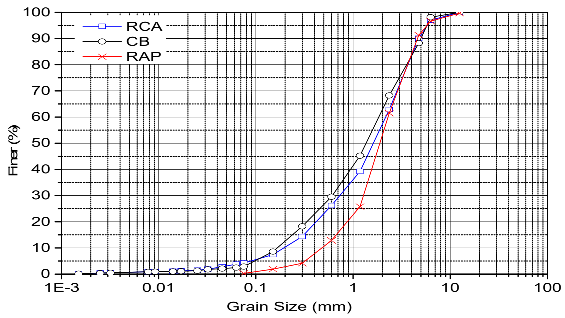

Figure 2: Grain size analysis plots of the untreated recycled samples

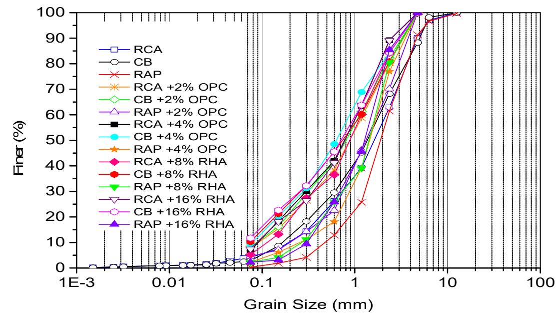

Figure 3: Grain size analysis plots of the treated samples

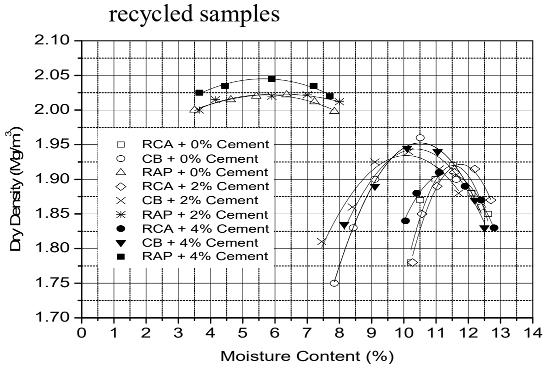

Figure 4: Laboratory compaction curves for unbound and cement treated RAP, RCA, and CB

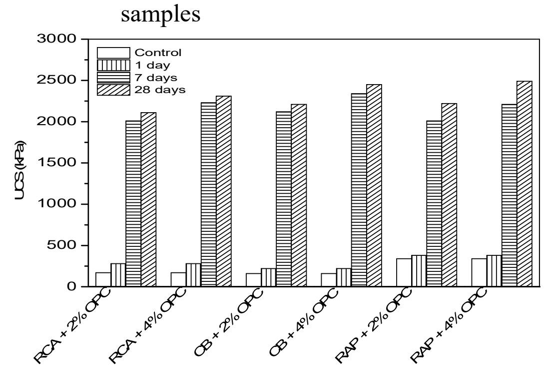

Figure 5: Development of UCS in C&D aggregates with curing period

Table 2: Chemical Constituents in Ordinary Portland cement Type I

Chemical Composition (%)	OPC Type I
SiO_2	21.62
Al_2O_3	5.24
Fe_2O_3	2.60
$SiO_2 + Al_2O_3 + Fe_2O_3$	29.46
CaO	63.61
MgO	2.30
Na_2O_3	0.15
K_2O	1.03
SO_3	2.78

The OMC value of RCA is approximately 9% higher than CB, and the OMC value of RAP is considerably smaller than the other two resources, which is believed to be as a result of the lower water absorption of RAP causing for the presence bitumen coating in the RAP materials. The UCS tests can be used to evaluate the performance of the C&D aggregates in the roadway. This test is carried out to research the improvement of compressive strength resulting from the stabilization with OPC. As per the authors' knowledge, there are no practical considerations on the UCS requirements of roads in Bangladesh. According to UFC (2004), the minimum required UCS test value of 7 days curing varies from approximately 1400 kilopascal for cement-treated pavement sub-bases to 5000 kilopascals for bases. The UCS tests on unstabilized control specimens without a cement treatment and testing are conducted immediately after compaction for comparison of the outcomes of the respective C&D material. Furthermore, UCS tests are conducted to evaluate the effects of curing duration and cement content on the development of compressive strength with 2 and 4% cement contents (Figure 5). The RAP shows the highest UCS value among all untreated C&D materials followed by RCA and CB. Design standards generally based on 7-day test results; however, for a better understanding of the development of UCS of the cement-stabilized C&D materials, 1 and 28 days of curing are also performed.

Noteworthy increments of UCS values are evident in the cement-stabilized C&D aggregates concerning the control samples after 1-day curing. Subsequently, the UCS values are increased considerably with the increase of the curing period to 7 days. Furthermore, the UCS values are increased moderately with the increase of the curing period to 28 days. The higher cement content led to higher UCS value as it increased the bond strength between the materials due to the hydration process with the progression of time. It is clear from the outcomes that the progression of the process of hydration dwindles with time, i.e., the strength values are increased at an impetuous rate at the commencement of the curing duration and start to plateau after 28 days. Better performance is observed for RAP than CB and RCA in all cases with the same OPC content under the same duration of curing; however, RCA presented higher UCS values concerning CB; which indicated that the quality of RAP is best among all the tested materials.

The RAP presented maximum compressive strength among the three tested C&D materials, with approximately 85% of 28 days strength of curing owing to the inclusion of OPC, and the remaining 15% attributed to the initial untreated strength of the material. However, the RCA and CB presented lower strength than RAP with about 93% of 28 days' strength of curing owing to the inclusion of OPC, and the remaining 7% attributed to the initial untreated strength of the material. Based on this study, the cement treatment can be a viable option for the improvement of strength of each of the C&D aggregates.The bond formation and hydration process are highest in RAP as compared with RCA and CB. The RAP reached almost 16% of 28 days strength of curing after 1-day curing, whereas the CB and RCA reached almost 7% of the 28 days cured strength after the same duration. The development of strength of cement-treated C&D samples is significant after the 7-day curing period (90-95% strength gain).

4. CONCLUSIONS

The laboratory characterization of cement-admixed stabilized C&D aggregates is assessed to evaluate the performance of treated materials compared with the untreated C&D aggregates. The strength development on the treated C&D materials is investigated varying curing duration. Based on the UCS test results, RAP, CB, and RCA are found to require 2% cement to meet the requirements specified by the U.S. army corps of engineers for subbase courses. A curing period of 7 days has been qualified for the requirement. The RAP presented better strength compared with RCA and CB in all cases with the designatedpercentage of cement under the nominated duration of curing. The initial dry density of the untreated RAP sample exhibits higher value that makes the initial strength of the RAP aggregates high.The research outcomes indicated that cement-stabilized materials are possible alternatives for the stabilization of unbound C&D aggregates.

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