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MECHANICAL PROPERTIES OF CONCRETE WITH RECYCLED COMPOSITE AND PLASTIC AGGREGATES

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ABSTRACT: The use of recycled materials in concrete applications is a genius alternative because it will significantly reduce impacts on the environment when waste material can be recycled for genuine uses. This project is aimed at studying the influence of incorporating recycled plastic and composite aggregate on the workability, mechanical property, water absorption, and electrical resistance of silica fume concrete. Secondly, the paper will evaluate the possibility to use recycled plastic concrete (RPC) in railway track application (i.e. traditional ballasted track and ballastless track). Two replacements (10% and 20%) of natural coarse aggregate by 3.35mm, 5.6mm and mixed size recycled plastic aggregate are introduced. The experimental results confirm that the workability is improved with an increase in the plastic aggregate replacement. In addition, it is found that mechanical strength and durability in terms of water permeability are reduced, whilst electrical resistance is improved. The result also reveals that application of this environment-friendly recycled plastic concrete in railway tracks sustainably can improve the ability to absorb vibration energy of the railway system.

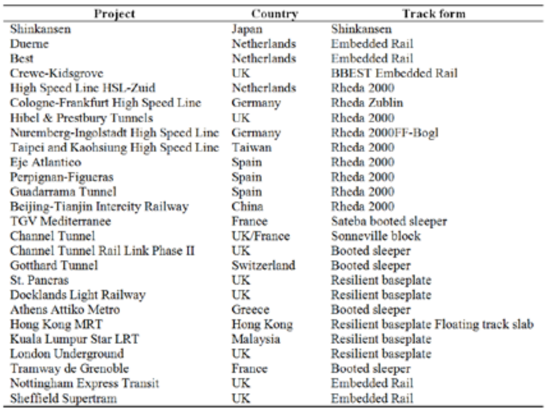
Keywords: Mechanical properties, Recycled composite, Plastic aggregates, Concrete

1. INTRODUCTION

Rapid industrialization and urban development globally have led to many waste handling and disposal problems. The rapid growth affects the uses of raw materials, which are available only in limited quantities. The pressure on finite resources and burdensome wastes results in both economic and societal constraints. The problem of remaining wastes is of major concern around the globe. However, plastic waste is one of the materials that have the potential for recycling. The management and recycling of plastic waste are rapidly growing. The utilization of recycled plastics in concrete is a partial solution to resolve environment and ecological problem. In this study, the research mainly focuses on the application of concrete to railway tracks and evaluates the feasibility to utilize recycle plastic aggregate concrete. Two types of railway track systems will be analyzed and compared including traditional ballasted tracks (sleeper) and ballastless track (Slab Track). A number of experiments will be carried out to evaluate the physical and mechanical properties of the plastic aggregate concrete. The concrete has included Mixed Engineering Polymer (MEP) aggregate as partial replacement of conventional coarse aggregate to create plastic aggregate concrete.

Over the past 50 years, railway systems have been revolutionizing rapidly. The train speed and axle load have come to commuters' primary concern nowadays. Because of these challenges, slab track has been a breakthrough technology to replace conventional ballasted track system. Slab track technology offers proven higher performance in services and a longer life span than traditional ballasted tracks. It is a modern form of track construction, which has been used successfully throughout the world for heavy rail, high-speed lines, light rail as well as tram systems. Slab track technology offers proven higher performance in service and longer life compared to traditional ballasted track. Table 1 shows how successful that slab track is constructed around the world.

Table 1 Slab track projects in the world



Project	Country	Track form
Shinkansen	Japan	Shinkansen
Dueme	Netherlands	Embedded Rail
Best	Netherlands	Embedded Rail
Crewe-Kidsgrove	UK	BBEST Embedded Rail
High Speed Line HSL-Zuid	Netherlands	Rheda 2000
Cologne-Frankfurt High Speed Line	Germany	Rheda Zublin
Hibel & Prestbury Tunnels	UK	Rheda 2000
Nuremberg-Ingolstadt High Speed Line	Germany	Rheda 2000FF-Bogl
Taipei and Kaohsiung High Speed Line	Taiwan	Rheda 2000
Eje Atlantico	Spain	Rheda 2000
Perpignan-Figueras	Spain	Rheda 2000
Guadarrama Tunnel	Spain	Rheda 2000
Beijing-Tianjin Intercity Railway	China	Rheda 2000
TGV Mediterranee	France	Sateba booted sleeper
Channel Tunnel	UK/France	Sonneville block
Channel Tunnel Rail Link Phase II	UK	Booted sleeper
Gotthard Tunnel	Switzerland	Booted sleeper
St. Pancras	UK	Resilient baseplate
Docklands Light Railway	UK	Resilient baseplate
Athens Attiko Metro	Greece	Booted sleeper
Hong Kong MRT	Hong Kong	Resilient baseplate Floating track slab
Kuala Lumpur Star LRT	Malaysia	Resilient baseplate
London Underground	UK	Resilient baseplate
Tramway de Grenoble	France	Booted sleeper
Nottingham Express Transit	UK	Embedded Rail
Sheffield Supertram	UK	Embedded Rail

There are five general types of slab track in the railway industry which are classified as embedded rail, booted sleepers, direct fixing, resilient baseplates, cast-in sleepers and floating slab [1]. The design life for traditional ballasted tracks is typically around 50 years. But concrete track slabs (see Fig. 1) offer longer design life up to at least 60 years. In addition, the track slab does not require frequent inspections and maintenance. Comparing to ballasted tracks, slab track system is fixed in position, therefore, it is not necessary to carry out the regular realignment of the rails. By considering the aspect of maintenance and design life, a track slab is a sustainable option over a 60 year and 120-year lifecycle.

Fig. 1 Typical slab track

2. DESIGN PARAMETERS

For the slab track construction (see Fig. 2), a stabilized subbase are required to provide a more uniform distribution of wheel load stresses which reduces the subgrade stresses and provides a degree of frost protection. Stable subgrade is also an important aspect to consider. The subgrade needs to be uniform, well prepared, with adequate strength and well drained. Poor subgrade may lead to pier settlement and cause rail deformation. Slab track will exhibit failure such as cracking, faulting and pumping due to poor subgrade condition. The failure modes are similar to concrete pavement. Weak subgrade soil and soils are susceptible to frost heave and should be removed and replaced with compacted granular soil. The adjustments to track geometry after construction is very limited. Hence, special preparation of subsoil before construction is essential.

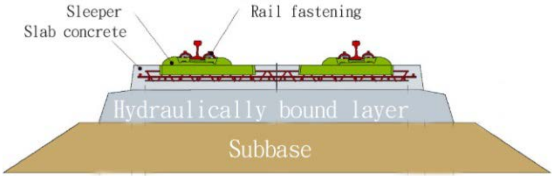


Fig. 2 Cross section of the slab track system

Concrete used for slab track construction is similar to highway pavement construction. Therefore, a material specification developed by the local jurisdiction (state or provincial railway agencies) can be directly adopted [2]. The followings are the minimum requirements:

- Minimum 28 days compressive strength - 27 MPa
- Minimum 28-day flexural strength - 4.1 MPa
- Cement meeting requirement of ASTM C150
- Aggregate meeting requirement of ASTM C33 A. 25 to 38 mm maximum aggregate size may be used. Special attention should be paid to susceptibly freezing, thawing and alkali-aggregate reactivity.
- Air entrainment based on exposure condition. Typically 4 to 7% of total air content is specified for mild to severe exposure conditions.

3. RECYCLED PLASTICS

As the world population increasingly growing, much more wastes are being generated. Plastic waste is one of the major issues affecting the global environment. In the past 50 years, world consumption and production of plastics have continued to go up. 260 million tons of plastic was generated worldwide in 2008, plastic consumption is to reach 297.5 million tons by the end of 2015 [3]. As its nature, plastics belong to a chemical family of high polymers, they are essentially made up of a long chain of molecules containing repeated units of carbon atoms. Because of this inherent molecular stability (high molecular weight), plastics do not easily breakdown into simpler components [4-5]. Therefore, it is very essential to find a sustainable way to solve this issue. It is extremely difficult that recycled plastic is used. That's because plastic waste contains many different types of plastic that have to be treated in different ways for recycling. Now, a new method designed to create expanded construction nodules from mixed plastic waste may replace the expanded clay traditionally used in light concrete that is not used for structural part of a building and often contains air bubbles [6-10].

Fig. 3 Mixed plastic waste

Plastic waste normally collected from the landfill and from other location in the environment and used to manufacture lightweight aggregate. The plastic waste sheet was shaped as desired, e.g. the plastic waste aggregate was modified by heat treatment (160 – 200˚C) in Plastic Granule Recycling Machine. Then, the hot aggregate was removed from the machine and allowed to cool at room temperature, but they were a mixture of angular shapes and round shapes, much like crushed stone. And the obtained plastic granules are ground in a grinding mill to a 20 mm downsize. Fig. 4 shows the plastic granules manufacture process [11].

Fig. 4 Plastic granules manufacture process

4. MATERIALS

4.1 Concrete Mix Design

For the concrete mix design used in this research, the proportion of content was calculated by the method documented in the “Design of normal concrete mixes” published by the building research Establishment. Prestressed concrete sleeper (or railroad ties) are usually designed using high strength concrete (around 50-80). Therefore, the control mixes were designed aiming to achieve a target mean strength of 63 MPa (also known as C 50/60) at 28 days. A water-cement ratio of 0.44 was designed on the basis of the target mean strength, the cement strength class and as well as the type of the aggregate. The amount of free water content used to achieve the designed w/c ratio was based on the desired slump, the maximum size and the type of aggregate. Cement content was calculated by the values of w/c ratio and the amount of free water. Mixed engineering polymers (MEP) sizes of 5.6mm and 3.35mm were used to replace 10% and 20% of coarse aggregate using direct volume replacement method. In addition, MEP without sieve was also used to replace 10% of the coarse aggregate. Silica fume was also added to replace 10% of cement by volume in all MEP concrete. Due to lack of time, 20% MEP without sieve concrete hasn’t conducted in the reports. Seven concrete mixtures are prepared (as tabulated in Table 2) for this research program to study the effect of MEP sizes and their distribution: RFC, SFC, SFRC-5.6-10, SFRC-5.6-10, SFRC-3.35-10, SFRC 3.35-20 and SFRC mix-10.

4.1.1 Cement

The cement used for the present investigation was Ordinary Portland type 1 with characteristic strength of 52.5MPa according to BS EN 197-1 [12].

Table 2 Concrete Mix Design (kg/m^3)

No	Mixes	Cement	Water	Gravel	Sand	Silica Fume	MEP
1	RFC	530	233	986	630	0	0
2	SFC	477	233	986	630	53	0
3	SFC-5.6-10%	477	233	887.4	630	53	98.6
4	SFC-5.6-20%	477	233	788.8	630	53	197.2
5	SFC-3.35-10%	477	233	887.4	630	53	98.6
6	SFC-3.35-20%	477	233	788.8	630	53	197.2
7	SFC mix-10%	477	233	887.4	630	53	98.6

4.1.2 Aggregate

Aggregate normally refers to gravel, pebbles, natural sand, and artificial sand. The size of coarse aggregates is greater than 4.75mm, while the size of aggregates less than 4.75mm is called fine aggregate. Fine aggregate with a maximum particle size of 4.75mm and coarse aggregate with a maximum size of 10mm are used in the mix.

4.1.3 Silica Fume

Silica fume is a very reactive pozzolan, which concrete containing silica fume can have very high strength and durability. In this study, Elkem Silica fume, grade 940 was replacing 10% of cement by volume in all recycled plastic concrete to enhancing the mechanical properties. Table 3 shows the properties of Silica Fume used in this research [13].

Table 3 Chemical and physical properties

Property	Value
SiO_2	Minimum 90%
Loss on ignition	Maximum 3%
Coarse particles > 45µm	Maximum of 1.5%
Bulk density (U)	200-350kg/m^3
Bulk density (D)	500-700kg/m^3

4.1.4 Recycled plastic aggregate

In this study, recycled plastic aggregates also called Mixed Engineering Polymers (MEP) were used to replace the coarse aggregate to study the property of plastic aggregate concrete. The MEP was kindly supplied by Axion Polymers. This type of MEP is a mixture of clean, wasted granular chips rich in PP with regular particle size. MEP sizes of 6.7mm, 5.6mm, 4.75mm and 3.35 mm were classified from the sieving vibrator. Two different sizes of MEP are used in this study: 5.6 mm and 3.35 mm.

5. EXPERIMENTAL RESULTS AND DISCUSSION

5.1 Workability

Slump test was carried out to determine the workability of the fresh concrete. The procedure of the slump test complied with BS EN 12350-2[22]. Fresh concrete was filled to the cone in three stages. In each stage, the layer was compacted 25 times with a rod or stick. At the end of the third stage, the protruding concrete on the top of the mold was struck off flush with a trowel. The mold was then lifted vertically upward. Finally, the slump was measured (see Fig. 6). Workability of concrete is measured in terms of ease and homogeneity with which a freshly mixed concrete or mortar can be mixed, transported to the construction site, placed in forms and compacted. The higher the slump, the easily the concrete to mixed, transported, placed and compacted. From the result obtained from the Slump test, replace 10% cement by silica fume to significantly reduce the workability about 50%. The workability can improve by low replacement rate of silica fume around 2-3% by mass of cement but can reduce workability when added at higher replacement rates. Fig. 7 clearly shows that adding plastic can enhance the workability.

Fig. 6 Slump test

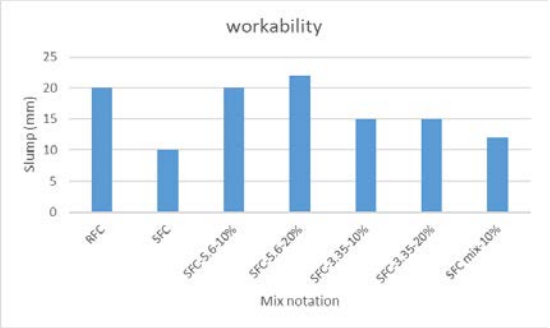


Fig. 7 Slump of concrete

5.2 Density

All 28 days concrete cubes mass of each concrete sample was measured before compressive strength test by Eq. (1):

$$\boldsymbol{\rho} = \frac{\boldsymbol{m}}{\boldsymbol{v}} \qquad (1)$$

where: $\boldsymbol{\rho}$ is desity (kg/m^3), $\boldsymbol{m}$ is mass (kg), and $\boldsymbol{v}$ is volume (m^3).

The dry density for all concrete mixtures is shown in Fig. 8. Replacing 10% silica fume by weight of cement slightly increase the Density by 2.6%. The density tends to decrease with an increase with EMP replacement content. 20% EMP replacement (SFRC-5.6-20% and SFRC-3.35-20%) reduce up to 50% in density compare with SFC. It is attributed to the lower density of plastic aggregate compare to normal aggregate. The size of MEP doesn't affect the dry density, SFRC-5.6-20% and SFRC-3.35-20% can consider as a lightweight concrete since its dry density is not more than 2200kg/m3. Concrete with lower weight can be ideally applied to slab track. Because of its lower weight property, it can reduce the subgrade weight and added stress. It is believed that plastic aggregate concrete with adoptable strength can enhance and controlling subgrade settlement in special soil areas.

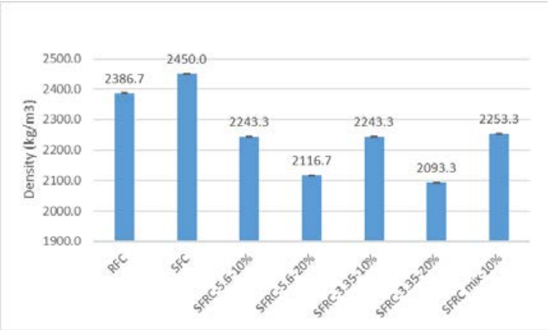


Fig. Density of concrete

5.3 Compressive Strength

Six 100mm x 100mm x 100mm cube test were casted per concrete mixture. Three cubes were tested at 7 days and the other three cubes were tested at 28 days (see Fig. 9). The compressive strength tests were carried out on those cubes. The compressive strength test was conducted according to BS EN 12390-3[23]. As earlier mentioned, this type of concrete is designed to apply for railway applications either a concrete sleeper or slab track. The control concrete (RFC) was designed to have the target mean strength of 62 MPa at 28day in order to meet the minimum requirement of a concrete sleeper which is 55 MPa. Each mechanical property value presented in Figure 10 is the average value obtained from tests performed on three specimens.

It can be seen that a reduction in the mechanical strength according to the increase in the percentage of MEP in the silica fume concrete.

Fig. 9 Compressive strength test

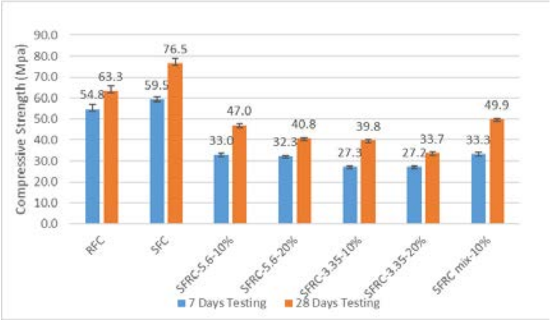


Fig. 10 Compressive strength of concrete

Compressive strength significantly drops after replace 10%wt MEP, around 38.6%, 48% and 34.8% of 5.6mm, 3.35mm and mixed size MEP respectively. Compressive strength slightly decreases after 10%wt further MEP addition around 13% and 15.3% reduction of 5.6mm and 3.35mm MEP respectively. It is attributed to the smooth surface of MEP result in a weaker interfacial region between MEP and cement matrix than that between natural aggregate and cement matrix. In addition, the strength of MEP is far lower that of the natural aggregate, therefore the strength of MEP concrete is lower than that of normal concrete. The higher the content of MEP results in a more weak interface between the plastic and cement matrix. Consequently, the compressive strength of MEP concrete decrease with an increased weight percentage replacement of MEP aggregate. On the other hand, the size of the MEP also affects the strength of the concrete. Figure 10 shows the relationship between 5.6, 3.35 and mixed size MEP. It can be clearly seen that compressive strength of concrete contained 5.6mm MEP such as SFRC-5.6-10% and SFRC-5.6-10% has higher strength than 3.35mm MEP (SFRC-3.35-10% and SFRC-3.35-10%) for both 7 and 28 days. 3.35mm MEP recorded a fall of 15.35% in 10%wt replacement and 17.4% in 20%wt replacement 28 days compared to 5.6mm MEP.

5.4 Splitting Tensile Strength

Cylinder splitting test was conducted according to BS EN 12390-6. Three samples of 100mm diameter x 200mm long concrete cylinder per mixture were used (see Fig. 11). The splitting tensile strength of concrete specimen in MPa was calculated by using the below formula according to BS EN 12390-6 [24].

$$\boldsymbol{f_t} = \frac{\boldsymbol{2P}}{\boldsymbol{\pi DL}} \quad (2)$$

where $\boldsymbol{f_t}$ is the splitting tensile strength (MPa), $\boldsymbol{P}$ is the applied failure load obtained from the testing machine, $\boldsymbol{D}$ is the cross-sectional diameter of cylithe nder (mm), and $\boldsymbol{L}$ is the cylinder length.

Fig. 11 Splitting tensile test

The effect of MEP content on the splitting tensile strength shows in Fig. 12. 28-day testing, the result shows that the splitting tensile strength of all concrete mixes has a similar trend in comparison with compressive strength. The SFC was still the highest tensile strength of 3.85Mpa which is approximately 22.9% increase compared to RFC. This increasing range between RFC and SFC was similar to the compressive strength (20.9% improvement). The splitting tensile strength of SFC containing 10% MEP replacement using 5.6mm, 3.35mm and mixed size was decreased by 38.1%, 43.6% and 37.7% respectively due to the weakened interface between the plastic and cement paste. The similar decreasing rate can be obtained in compressive strength which is 38.6%, 48% and 34.8%. But no obvious reduce is observed up to the level of 20% MEP replacement in SFRC-5.6-20% and SFRC-3.35-20%, only 8% and 11.5% reduction of 5.6mm and 3.35mm. The SFRC-mix-10% still was the highest tensile strength due to its well-graded effect. It can be summarized the variation is very similar to that of compressive strength.

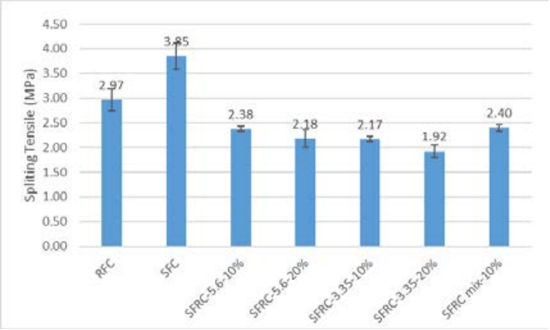


Fig. 12 Splitting tensile strength of concrete

5.5 Flexural Strength

Flexural tensile strength test was carried out to investigate the tensile strength of the concrete mix (see Fig. 13). The experimental set up was a 4-point beam test and it was conducted according to BS EN 12390-5 [25]. Three samples of W100 x H100 x L500mm per mix were tested. The splitting tensile strength of concrete specimen in MPa was calculated by using the below formula according to BS EN 12390-5.

$$\boldsymbol{f_{cf}} = \frac{\boldsymbol{F \times I}}{\boldsymbol{d_1 \times d_2^2}} \quad (3)$$

where $\boldsymbol{f_{cf}}$ is the flexural strength (MPa), $\boldsymbol{F}$ is the maximum load applied, $\boldsymbol{I}$ is the distance between the roller supports (mm), and $\boldsymbol{d_1}$ and $\boldsymbol{d_2}$ are the cross-sectional dimension of concrete the specimen (mm).

Fig. 13 Flexural strength test

The tendency of 28-day flexural tensile strength varying with coarse aggregate replacement content is shown in Fig. 14. As the 5.6mm, 3.35mm and mixed size MEP content increase to 10%wt, the flexural strength is apparently reduced 28%, 29% and 24.5% respectively. The reduction rate is much less than in both compressive strength and tensile strength test. No significant difference is obtained at 10%wt

MEP replacement in 5.6mm, 3.35 mm and mixed size MEP, which can demonstrate that size of MEP in the range on this study doesn't have a great influence to flexural strength when replacing 10 %wt of coarse aggregate. However, significant variation happens at 20%wt replacement in comparison with 10%wt. A 10% reduction in flexural strength was observed in SFRC-5.6-20%, while 28.3% reduction was seen in SFRC-3.35-20%.

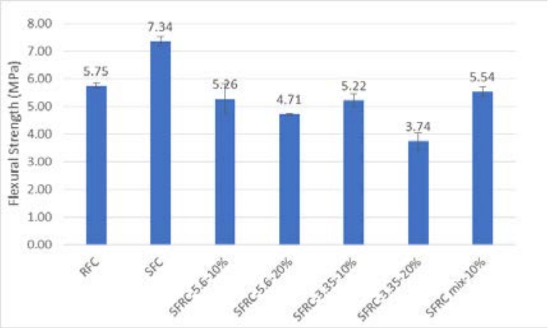


Fig. 14 Flexural strength of concrete

6. CONCLUSIONS

This research focused on the study and evaluation of the environment-friendly concrete containing with recycled plastic aggregate (5.56mm, 3.35mm and mixed size) to utilize for railway concrete sleepers and ballastless tracks. Seven concrete mix tests were conducted to investigate the possibility of using those concrete in the railway industry. The test aimed to study the effects on workability and mechanical properties due to the presence of plastic inside the concrete. The experiment results have shown that the utilization of the plastic material in making concrete can provide an alternative solution to minimize the environmental impact due to unscientific disposal of waste plastic. The following conclusions are drawn from this study:

- Plastic can enhance the workability of concrete which facilitates mix, transport, place and compact process.
- Presence plastic aggregate will lead to a significant reduction in mechanical strength e.g. Compressive and tensile strengths, however, adding 10%wt silica fume can slightly compensate for the loss of the strength. SFCA-5.6-10% and SFCA-mix-10% obtain the highest strength compare to other plastic.
- All of the EMP concrete failed to meet the concrete sleeper minimum compressive strength requirement of 55MPa. However, all the MEP concrete can be used in ballastless track since all the concrete compressive strength excess 27 MPa
- SFCA -5.6-20% and SFCA-3.35-10% can be used in a light weight concrete such as a back-filling trench, pavement, or in a nonstructural element which not required high strength.
- SFCA-5.6-10% has excellent mechanical property. It is highly recommended to use in the highway-rail slab track system.

7. ACKNOWLEDGMENTS

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